John A. Burt
Editor

A Natural History of the Emirates

OPEN ACCESS

Springer

A Natural History of the Emirates

John A. Burt
Editor

A Natural History of the Emirates

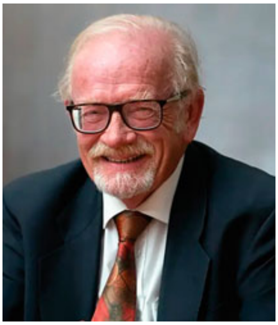
Springer

Editor
John A. Burt
Arabian Center for Climate and
Environmental Sciences
New York University Abu Dhabi
Abu Dhabi, United Arab Emirates

ISBN 978-3-031-37396-1 ISBN 978-3-031-37397-8 (eBook)
https://doi.org/10.1007/978-3-031-37397-8

This work was supported by New York University Abu Dhabi

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland



This book is dedicated to the memory of Peter Hellyer, whose deep understanding and love for the UAE's natural world has been an inspiration to us all. In his honor, we invite you to delve into these pages, to explore the UAE's rich tapestry of life, and to share in Peter's deep passion for natural history.

Foreword

From sprawling deserts and soaring mountains to vibrant coastal and marine ecosystems, the United Arab Emirates is home to a stunningly diverse array of natural environments.

The UAE is also situated in a region that is highly vulnerable to the consequences of climate change. Climate-related impacts like extreme heat, scarce precipitation and higher sea levels not only threaten our way of living as human beings—but they also put entire ecosystems and all of the organisms they contain at risk. The UAE is deeply conscious of this and has long been committed to the conservation of the natural environment, through initiatives such as implementing the region's largest coral reef rehabilitation project and bringing endangered species like the Arabian oryx back from the brink of extinction. It is also why the country is taking a leading role in driving climate action, both in the UAE and beyond, in collaboration with public, private and civil society stakeholders.

Professor John Burt and his associated authors have provided a wonderful exploration of the natural history of the Emirates. This work, a first of its kind, is an important contribution to literature on this topic and captures in sweeping detail the richness and diversity of the UAE's environment. It also underscores the critical need to protect these precious ecosystems and sustain biodiversity under a changing climate.

Razan Al Mubarak

International Union for Conservation of Nature (IUCN), Gland, Switzerland

Environment Agency – Abu Dhabi, Abu Dhabi, United Arab Emirates

Mohamed bin Zayed Species Conservation Fund, Abu Dhabi, United Arab Emirates

UN Climate Change High-Level Champion for COP28, Abu Dhabi, United Arab Emirates

Contents

1 A Natural History of the Emirates: An Introduction 1
John A. Burt

Part I An Extreme Environment: Physical Setting of the Emirates

2 Geography and Geology of the United Arab Emirates: A Naturalist's Introduction 13
Gary R. Feulner

3 Climate of the United Arab Emirates: Present, Past and Impacts on Life 65
Francesco Paparella and John A. Burt

4 The Marine Environment of the Emirates 95
John A. Burt and Francesco Paparella

Part II Ecosystems of the Emirates

5 The Vegetation of the United Arab Emirates and Ecosystem Management Issues 121
Gary Brown and Gary R. Feulner

6 The Mountain Regions of the United Arab Emirates: An Ecosystem Perspective 161
Gary R. Feulner

7 Mangrove Ecosystems of the United Arab Emirates 217
Guillermo Friis and Mary E. Killilea

8 Coastal Lagoons (*Khors*) of the Emirates 241
Daniel Mateos-Molina, Simon J. Pittman, Marina Antonopoulou, Stephen Carpenter, Mona Möller, Sabir Bin Muzaffar, and Ivonne Bejarano

9 Seagrasses of the United Arab Emirates 267
Noura Al-Mansoori and Himansu Sekhar Das

10 Seaweeds of the Emirates 287
David M. John

11 Coral Reefs of the Emirates 325
John A. Burt

12 Oyster Beds and Reefs of the United Arab Emirates 353
Ivonne Bejarano, Daniel Mateos-Molina, Sandra L. Knuteson, Nadia Solovieva, Fadi Yaghmour, and Fatin Samara

Part III Organisms and Their Environment

13 The Vascular Flora of the United Arab Emirates 387
Gary Brown and Gary R. Feulner

14 Terrestrial Mammals of the United Arab Emirates 427
Jacky Judas

15 An Introduction to the Birds of the United Arab Emirates 469
Oscar Campbell

16 Terrestrial Reptiles and Amphibians of the United Arab Emirates 507
Johannes Els, Salvador Carranza, and Andrew Gardner

17 Terrestrial Arthropod Diversity in the United Arab Emirates 531
Brigitte Howarth

18 Marine Mammals of the Emirates: Whales, Dolphins, Porpoises and Dugongs 557
Ada Natoli and Shamsa Al Hameli

19 Marine Reptiles of the United Arab Emirates 585
Fadi Yaghmour, Johannes Els, Clara Jimena Rodríguez-Zarate, and Brendan Whittington-Jones

20 Sharks and Rays of the United Arab Emirates 621
Aaron C. Henderson and Shamsa Al Hameli

21 Fishes of the Emirates 645
Matthew D. Mitchell, Johannes Els, and Marie Seraphim

Part IV Human Interactions with the Environment

22 Human–Environment Interactions in the United Arab Emirates: An Archaeological Perspective 673
Timothy Power

23 Cities as Ecosystems in the Emirates 703
John A. Burt, Oscar Campbell, and Jacky Judas

Part V The Future Emirates

24 The Emirates at 2050: Balancing Development and Environmental Stewardship 735
John A. Burt, Noura Al-Mansoori, Ivonne Bejarano, Gary Brown, Oscar Campbell, Johannes Els, Gary R. Feulner, Guillermo Friis-Montoya, Aaron Henderson, Brigitte Howarth, David M. John, Jacky Judas, Daniel Mateos-Molina, Matthew Mitchell, Ada Natoli, Francesco Paparella, and Fadi Yaghmour

Chapter 1
A Natural History of the Emirates: An Introduction

John A. Burt

1.1 Nature in the Context of a Rapidly Growing Nation

The United Arab Emirates (UAE) has witnessed exceptional growth in both its population and economy since its formation in 1971. Its rapid development and the expansion of trade, tourism, and industry have catapulted the UAE onto the world stage, earning it international recognition for its ultramodern cities and architectural marvels. This transformation has turned the country into a global hub for business, innovation, and cultural exchange, attracting millions of visitors and expatriates from around the world.

While the country's achievements in infrastructure, industry and commerce are truly remarkable, it is equally important for residents and visitors alike to appreciate and gain a deeper understanding of the UAE's nature and natural history. The unique ecosystems, and diverse flora and fauna that call the UAE home, not only provide the foundation for the nation's rich cultural heritage, but also serve as a testament to the resilience and adaptability of life in this arid region. From the majestic sand dunes of the Rub' al Khali to the vibrant marine life in the Arabian Gulf, the UAE's natural landscapes offer a fascinating window into the complex interplay between humans and their environment throughout history.

Natural history research in the UAE has played a pivotal role in deepening public awareness and appreciation for the country's diverse ecosystems and its unique biodiversity. Over the years, dedicated researchers and institutions have endeavored to uncover the distinctive biodiversity and complex dynamics of the UAE's natural environments. This continuing pursuit of knowledge has led to important discoveries and insights that have not only enriched our understanding of the region's unique

J. A. Burt (✉)
Arabian Center for Climate and Environmental Sciences (ACCESS) and Water Research Center (WRC), New York University Abu Dhabi, Abu Dhabi, UAE
e-mail: John.Burt@nyu.edu

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_1

ecology, but also highlighted the need for enhanced conservation and sustainable development. As natural history research in the UAE continues to evolve, it will serve as a powerful tool to support growing public awareness, instilling a sense of pride and responsibility in the nation's natural heritage, and promoting environmentally conscious policies and practices that will ensure a sustainable future for generations to come.

1.2 The Evolution of Natural History Research in the Emirates

The early records of natural history in the Emirates originated from military and consular excursions to the region in the nineteenth century. Captain Atkins Hamerton was the first European known to have visited the area of the Al Ain oasis in 1840, while Lt Col S.B. Miles, the Muscat Consul, referred to the presence of Arabian oryx (*Oryx leucoryx*), cape hare (*Lepus capensis*), and gazelle (*Gazelle* sp.) in the desert areas of Abu Dhabi and Al Ain during a 1975 visit. A decade later, Surgeon Major A.S.G. Jayakar of the Indian Army visited the area and contributed to scientific knowledge with his discoveries of the Arabian tahr (*Hemitragus jayakari*) and two species of reptile (*Agama jayakari* and *Lacerta jayakari*), commemorated in specimens still held by the Bombay Natural History Museum and the British Natural History Museum (Hellyer and Aspinall 2005).

In the early twentieth century the famous *Gazetteer* author, J.G. Lorimer, compiled a species list of fishes found in the waters of the Arabian Gulf (Lorimer 1908), while an expedition by the Peabody Museum at Harvard University in 1954 found a total of 64 species of mollusks in the Emirates, then known as the Trucial Coast (Hellyer and Aspinall 2005). Sir Wilfred Thesiger explored much of southern Arabia after the Second World War, recording the presence of the Arabian tahr and red foxes on and around Jebel Hafit (Thesiger 1959) (Fig. 1.1).

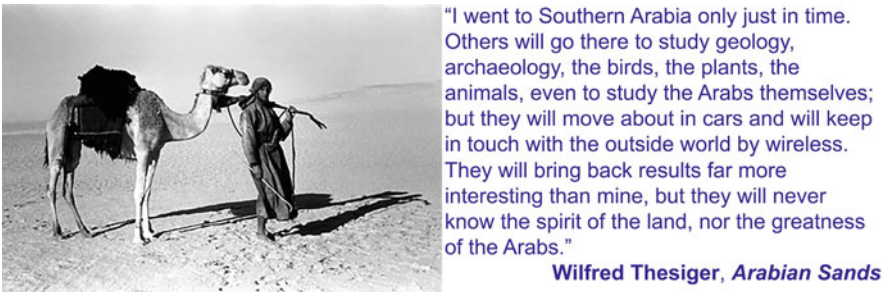


Fig. 1.1 British explorer Sir Wilfred Thesiger is best known for his book "Arabian Sands," which chronicles his journeys across the Rub' al Khali or "Empty Quarter" in the late 1940s. Image: Wilfred Thesiger by Falvialoner (CC-BY-SA-4.0). Quotation from Thesiger (1959)

As oil exploration grew in the wake of the Second World War, studies of the UAE's natural history evolved from occasional opportunistic reports to more focused studies as the nascent oil companies recruited international scientific expertise to study the region (Hellyer and Aspinall 2005). While the main thrust was in geology and geomorphology, many research teams included specialists in mammals, birds, marine ecosystems, and other elements of natural history, many of which left their mark by publishing some of the first comprehensive records for the area. For example, Kinsman (1964) published the first records of the unusual heat-tolerance of Abu Dhabi corals in the preeminent scientific journal, *Nature*, in 1964, and others followed with deeper and more comprehensive reef descriptions in the following decade (Kendall and Skipwith 1969; Evans et al. 1973; Shinn 1976) (see Chap. 4).

While growing research by international experts was adding to the corpus of knowledge about the natural history of the Emirates, it was often collected by transient foreign visitors, with records published in international journals and collections kept in overseas museums that were largely inaccessible to residents of the UAE (Hellyer and Aspinall 2005). Additionally, while much local ecological knowledge existed within the citizenry of the nascent UAE (e.g. timing and location for fishing or hunting), it was typically only shared through oral history between people for whom it had practical value, making it vulnerable to loss as the economy evolved (Hellyer and Aspinall 2005).

The establishment of the Emirates Natural History Group (ENHG) in Abu Dhabi in 1977 shifted this perspective (Hellyer n.d.). As the Emirates' economy developed, the number of expatriates taking up residence in the UAE grew rapidly, coinciding with explosive growth of interest in the ecosystems and organisms living in the newly adopted home of these international travelers. Many of these individuals were keen amateur naturalists rather than professional scientists, yet their group became the leading producers of scientific knowledge in the Emirates over the coming decades. The group conducted regular field trips to remote parts of the UAE, sharing their observations through public seminars and documenting their records in the ENHG *Bulletin*, which published 42 issues between 1977 and 1991 alone. By 1979 a new ENHG chapter was established in Al Ain, followed by the Dubai chapter in 1984 (Jongbloed 2003; Hellyer and Aspinall 2005). The outings by ENHG members have led to numerous discoveries over the years, such as the re-discovery of the Arabia tahr (*Hemitragus jayakari*) in March 1997 on Jebel Hafit by members of an ENHG bird-watching group. This mammal was previously considered extinct, as it was last seen over 15 years earlier and it had gone unobserved during two extensive official surveys in 1986 and 1990 (Jongbloed 2003).

As records and reporting grew more extensive in the *Bulletin* and its sister publication of the Dubai ENHG, the *Gazelle*, the peer-reviewed scientific journal *Tribulus* was established in 1991 and continues to be published today (named after the national flower of the UAE, *Tribulus omanense*, Fig. 1.2). *Tribulus* has become the journal of record for the UAE's natural history, and includes numerous highly impactful articles describing new records of species' occurrence in the Emirates, species new to science, unique methods used by organisms to cope with the environmental extremes of the area, and approaches for conservation and

Fig. 1.2 *Tribulus omanense* is the national flower of the United Arab Emirates, inspiring the title *Tribulus* for the long-running peer-reviewed scientific journal of the Emirates Natural History Group. Image credit: Gary Brown

management of local organisms and ecosystems (Hellyer and Aspinall 2005). All ENHG groups are non-profit, volunteer-led organizations, with the purpose "to give encouragement and assistance towards the appreciation and study of the natural history, natural sciences and history of the United Arab Emirates and neighbouring states" (Jongbloed 2003), and readers of this book are encouraged to join their local chapter.

While amateur natural historians have made the most important contributions to our knowledge of the Emirates in the past, in recent years there has been a shift towards wider engagement of professional scientists and academics as the number and size of universities has grown. Beginning with the establishment of UAE University in Al Ain in 1977, followed by Zayed University in Dubai and Abu Dhabi in 1998, and later by international institutions such as New York University Abu Dhabi in 2010, among others (Hellyer and Aspinall 2005; Burt et al. 2019), there has been substantial growth in the number of professional researchers living in the UAE, with many focusing their research on the environment and ecosystems of the Emirates (Burt 2013; Vaughan and Burt 2016; Friis and Burt 2020). This has been particularly true of the past decade, as regionally-focused environmental research centers have been established at several institutions and as recent graduates have joined local government agencies to establish and nurture research agendas at those institutions (Burt et al. 2011; Alsharari 2018). As a result, the number of historic publications related to several distinct ecosystems in the Emirates has more than doubled in just the past decade, and publications are predominantly from researchers based in the region, rather than transitory researchers visiting from other parts of the world as had often been the case in the past (Vaughan and Burt 2016; Friis and Burt 2020).

While research by amateur and professionals alike has added a phenomenal volume of knowledge on the natural history of the Emirates in the past 50 years, there is still much to learn. For example, the Bird Database of the Emirates has

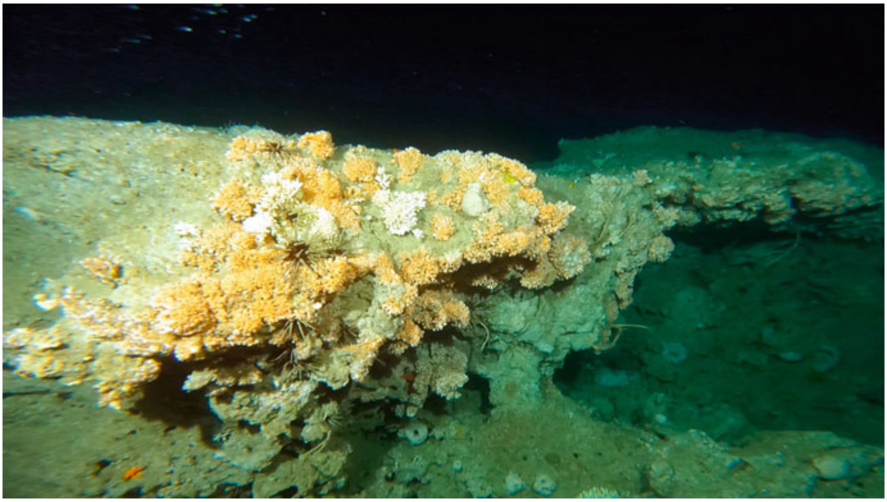


Fig. 1.3 In 2022 a mesophotic coral reef was discovered in Fujairah, UAE, at 145 m depth, where organisms live in permanent darkness. Such discoveries show that we still have much to learn about the natural history of the Emirates. Image credit: Simon Nadim

grown from 20,000 records in 2003 to over 772,000 by 2022, with over 60,000 records added annually at present, expanding our knowledge of species-specific habitat use across the UAE (Jongbloed 2003; Tommy Pederson, pers. comm.). Likewise, recent surveys of insects and other arthropods identified over 2000 species not previously known to occur in the UAE, of which over 370 were species new to science (Villet 2010; Barclay 2011; Wakeham-Dawson 2015). Species revisions and additions continue for numerous other groups of organisms as well (Carranza et al. 2016; Kirchner et al. 2020). It is not only new species that are being discovered, but also whole ecosystems. Deep-water mesophotic (low light) coral reefs were not known to occur in the Emirates until 2022, when one was discovered at 145 m depth off the coast of Fujairah (Fig. 1.3), and subsequently surveyed by specialist technical divers (Dennehy 2022). These few examples demonstrate that as research continues to develop, the depth and breadth of our knowledge of ecosystems, organisms and the environment of this young nation will continue to expand.

1.3 An Overview of ‘A Natural History of the Emirates’

This book represents a comprehensive summary of the current state of knowledge of the natural history of the Emirates. Building on the strong foundations laid by earlier amateur and professional natural historians alike, the contributing authors have compiled their collective knowledge of the geology, environment, ecosystems and organisms of the Emirates into a single volume that provides readers with a comprehensive overview of the natural environment of the United Arab Emirates (UAE).

The first section of the book focuses on the physical environment of the Emirates, including an overview of the geography, geology and climate of the UAE. Gary Feulner opens the book with an introduction to the geological history and biogeographic affinity of the region (Chap. 2), emphasizing its main geographic sub-environments that foster diverse plant and animal communities across the nation. Francesco Papparella and John Burt then explore the climate of the UAE by examining the geographic processes that drive today's extreme aridity, before exploring current climate change and its implications for life (Chap. 3). The section also covers the marine environment of the Emirates (Chap. 4), which contains one of the most environmentally unique seas on earth in the Arabian Gulf as well as the diverse and productive Gulf of Oman coast.

The major terrestrial and marine ecosystems of the UAE are discussed in the second section. Gary Brown and Gary Feulner describe the vegetation of the UAE in the context of broad terrestrial habitats, and challenges related to its management in this rapidly developing nation (Chap. 5). Feulner then covers the biogeographically unique mountain region (Chap. 6), shedding light on its unique geological and climatic sub-features that drive patterns of life towards the UAE's east coast.

Shifting towards the coast, the mangroves of the UAE are discussed by Guillermo Friis-Montoya and Mary Killilea (Chap. 7). They highlight mangroves' importance as an 'ecosystem engineer' that support numerous resident and migratory species by providing food, shelter and spawning habitat, with mangrove forests in the Emirates making up over half of the total area of Gulf forests and continuing to grow due to local conservation and afforestation efforts. Likewise, coastal lagoons (*khors*) are addressed by Daniel Mateos-Molina and colleagues (Chap. 8), who emphasize their incredible significance to biodiversity as mosaics of ecosystems such as mangroves, mudflats and seagrass beds that are interconnected and highly productive areas supporting rich biodiversity. Moving offshore, seagrasses of the UAE are explored by Noura Al-Mansoori and Himanshu Das (Chap. 9), while David John provides an account of the regional seaweeds (Chap. 10). John Burt focuses on the coral reefs (Chap. 11), discussing their importance to biodiversity and science and the challenges of managing these systems under considerable local and global pressure. Lastly, Ivonne Bejarano and colleagues explore the oyster beds and reefs of the UAE, which are of significant ecological and cultural importance (Chap. 12).

The third section of this book delves into the diverse flora and fauna found in the UAE, showing that despite the generally extreme conditions a wide array of uniquely adapted species call the Emirates their home. Chapters provide an overview of the diversity of species within their groups, their biogeographic affinities, and explore unique features of these organisms that allow them to survive and often thrive in the UAE's environment. Gary Brown and Gary Feulner provide an account of the vascular flora (Chap. 13), while Jacky Judas covers the terrestrial mammals (Chap. 14). Oscar Campbell presents an introduction to the birds of the UAE (Chap. 15), highlighting their diversity and distribution in natural ecosystems, including both resident and migrant bird communities that utilize the Emirates as a stopover ground on their long-distance transits. Terrestrial reptiles and amphibians are discussed by Johannes Els, Salvador Carranza and Andrew Gardner (Chap. 16), who provide insights into their ecology and conservation, while Brigitte Howarth focuses on terrestrial arthropod diversity (Chap. 17), emphasizing the importance of invertebrates in ecosystem functioning and food webs.

Moving into the marine realm, marine mammals of the Emirates, including whales, dolphins, porpoises, and dugongs, are covered by Ada Natoli and Maitha Al-Hameli (Chap. 18), while marine reptiles including turtles and snakes are discussed by Fadi Yaghmour, Johannes Els, Clara Jimena Rodríguez-Zarate and Brendan Whittington-Jones (Chap. 19), who provide insights into the ecology and conservation of these species in the UAE. Sharks and rays are addressed by Aaron Henderson and Shamsa Al-Hameli (Chap. 20), while Matthew Mitchell, Marie Seraphim and Johannes Els discuss the diverse fish species found in the Emirates, including both marine and freshwater bony fishes (Chap. 21).

The final section of the book examines the complex relationship between humans and the environment in the UAE. Tim Power provides an archaeological perspective on human-environment interactions (Chap. 22), highlighting the changes that have occurred over time. John Burt, Oscar Campbell and Jacky Judas then discuss how today's cities serve as unique ecosystems in their own right, and explore the ways in which urbanization has impacted the natural environment and how commensal organisms are taking advantage of the unique artificial microclimates and habitats that incidentally arise from development (Chap. 23). The book concludes with a forward-looking chapter titled The Emirates at 2050 (Chap. 24) which explores what nature in the UAE may look like in the coming decades if bold steps are taken by decision-makers to enhance public awareness, understanding and appreciation of the distinctive ecosystems and organisms that reside here, as well as to enhance their conservation for the enjoyment of future generations.

Overall, this book provides a comprehensive understanding of the natural environment of the United Arab Emirates, with a focus on its unique ecosystems, diverse flora and fauna, and the human impacts on these fragile habitats. It is a valuable resource for researchers, students or others interested in the ecology and environment of the UAE and its natural history. By acknowledging the significance of the UAE's natural resources, it is our hope that readers will walk away from this book with a deepened appreciation for the importance of nature in the UAE and a newfound commitment to preserving and protecting its ecological wonders. Through increased awareness and appreciation of the UAE's natural history, we can better understand the intricate relationships between humans and their environment, and work together to strike a balance between development and conservation. This book serves as an essential foundation for those seeking to contribute to this vital mission, fostering an informed and proactive community that is dedicated to safeguarding the rich natural heritage of the United Arab Emirates for future generations to enjoy.

References

Alsharari NM (2018) Internationalization of the higher education system: an interpretive analysis. Int J Educ Manag 32:359–381. https://doi.org/10.1108/IJEM-04-2017-0082

Barclay MVL (2011) Arthropod Fauna of the UAE, volume 2. Syst Biodivers 9:175–176. https://doi.org/10.1080/14772000.2011.589968

Burt J (2013) The growth of coral reef science in the Gulf: a historical perspective. Mar Pollut Bull 72:289–301

Burt J, Al-Harthi S, Al-Cibahy A (2011) Long-term impacts of bleaching events on the world's warmest reefs. Mar Environ Res 72:225–229

Burt JA, Killilea ME, Ciprut S (2019) Coastal urbanization and environmental change: opportunities for collaborative education across a global network university. Reg Stud Mar Sci 26:1–10. https://doi.org/10.1016/j.rsma.2019.100501

Carranza S, Simó-Riudalbas M, Jayasinghe S, Wilms T, Els J (2016) Microendemicity in the northern Hajar Mountains of Oman and The United Arab Emirates with the description of two new species of geckos of the genus Asaccus (Squamata: Phyllodactylidae). PeerJ 4:e2371. https://doi.org/10.7717/peerj.2371

Dennehy J (2022) Dive to 144 metres off UAE reveals mysterious 'Mars-like' reef the national, Abu Dhabi

Evans G, Murray JW, Biggs HEJ, Bate R, Bush PR (1973) The oceanography, ecology, sedimentology and geomorphology of parts of the Trucial coast Barrier Island complex, Persian gulf. In: Purser B (ed) The Persian Gulf. Springer, Berlin, pp 233–277

Friis G, Burt JA (2020) Evolution of mangrove research in an extreme environment: historical trends and future opportunities in Arabia. Ocean Coast Manag 195:105288. https://doi.org/10.1016/j.ocecoaman.2020.105288

Hellyer P (n.d.) A brief history of the emirates natural history group. Emirates Natural History Group, Abu Dhabi

Hellyer P, Aspinall S (2005) Researching the emirates. In: Hellyer P, Aspinall S (eds) The emirates: a natural history. Trident Press Ltd, London, pp 13–26

Jongbloed M (2003) Looking at nature: the history and achievements of the natural history groups in the UAE. Al Shindagah 55. https://www.alshindagah.com/novdec03/lookingatnature.htm

Kendall C, Skipwith P (1969) Geomorphology of a recent shallow-water Carbonate Province: Khor Al Bazam, Trucial coast, southwest Persian gulf. GSA Bull 80:865–892. https://doi.org/10.1130/0016-7606(1969)80[865:Goarsc]2.0.Co;2

Kinsman DJJ (1964) Reef coral tolerance of high temperatures and salinities. Nature 202:1280–1282

Kirchner S, Kruckenhauser L, Pichler A, Borkenhagen K, Freyhof J (2020) Revision of the Garra species of the Hajar Mountains in Oman and The United Arab Emirates with the description of two new species (Teleostei: Cyprinidae). Zootaxa 4751. zootaxa 4753.4756

Lorimer JG (1908) Gazetteer of the Persian Gulf,'Omān, and Central Arabia. Superintendent Government Printing, Calcutta, India

Shinn E (1976) Coral reef recovery in Florida and the Persian Gulf. Environ Geol 1:241–254

Thesiger W (1959) Arabian sands. Longmans, London

Vaughan GO, Burt JA (2016) The changing dynamics of coral reef science in Arabia. Mar Pollut Bull 105:441–458. https://doi.org/10.1016/j.marpolbul.2015.10.052

Villet MH (2010) Arthropod Fauna of the UAE Vol. 3, A. van Harten (Ed.): book review. Afr Entomol 18:383. https://doi.org/10.10520/EJC32858

Wakeham-Dawson A (2015) Book review: arthropod Fauna of the UAE, volume 5. Entomol's Mon Mag 151:142–143

Part I
An Extreme Environment: Physical Setting of the Emirates

Chapter 2
Geography and Geology of the United Arab Emirates: A Naturalist's Introduction

Gary R. Feulner

2.1 Introduction

The natural history of the United Arab Emirates (UAE) can be envisioned as a stage drama in which all the plants and animals, even human beings and their different cultures through time, play their parts and live out their lives (Fig. 2.1). Viewed this way, geography and geology are literally the stage sets for the drama of life. They are the physical background where all the different action takes place.

This chapter will introduce the landscapes of the UAE and its many 'stage sets' from a naturalist's perspective. Although the UAE is not a large country, it has many physical environments that are unusual on a global scale, yet at the same time relatively accessible and relatively safe to explore. An added bonus is that the flora and fauna and other phenomena of many of those environments remain to be fully explored, so there are still new discoveries to be made.

The geography of a particular location comprises the different landforms that we can see there and the physical qualities and characteristics that are associated with them, including global geographical position (latitude and longitude), elevation, surface composition (rock, soil, sand, marsh, etc.), slope, surface roughness, hydrology (plumbing) and proximity to major water bodies, as well as climatic factors such as temperature, rainfall, humidity, wind regime and seasonality (discussed in the next paper, Chap. 3). Vegetation cover, height and density are also part of the description of the geography of a place (Fig. 2.2).

One difference between stage sets and the real world is that real world environments typically change continuously through time, sometimes gradually and other times very rapidly. The history of those changes can be read and understood by studying and interpreting the geological and geographical features we see today. The prevailing plant and animal life of a place inevitably changes as the environment

G. R. Feulner (✉)
Dubai Natural History Group, Dubai, UAE

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_2

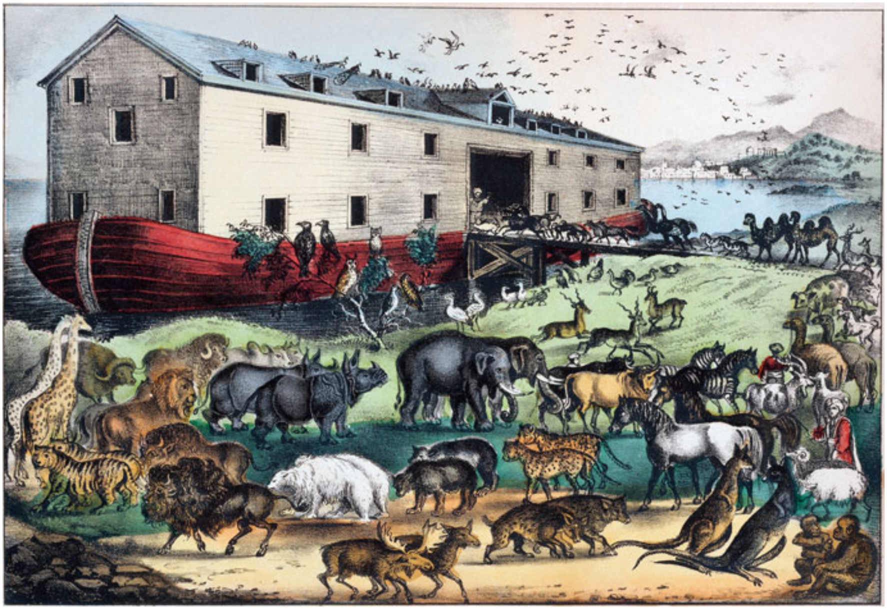


Fig. 2.1 "Noah's Ark". Hand-colored lithograph by Currier & Ives, 1868–1878. The original is held at The Metropolitan Museum of Art in New York and is reproduced here by courtesy of the Met's Open Access policy, modified to remove border

changes, but biological systems often take more time to change, so the geological and geographical history of a place, especially the recent history, can impose limits on current and even future possibilities for the local biosphere.

2.2 The Principal Geographical Units of the UAE

The UAE today features four principal geographical divisions (Fig. 2.3):

(a) the Coastal Plains of the Arabian Gulf and the Gulf of Oman.
(b) the Sand Deserts of the west, south and central UAE.
(c) the Mountain Regions of the eastern UAE.
(d) the Alluvial Plains that flank the mountain regions on the east and west.

These four basic units and some of their most distinctive sub-units are described and discussed below. In general, they correspond to the units that will be discussed from an ecosystem point of view in Chaps. 5, 6 and 13.

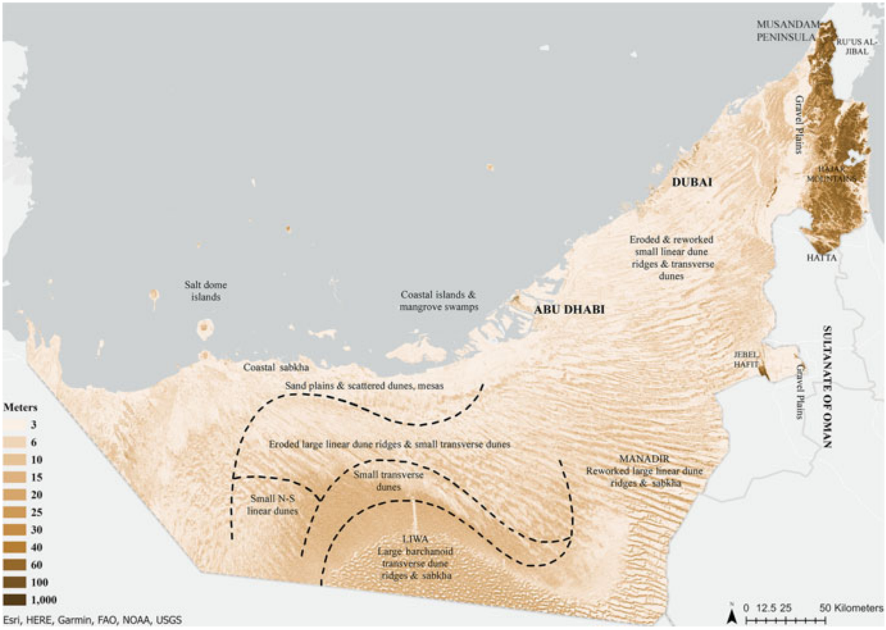


Fig. 2.2 A topographic map of the UAE, annotated to show the variety of UAE landforms. Topographic data from ESRI, created in ArcGIS. Annotations modified from Glennie 1991 and reused with permission

2.2.1 *The Coastal Plains*

The coastal plain constitutes the more or less flat topography that, along UAE coastlines, extends inland from the low tide line for up to several kilometers before encountering terrain of more substantial relief, usually sand dunes or, along the East Coast, mountain ridges or foothills.

Prior to modern development, the flat coastal plain along the Arabian Gulf was essentially unbroken between Sha'am in northern Ras Al Khaimah and the Sila'a peninsula at the Saudi Arabian border, except for coastal hills at a few remote places such as Ras Al Aysh and the Shuwaihat peninsula in the west of Abu Dhabi emirate. But the nature of the coastal plain was (and is) far from uniform. Although much of the former coastline has been highly modified, the Coastal Plain still includes all of the following:

(a) White sand beaches, especially in the area from Ras Al Khaimah to Taweelah (Abu Dhabi) (Fig. 2.4).
(b) Coastal sabkha, or salt flats, especially along the Arabian Gulf coast west of Abu Dhabi Island, where they are reckoned to be the world's finest examples of this geologically significant environment (Fig. 2.5).

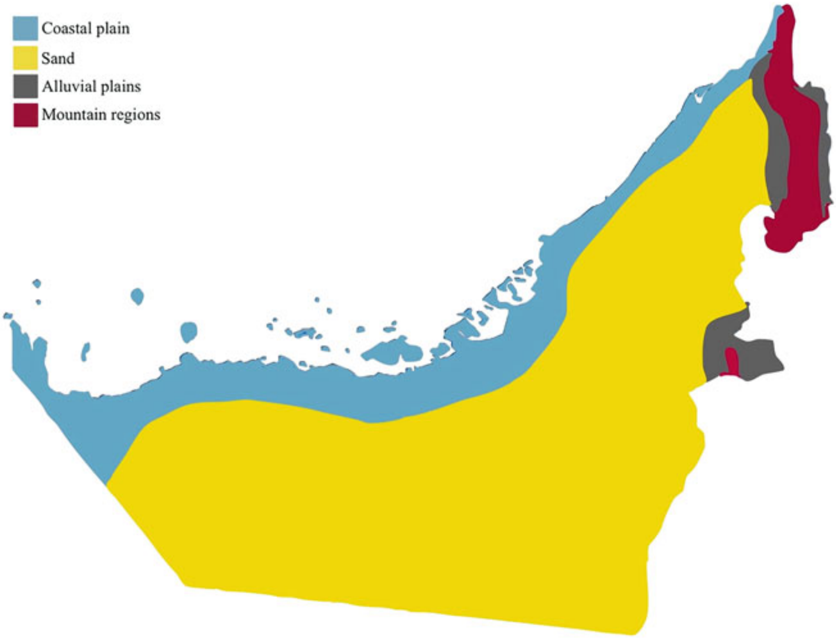


Fig. 2.3 The four principal geographical divisions of the UAE, which correspond to the four principal terrestrial environments/ecosystems. Image credit: Gary Brown

(c) Sheltered coastal lagoons (Arabic: *khors*), many of them so shallow that they empty almost entirely at lowest tides, exposing vast mudflats and a rich diversity of associated intertidal marine life, including food resources relied on by hunter-gatherer ancestors (see Chap. 8) (Figs 2.6 and 2.7).

(d) Mangrove forests, monospecific stands of the local mangrove *Avicennia marina* occupying the intertidal zone, sometimes tall and dense, representing the only true “forests” in the country, most of them associated with coastal lagoons or channels representing the outlets of former terrestrial watercoursess debouching to the sea (see Chap. 8) (Fig. 2.8).

(e) Salt marsh, stands of dwarf shrubs, sedges and grasses occupying the uppermost intertidal zone, typically on the margins of coastal lagoons where freshwater input is localized.

(f) Remnant outcrops of eroded coastal dunes and shallow marine sediments, mostly Pleistocene and Holocene (Recent) in age, reflecting a long history of repeated emptying and filling of the Arabian Gulf due to ‘Ice Age’ changes in sea level; also more substantial mesas of older, mostly Miocene sedimentary rocks, as at Ras Al Aysh and the Sila’a Peninsula (Fig. 2.9).

(g) Rocky headlands/cliffs, on the UAE’s East Coast, where salient ridges or foothills of the Hajar Mountains extend to the sea and form headlands at the

Fig. 2.4 A white sand beach near Saih Shuaib, Dubai, near the Abu Dhabi border. In the distance is a massive artificial headland, built to accommodate planned development. Photo credit: Gary Feulner

water's edge, as at Khor Fakkan, Sharm or Dadnah. In these locations the coastal plain is absent and the beaches adjacent to them may be littered with eroded and wave-tumbled rocks (see Chap. 4) (Fig. 2.10).

Several of the foregoing geographical/ecological units are discussed independently in later chapters of this volume.

2.2.2 The Sand Deserts

2.2.2.1 The Sand and its Sources

The majority of the UAE is covered by sand (technically, rock or mineral particles having dimensions from ca. 0.06 to 2.00 mm) (Fig. 2.3), but the land surface is nevertheless far from uniform. Putting aside smaller-scale local variations, at least three broad trends are evident.

First, the highest dunes and dune ridges are found in the south of Abu Dhabi, and they become smaller towards the Arabian Gulf coast (Figs. 2.11 and 2.12). In the

Fig. 2.5 Coastal sabkha in the far west of Abu Dhabi emirate. Photo credit: Gary Feulner

south, the sands of the UAE are continuous with the Rub' Al Khali, the famous Empty Quarter, which brings to mind the names of explorers like Bertram Thomas, St. John Philby and Wilfred Thesiger.

Second, the color of the sands changes from reddish inland to white near the coast, primarily as a result of changing mineral composition. Most of the sand in the interior was transported from the northwest, and derives from erosion of the rocks found in the mountains and plateaux of western and central Saudi Arabia, as they have been raised and exposed by the rifting of the Red Sea (Glennie 2001). That sand consists predominantly of quartz (SiO_4) grains and the red color results from trace amounts of iron that has been oxidized to hematite (Fe_2O_3) (Fig. 2.13). Locally, erosion of outcrops of nearby rocks may contribute to the neighboring sands. Adjacent to the inland Sabkha Matti in western Abu Dhabi, the surface sand occasionally features conglomerates representing paleo-rivers that once traversed the area, probably 5–10 million years ago.

Nearer the Arabian Gulf, today's sands are primarily white calcium carbonate ($CaCO_3$) grains derived both directly from the broken and weathered shells of marine organisms and from carbonate sediments deposited in the shallow Gulf, many of which incorporate substantial amounts of weathered shell material

Fig. 2.6 Intertidal mud flats in Umm Al Qaiwain. The hundreds of thousands of dark spots on the mud are intertidal gastropod molluscs, mostly the mudcreeper *Cerithidea cingulata*. The water-filled holes in the foreground are feeding rings left by flamingoes, who can be seen in the distance. Photo credit: Gary Feulner

(Fig. 2.14). These carbonate sand grains are often somewhat flattened or irregular compared to the more equidimensional quartz grains of the interior sands.

Third, in the northeast of the country, where the sands generally meet the alluvial gravel plains bordering the mountains, the dunes are engaged in a ballet of advance and retreat, choreographed by climate and danced in partnership with floodwater runoff and alluvium. In this area the dunes have mostly advanced over the past 6000 years, following deterioration of a previously somewhat wetter climate (Parker 2009; Parker et al. 2004, 2016) (Fig. 2.15) (read more on recent climate change in the UAE in Chap. 3).

2.2.2.2 Rainfall and Temperature

Climatically, the UAE today is very hot and very dry. Basic details are presented here for convenience, but for a more complete understanding the reader should

Fig. 2.7 An aerial view of Khor Hulaylah, Ras Al Khaimah, north of Al Rams and seaward of Dhayah, viewed from Sal Dhayah at ca. 500 m elevation. This photo was taken in the mid-1990s before construction of free zone infrastructure and residential housing. Photo credit: Gary Feulner

consult Chap. 3. Mean annual rainfall shows a clear geographical gradient, decreasing to the southwest and away from the mountain areas (UAE University 1993). Annual rainfall for most of the south and west of Abu Dhabi is almost invariably less than 40 mm, classifying those areas securely as hyper-arid (Kwarteng et al. 2009). Moreover, rainfall in the sand deserts is notoriously unpredictable and often highly localized. Mean annual rainfall rises to 80–100 mm for much of Dubai emirate and 100–150 mm for the sand desert areas of the northern emirates. Annual variation can be substantial, however, and may be periodic (Feulner 2006).

Mean maximum summer temperature (June, July and August) exceeds 40°C everywhere throughout the sand deserts of the UAE, from Ras Al-Khaimah to the Western Region of Abu Dhabi. Mean minimum winter temperature for all but the coastal margin is below 13°C. Extremes generally increase in a southwesterly direction from Ras Al-Khaimah to the Western Region of Abu Dhabi. Diurnal temperature variation is especially high in sand desert areas; in early summer (June) the diurnal change can reach nearly 25°C in western Abu Dhabi emirate (Bu Hasa), further emphasizing the extreme climate of the desert interior of the country. The past 30 years have been slightly but steadily hotter, with the average temperature rising 0.75°C since 1990, a trend which is expected to continue (Hill 2021). The past 20 years and more have also been markedly drier. The UAE's climate regime and recent changes in temperature and precipitation are described in more detail in Chap. 3.

Fig. 2.8 A peaceful creek within the mangrove forest at Khor Zowra, Ajman, in the early 2000s. The mangroves trees (*Avicennia marina*) are fully exposed by a spring low tide. Photo credit: Gary Feulner

Fig. 2.9 Eroded recent coastal sediments, inland from Jebel Ali, Dubai. The column consists of 'fossil' dune sands capped by resistant shallow-water marine limestone. Photo credit: Gary Feulner

Fig. 2.10 A rocky headland on the East Coast, north of Sharm and south of Snoopy Rock, an offshore landmark. Photo credit: Gary Feulner

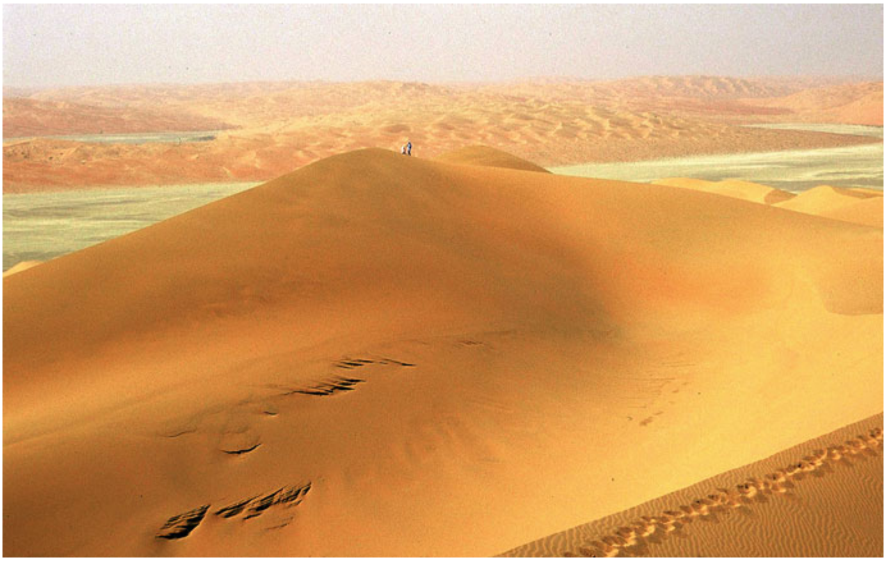


Fig. 2.11 In the south of Abu Dhabi, on the edge of the Empty Quarter, huge dune ridges are interspersed with sabkha flats (salt pans). This photo was taken in the eastern half of the Liwa crescent, looking southwest. Photo credit: Gary Feulner

Fig. 2.12 A small herd of camels crosses a sand-swept salt pan in the Manadir area, east of Liwa. Photo credit: Gary Feulner

These rainfall and temperature conditions, and the southwest to northeast gradient, are reflected in the vegetation of the UAE's sand desert areas, as described in Chap. 5. Nevertheless, temperature and rainfall alone do not tell the entire story of the desert's ability to support life. Humidity can also play a significant role. Relative humidity decreases inland, away from the UAE coasts, and is low in the interior, enhancing the effect of higher temperatures on evapotranspiration (water loss) by plants. But seasonally, especially in late autumn and winter, and occasionally at other times, fog forms even in the interior deserts (Fig. 2.16), and the fog can be so dense that it condenses on the sand surface and on plants, which literally drip with dew, supplying moisture equivalent to a gentle rain (Fig. 2.17). Moreover, if the water which reaches the sand surface is able to percolate to 1.5 to 2.0 m beneath it, it is effectively protected from evaporation and can continue its gravity driven descent until it reaches stable sands at the base of large dune ridges, where established vegetation with sufficient root depth can make use of it (Fig. 2.18). Heavy rain can have an even more dramatic effect (Fig. 2.19).

Fig. 2.13 Even small dune ripples sort (and re-sort) the sand grains by size and composition. Photo credit: Gary Feulner

Fig. 2.14 Close-up of white carbonate sand from a Dubai beach. Most of it consists of material derived from the shells of marine invertebrates. The individual grains are often flattened or irregular rather than equidimensional. Photo credit: Gary Feulner

Fig. 2.15 In the northeast of the country, where the sands meet the alluvial plains bordering the mountains, the dunes advance and retreat in response to climate, mediated in part by floodwater runoff and alluvium. The dunes in this area are reckoned to be no more than about 6000 years old. They commenced their current advance at the end of the Climatic Optimum, a relatively humid interval of about 5000 years. This photo looks northeast; the mid-ground shows the bed of Wadi Faya and in the distance is the foreland ridge of Jebel Faya. Photo credit: Gary Feulner

Fig. 2.16 Humidity can make a significant contribution to the water budget of sand desert shrubs. Fog sometimes forms, seasonally and occasionally, and condenses as dew, which drips from plants. Shown here is a winter morning in the desert of the Manadir area to the east of the Liwa crescent. Photo credit: Gary Feulner

Fig. 2.17 Dew dripping from a *Calligonum* shrub on a foggy winter morning in central Liwa in the early 1990s. Photo credit: Gary Feulner

2.2.2.3 Regional Variations in the UAE's Sand Desert Landscapes

Huge dune ridges and intervening sabkha flats (salt pans) characterize the south of Abu Dhabi, from the Liwa crescent in the center, where the dunes are arrayed in a pattern of sinuous parallel ridges, each half a wavelength out of phase from the next (Fig. 2.20), to the Manadir area in the southeast, where the dune ridges and pans are elongated in a compass direction of about 110 degrees (Glennie 1991, 1996; Feulner 2005) (Figs. 2.21 and 2.2). Although these areas are ca. 100–150 km inland and although the dune ridges reach ca. 150 m above the adjacent pans (Glennie 2001), the base level of the flats is only ca. 80–90 m above sea level and the areas as a whole are actually slightly lower than the more continuous rolling sands to the north. Moreover, the water table in these areas is less than a few meters below the sabkha surface (Fig. 2.22). The rolling sands of the intermediate desert areas give way seaward to sand plains, which in most places merge gradually into the sand and gravel plains of the Arabian Gulf coast (Figs. 2.23 and 2.24). At that junction, on the

Fig. 2.18 Vegetation in the deserts in the south of Abu Dhabi is often concentrated on stable sand pediments at the base of steep dune slopes, where it is nourished by rainwater that percolates down through the high dunes. Photo credit: Gary Feulner

Fig. 2.19 Rare rainfall in the sand deserts can sometimes be heavy. Playa lakes may persist for weeks or months. Seen here are the sabkha flats at Qaraytisah. Photo credit: Gary Feulner

Fig. 2.20 Within the Liwa crescent, sinuous parallel dune ridges isolate discrete sabkha pans among them. Photo credit: Gary Feulner

gravel plains, fields of individual, mobile barchan (crescent) dunes can be seen in a number of places in the Western Region of Abu Dhabi (Fig. 2.25).

In the east and northeast of the country, the sands are occasionally graced by groves of the ghaf tree *Prosopis cineraria*, sometimes localized on small dunes which the trees themselves may have helped to create, and other times on flats at the base of higher dune ridges, perhaps coincident with remnant water channels in the subsurface (Fig. 2.26). Still further to the northeast, the sands are occasionally punctuated by rocky outcrops of sedimentary ridges raised up by tectonic movements in the foreland of the main mountain front, but at a distance of 15–25 km (Fig. 2.27). Those ridges have been confirmed as the loci of distinctive floral associations (see Chap. 6 and Sect. 2.2.3.3 below).

2.2.3 The Mountain Regions

The mountains of the UAE are part of the chain of mountains that extends parallel to the Gulf of Oman coast for more than 600 km from the tip of the Musandam

Fig. 2.21 In the Manadir area in the southeast of Abu Dhabi, the dune ridges and sabkha pans are elongated in a compass direction of about 110 degrees. The sabkha surface is always "puffy" due to the hygroscopic nature of the saline sediment. Photo credit: Gary Feulner

Fig. 2.22 On inland sabkha flats the water table is no more than a few meters below the surface. Photo credit: Gary Feulner

Fig. 2.23 A track on sand flats in the western desert of Abu Dhabi, dominated by profuse growth of *Zygophyllum*. This photo was taken south of Umm Al ‘Ashtan in the wet years of the mid-1990s. Photo credit: Gary Feulner

peninsula almost to Ras Al Hadd in Oman, at the southeastern tip of Arabia. These have been called, variously, the Oman Mountains, the Hajar Mountains, and the Oman/UAE mountains. In the UAE, the mountain environment occupies most of Fujairah emirate, much of Ras Al Khaimah, parts of Sharjah, and the Dubai and Ajman enclaves of Hatta and Masfut, respectively.

The mountain areas of the UAE are cooler and wetter overall than the coastal and desert areas to the west (UAE University 1993; Feulner 2011); see also Chaps. 3 and 6. Temperature decreases with elevation and the UAE mountains, like mountains everywhere, induce so-called orographic rainfall by causing passing air to rise and cool, condensing whatever water vapor it carries (Fig. 2.28). In addition, the UAE’s mountains receive life-sustaining moisture from two weather systems—the northwesterly winds of the temperate zone and, less frequently but significantly, southeasterly winds from the tropical Indian Ocean. Annual rainfall over the UAE’s mountain areas is extremely variable but the long-term average is in the range of 160–190 mm per year (UAE University 1993; Feulner 2011), so the mountain climate is classified as arid, but not hyper-arid like most of the rest of the UAE.

Fig. 2.24 This sand plain in the western desert of Abu Dhabi is relatively flat, firm and deflated by wind. It is colonized almost exclusively by the perennial sedge *Cyperus conglomeratus*. The photo is another taken in the wet years of the mid-1990s. Photo credit: Gary Feulner

Fig. 2.25 In the Western Region of Abu Dhabi, fields of individual barchan dunes can be found at the geographical boundary where the deflated coastal plain grades inland to sand desert. Photo credit: Gary Feulner

The UAE's mountain areas are much more physically variegated than its desert areas in terms of surface attributes, so they feature a greater diversity of microhabitats. The mountain areas of the UAE constitute only about 5% of its surface area, but the combination of more moderate temperatures, higher rainfall, range of elevations, and diversity of microhabitats gives the mountain areas a disproportionate amount of the country's biodiversity. Approximately 60% of the UAE's native terrestrial plant

Fig. 2.26 In the east and northeast of the UAE, the sand deserts are occasionally punctuated by groves of ghaf trees *Prosopis cineraria*. Shown here is Wadi Qarhah in the greater Sweihan area in the Eastern Region of Abu Dhabi. Photo credit: Gary Feulner

species are found in mountain areas and many are found only there (see Chap. 6). A similar relationship is estimated for UAE fauna (see, e.g., van Harten 2008, 2009, 2010, 2011, 2014, 2017 Judas 2015).

As a foundation for discussion of the natural history of the UAE, it is advantageous to recognize two main ranges within the mountain areas, which have very different geographical, geological and ecological characteristics, the Hajar Mountains and the Ru'us Al Jibal (see also Chap. 6).

2.2.3.1 The Hajar Mountains

The Hajar Mountains stretch southwards from Dibba along the Gulf of Oman coast, through Khor Fakkan and Fujairah to the Oman border (Fig. 2.29). These are the mountains that one crosses en route to or from the east coast. On their west flank they extend, in the UAE, from Tawiyan to the Hatta Road. The mountains do not end at the international border, however; the same range continues unbroken for another 200 km into Oman (where it is called the Western Hajar) until it meets the Jebel Akhdar range west of Muscat.

Fig. 2.27 In the northeast of the country, mobile sands sometimes lap onto rocky carbonate ridges west of the main Hajar Mountains. Seen here in the background is Jebel Mleiha, a/k/a Fossil Rock. The carbonate ridges host floral associations distinct from those of the surrounding desert or the main Hajar Mountains. This photo was taken in the very 'wet' years of the mid-1990s; the author is pictured at right. Photo credit: Gary Feulner

Although rugged, the Hajar Mountains in the UAE are the lowest area of the entire chain, with only three scattered peaks and two high ridges reaching as much as 1000 metres. By contrast, in Oman, south of Hatta, summits along the spine of the Western Hajar range from 1400 to 1800 m, culminating to the southeast in the much higher elevations of the Jebel Akhdar, which rises to just over 3000 m.

2.2.3.1.1 Hajar Mountain Geology

The rocky hillsides in the Hajar Mountains typically weather reddish-brown, but seen in road cuts they are usually greenish, blackish or pale. They are composed of a suite of interrelated igneous rocks collectively called ophiolite. (Igneous rocks are rocks that formed by crystallisation from hot, molten rock. They can sometimes form

Fig. 2.28 A rainy day in the mountains above Wadi Khabb, in the Ru'us Al Jibal range (the mountains of the Musandam peninsula). Native trees are well established in slope rubble. The large trees at left and right are Sidr *Ziziphus spina-christi* (Rhamnaceae); the smaller tree in the center is Umbrella Thorn *Acacia tortilis* (Fabaceae). Photo credit: Gary Feulner

at the earth's surface, as in the case of volcanic lavas, but more often they form by slow cooling of molten rock deep within the earth.)

Within the ophiolite of the UAE, two rock types predominate: harzburgite and gabbro (Fig. 2.30). Harzburgite, representing exposures of the earth's uppermost mantle, occupies most of the northern areas (north of the Dhaid-Masafi-Fujairah roads, including Wadi Wurayah, Wadi Zikt, Wadi Madha, upper Wadi Shi, upper Wadi Siji, Wadi Asimah and Wadi Maydaq) as well as a narrow belt along the west flank of the mountains. In the southwest, the harzburgite includes minor areas of a rock type called dunite, which differs by only a few percent in its statistical mineral composition. In most areas of harzburgite, the surface rock is highly fractured and forms steep, rubble-covered slopes that are very difficult to climb; the summits are normally narrow, rocky ridges (Fig. 2.31).

The chemical composition of harzburgite is extreme among rocks found at the earth's surface. It is very low in silica (SiO_2), the building block of most igneous rocks (a condition geologists call "ultrabasic" or "ultramafic"). It is also high in magnesium, and high in heavy metals such as chromium and nickel, as a result of which it is considered unfriendly to typical plant life (Harrison and Kruckeberg 2008). Along the west flank of the mountains the harzburgite exposures are almost completely weathered to serpentine, a fibrous clay mineral. Ultrabasic terranes elsewhere, and especially serpentinite terranes, are associated with limited floral diversity but high endemism (Harrison and Kruckeberg 2008; Anacker 2011).

Fig. 2.29 The Hajar Mountains of the UAE closely parallel the Gulf of Oman coastline. This photo looks out from above the mountains across the broad alluvial fan at the mouth of Wadi Wurayah, the largest of the East Coast wadis. Photo credit: Gary Feulner

In the center and southeast of the UAE's ophiolite terrane (including Wadi Ashwani, Wadi Asfani, Wadi Hiluw, Wadi Safad and Wadi Mayy), gabbro predominates. Gabbro is the principal component of oceanic crust and has a more normal chemistry for surface rocks, equivalent to volcanic basalt. It is visibly coarsely crystalline and weathers in a more blocky fashion, often creating more gentle and somewhat more navigable slopes and summits (Fig. 2.32). Gabbro in the UAE often features conspicuous dark and light banding.

2.2.3.1.2 The Mountain Wadi Environment

Major wadis in the Hajar Mountains can be very stark and the wadi beds may appear to be almost devoid of vegetation, because they are swept clean from time to time by flood waters that are consolidated rapidly from many smaller tributaries (Fig. 2.33). In fact, this is what happens to most of the water that falls during very heavy rains. There is not enough capacity in the gravel wadis, or in the network of subterranean fractures in the bedrock, or in the very limited soils, to soak up all the water that falls in a short time during heavy rain, so much of it flows directly down the wadis and towards the mountain front as muddy, brown, turbulent floodwaters. In recent

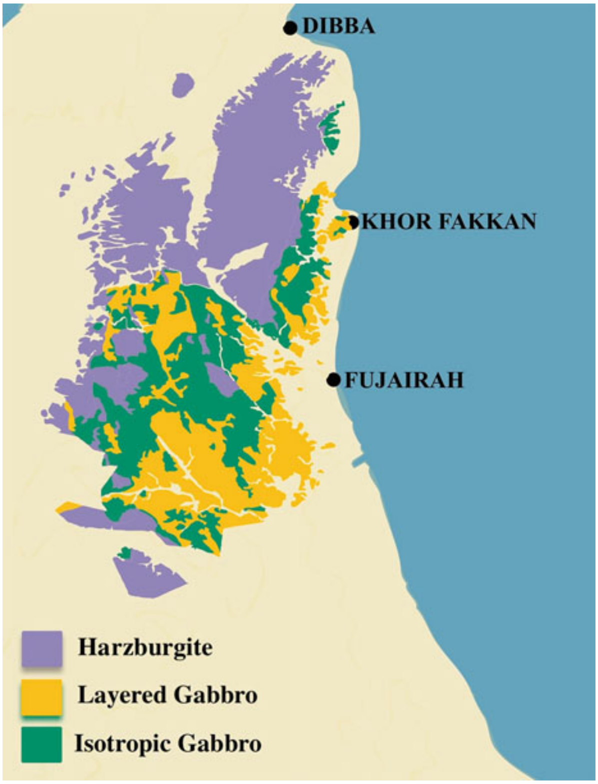


Fig. 2.30 Geological map of the Hajar Mountain ophiolite in the UAE, showing the distribution of the principal rock types. Image credit: Gary Feulner

decades, dams have been built in most Hajar Mountain drainages to try to prevent damage from flood waters and to collect the excess water.

Smaller wadis, on the other hand, including tributaries of larger wadis and the many steep ravines and gulleys that feed the tributaries, can be oases of life (Figs. 2.34 and 2.35). That is partly because the volume of flow in those channels is not so great as to uproot or inundate small shrubs. But equally important is that some of the water that falls as rain enters the shallow subsurface through cracks in the bedrock, scree and gravel terraces of the hillsides, where it resides long enough to nourish the natural, dry-adapted vegetation.

No mountain wadis in the UAE or Oman sustain continuous surface flow along their lengths, but a number of Hajar Mountain wadis have permanent water in pools at discrete locations (Feulner 1998, unpublished data) (Fig. 2.36). This is because rainwater that has entered the groundwater system, if it has not been absorbed by plants (or chemically incorporated into clay minerals that are the subsurface weathering products of the ophiolite rocks), percolates gradually through the bedrock and terraces and into the gravel fill of the main wadi channels. There, it flows slowly downstream through the gravel, saturating the lowest horizons and sometimes appearing intermittently at the surface (see next paragraph), so becoming available for hygrophilic (i.e., water-loving) plants and for selected animals.

Fig. 2.31 Summits and summit ridges in harzburgite terrane are generally narrow, rocky, barren of vegetation and difficult to traverse. Here, the author overlooks upper Wadi Shees from a ridge ascended via a tributary of Wadi Deftah. Photo credit: Gary Feulner

Figure 2.37 shows cross-sections of a typical Hajar Mountain wadi. The wadi bed is cut into bedrock and filled with coarse gravel. Water flows within the porous gravel, as well as on top of it when flow is sufficient. The wadi bed beneath the gravel is not always smooth and even, however. At intervals, the underlying bedrock is resistant to erosion and punctuates the gravel fill, forming barriers. Pools of water form behind those barriers, and the barriers themselves may become small waterfalls after rain. Larger waterfalls may create deep pools at their base. Although many wadi pools appear calm or stagnant, flow is usually continuous, although very slow, facilitated by fractures in the underlying bedrock and by continuing drainage from the slopes on either side.

The amount of gravel fill in a wadi bed varies greatly from point to point, but it gives a sense of scale to know that in the middle and lower reaches of Wadi Wurayah, early contractors recorded a maximum depth to bedrock of 40 m; beyond the mountain front, but within the alluvial fan, the depth was somewhat more than 90 m (Tourenq et al. 2011). For comparison, Parton et al. (2015) studied a 42-m thick section of an alluvial fan exposed at a quarry west of the mountains near Al Foah,

Fig. 2.32 A ridgetop at 1000 m in the Olive Highlands, south-west of Fujairah city. Summits in gabbro bedrock are normally somewhat broader and gentler than those in harzburgite. Photo credit: Gary Feulner

north of Al Ain, UAE; there the oldest exposed sediments dated back to (only) ca. 160,000 years.

Apart from downstream drainage, water in mountain wadis is lost by evaporation. This can be substantial at the UAE's high summer temperatures, when shallow pools fully exposed to the sun may shrink by as much as 2 cm depth per day. Within the gravel, however, the water is protected from extreme temperatures (Emirates Wildlife Society–WWF 2006) and, below a depth of about 1.5 to 2.0 m, it is effectively protected from evaporation (Valett 1991). Subterranean flow helps to buffer the temperature of surface pools and streams (Emirates Wildlife Society–WWF 2006).

Today, the greatest threat to the continued presence of surface or near-surface water in most natural wadi environments in the Hajar Mountains is mechanical extraction by pumping.

2.2.3.1.3 Geological 'Windows' Exposing Metamorphic Rocks

The Hajar Mountain region of the UAE includes two areas of generally pale colored, often silvery, metallic-looking rocks—one surrounding Asimah and Tayyibah, north of Masafi, and the other encompassing Wadi Shees, deep within the mountains overlooking the east coast and west of the Oman enclave of Madha (Fig. 2.38). Both areas expose rocks that were originally deposited as sediments on the edge of the Arabian continent and were later deformed and metamorphosed by partial

Fig. 2.33 Major wadi channels in the Hajar Mountains are often very stark because the vegetation is swept clean by floods from time to time. Shown here is a gorge in the middle reaches of Wadi Wurayah. A tall human figure at lower left emphasizes the scale. Photo credit: Gary Feulner

subduction beneath the ophiolite slab, being the leading edge of the oceanic plate to the east (see Sect. 4.2 below, Emplacement of the ophiolite rocks and creation of the Hajar Mountains). Because those areas allow us to 'look through' the ophiolite and see the rocks that underlie them, they are called geological windows. And because of their relationship to the ophiolite, the metamorphic rocks themselves are known collectively to geologists as the Metamorphic Sole.

2.2.3.2 The Ru'us Al Jibal

The Ru'us Al Jibal range (the traditional local name for the mountains of the Musandam peninsula) is dramatically different, geographically and geologically, from the Hajar Mountains to the south (Feulner 2011). This is evident even to the casual observer. Ru'us Al Jibal (pronounced *roo-OOS al-ji-BAL*) means, literally, "the Heads of the Mountains" and reflects the fact that the summits in this area are higher than any others for about 275 km to the south (in the Jebel Akhdar region of Oman). Much of the Ru'us Al-Jibal lies within the Musandam province of Oman,

Fig. 2.34 Smaller mountain wadis, and gentle tributaries of larger wadis, can be genuine oases of life. Photo credit: Gary Feulner

but the margins in the west and south belong to the emirates of Ras Al Khaimah and Fujairah, respectively.

The rocks of the Ru'us Al Jibal comprise a thick pile (ca. 3 km) of relatively flat-lying, greyish, carbonate sedimentary rocks (Fig. 2.39). Physiographically, the Ru'us Al Jibal is characterised by steep-sided, boulder-filled wadis and steep lower slopes, including many sheer cliffs, but culminating in summit areas of rolling, stony plateaux, layered hills and intermittent basins at elevations of 500–1500 m. A handful of ridges and summits exceed 1600 m, of which the highest is Jebel Harim, in Oman, at just over 2000 m. The whole gives the impression of a relatively mature landscape that has been rapidly uplifted as a block (Fig. 2.40).

The Ru'us Al Jibal is separated from the Hajar Mountains by the Dibba Zone, an elongated geographical and geological boundary trending SW-NE and extending from Tawiyan and Jareef in the southwest to Ghub and Dibba in the northeast. The Dibba Zone marks the locus of major tectonic movement and consists of a mixed and colorful array of mostly deep water sedimentary rock units, all now discontinuous and divorced from their original stratigraphic context (Glennie et al. 1974; Feulner 2005; Searle 2019).

The hydrology of the carbonate bedrock of the Ru'us Al Jibal is very different from that of the Hajar Mountains. The carbonate rocks can be dissolved by groundwater, which creates its own network of subterranean drainage channels and even small caves, quickly conveying most excess rainwater to the main wadi systems or deeper underground (Borreguero and Jeannin 1990). As a result, there is almost no

Fig. 2.35 A third order tributary in Wadi Wurayah National Park, well-vegetated after rain. Photo credit: Gary Feulner

permanent surface water in the wadis of the Ru'us Al Jibal, and few permanent springs.

The Ru'us Al Jibal is also characterized by its distinctive traditional human culture based on the cultivation of wheat and other crops in seasonal agricultural settlements at high elevation, often very picturesque, whereas cultivation in the ophiolite of the Hajar Mountains is invariably along wadi banks at low elevations (Fig. 2.41).

2.2.3.3 The Foreland Ridges (Jebel Hafeet et al.)

Jebel Hafeet, on the outskirts of Al Ain in the Eastern Region of Abu Dhabi emirate, is a foreland ridge set at a distance of ca. 25 km from the main mountain front. It is the largest, by far, of a chain of similar ridges stretching north almost to Dhaid, composed of tightly folded carbonate sediments much younger than those of the Ru'us al-Jibal (Fig. 2.42). Rising to 1200 m, Jebel Hafeet is higher than any of the UAE's Hajar Mountain peaks except Jebel Hatta. It is also 75 km further south. The steep, rocky slopes are relatively barren, but it is nevertheless home to several species of plants that are absent or uncommon elsewhere in the UAE, and to several butterflies associated with those plants or more common to the south, in Oman (see

Fig. 2.36 A number of Hajar Mountain wadis have permanent surface water and can be idyllic in wet years. Unfortunately, the site shown here was later destroyed when a large roadhead farm was created and was permitted to tap the local spring. Some native species, like the wadi fish *Garra barreimiae*, will never return. Photo credit: Gary Feulner

Chap. 6). The smaller and more northerly ridges are mostly situated in Sharjah (Jebel Faya, Jebel Buhais, Jebel Mleiha et al.) and are also associated with distinctive floral elements.

2.2.4 The Alluvial Plains

Gravel plains flank the mountain regions of the UAE to the east and west. In the extreme northwest of Ras Al Khaimah and along the entire east coast, the gravel plains are equivalent to the coastal plain. Everywhere, the gravel plains consist of alluvium—weathering products from the erosion of the adjacent mountains, washed down the wadis by moving water and eventually deposited in flatter, lower energy

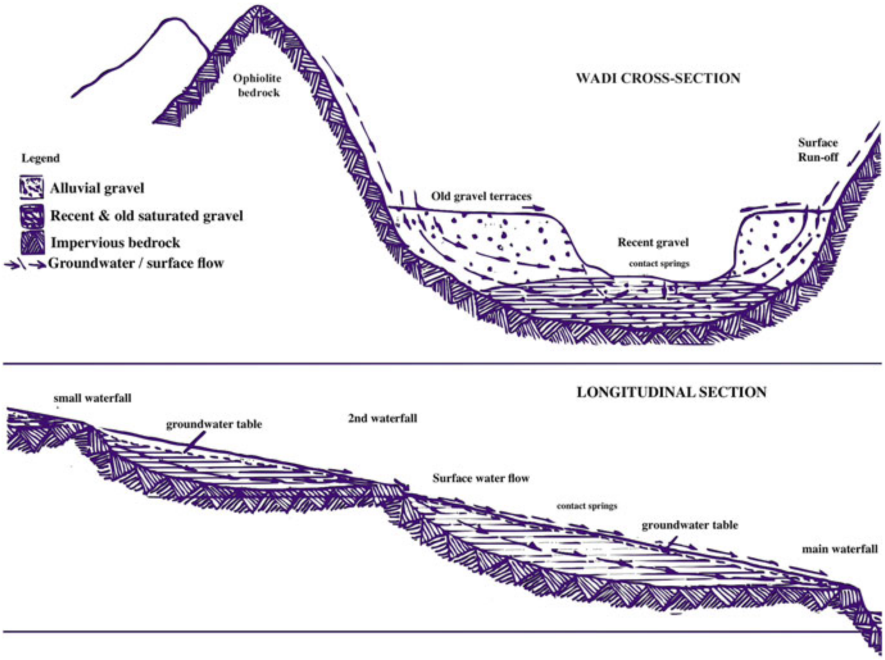


Fig. 2.37 Schematic cross-section (top) and longitudinal section (bottom) of a typical Hajar Mountain wadi (modified from Emirates Wildlife Society–WWF 2006)

environments beyond the mountain front (Fig. 2.43). The gravel plains inter-finger with the mountain front in the upstream/uphill direction, and with the desert sands or the coastal plain in the other direction (Figs. 2.44 and 2.45). At various times in the past, rainfall and erosion rates have been significantly greater than today. One line of evidence for this conclusion is that outwash gravels from the Hajar Mountains can be found in the subsurface under today's Arabian Gulf coastal cities in the northern emirates, including Dubai (Zander and Brückner 2005).

In Paleolithic (Old Stone Age) times, the alluvial plains to the west of the Hajar Mountains were the locus of human tool industries based on flint resources. Flint is found (i) as scattered concretions within the carbonate rocks of the foreland ridges along the western margin of today's plains, south of Dhaid (Jebel Faya et al.) (Bretzke et al. 2013); and (ii) along the eastern margin of the plains, where pervasive silicification affected the foothills along the main mountain front, from serpentinized ophiolite bedrock hills near Fili in the south to remnant channel deposits of limestone and metamorphic rocks along the southwesterly salient of the Ru'us Al Jibal carbonates, in the area of Khatt and Habhab (Scott-Jackson et al. 2008).

Analysis of the outwash gravels can give us a better understanding of the timing and nature of the uplift and erosion of the Hajar Mountains — which occurred primarily over the past 25 to 30 million years (Glennie 2001) — as well as of the

Fig. 2.38 A plateau of silvery micaceous schist within the Asimah-Tayyibah metamorphic window—a very unusual mountain landscape for the UAE. The more familiar ophiolite (harzburgite) terrane is seen on the horizon. Photo credit: Gary Feulner

details of paleoclimate (e.g. Parton et al. 2015). However, that potential utility has earned those deposits little respect from the general populace. Today, the gravel plains are almost everywhere degraded by infrastructure construction, quarrying and rampant overgrazing (Fig. 2.46). In recent decades the cutting of live trees has been added to the list of environmental sins visited on these already-insulted lands.

2.3 Biogeography

The geography of a place properly includes consideration of its global position in relation to not only climatic boundaries but also biogeographical ones. In the case of the UAE, the country occupies a privileged position at the junction of the three major biogeographical regions of the Old World—the Palearctic, the Afrotropical and the Oriental (Fig. 2.47). As a result, it has received plant, animal and human influences from all three regions. And, of course, the modern UAE receives influences from the entire world.

Currently the mutual boundaries of the three major regions are overlain by what has been called the Eremic zone (Larsen 1984), a climatic belt extending from West Africa to northern India, characterized by substantial aridity, that has developed many of its own distinctive floral and faunal elements. This adds yet a fourth

Fig. 2.39 The Ru'us Al Jibal range (the mountains of the Musandam peninsula) contrasts greatly with the Hajar Mountains. The rocks of the Ru'us Al Jibal comprise a thick pile of relatively flat-lying carbonate sedimentary rocks. Photo credit: Gary Feulner

Fig. 2.40 The Ru'us Al Jibal range as a whole gives the impression of a relatively mature landscape that has been rapidly uplifted as a block. Photo credit: Gary Feulner

Fig. 2.41 The high Musandam has been used for seasonal cultivation for hundreds of years, and features many remote and picturesque settlements. Most are now disused but some have been refurbished in the twenty first century. Photo credit: Gary Feulner

contributor to the biodiversity of the Emirates. Some examples of UAE flora and fauna derived from those four sources are set out in the following paragraphs.

Afrotropical: Many of the plant and animal species of the sand deserts and gravel plains of the UAE are of Afrotropical origin—the semi-arid Sahel and savannah regions of West, Central and East Africa. Examples include species such as Umbrella Thorn *Acacia tortilis* and Desert Broom *Leptadenia pyrotechnica* (Fig. 2.48a).

Oriental: Mountain Spurge *Euphorbia larica*, a normally leafless, yellow-green shrub that is one of the most common and characteristic plants of Hajar Mountain slopes, has its global distribution in southern and eastern Arabia and the Makran region and across southern Iran, extending eastward from the Hajar Mountains to Baluchistan (Fig. 2.48bi). The ghaf tree *Prosopis cineraria* has a similar native distribution, but extending further eastward to northern India (Fig. 2.48bii).

Palearctic/Mediterranean: The Wild Olive *Olea europaea* is found in discrete high elevation locales in the Hajar Mountains of the UAE and northern Oman (Fig. 2.48c). It is considered native to the Mediterranean region (Palearctic), but it had spread by the late Pleistocene (tens of thousands of years ago) to the mountains of South Asia and Eastern Arabia, and to East Africa. Today, the closest populations to the UAE and northern Oman are in the Makran region—the coastal mountains of southern Iran, Baluchistan and Pakistan.

Fig. 2.42 The foreland anticline of Jebel Hafeet rises ca. 800 m from the surrounding plain, ca. 25 km west of the main mountain front. Its slopes and wadis are home to a number of plants and animals rarely seen elsewhere in the UAE. The traditional ascent route, shown here, is formidable. See also Chap. 6, Fig. 6.41. Photo credit: Gary Feulner

Eremic: The Desert White butterfly *Pontia glauconom*e is one of the most common butterflies in wild areas of the UAE and is also common elsewhere throughout the Eremic zone (Fig. 2.48di). It is an arid region specialist that has evolved in place to survive as its homeland has dried out. Its larvae can develop on a variety of regional plants in both mountain and sand desert environments, and reportedly can delay emergence of the adult butterfly from the pupal state for up to several years, in order to await favorable conditions (Feulner et al. 2021). Two of the UAE's seven native land snails, *Zootecus insularis* and *Pupoides coenopictus*, are also widespread throughout the Eremic zone, but essentially absent outside it (Feulner and Green 2003) (Fig. 2.48dii).

Fig. 2.43 Alluvial plains, often composed of coarse gravel, border the mountain regions on the east and west flanks. They represent the outwash from erosion of the mountains. Seen here is the west flank of the Ru'us Al Jibal, north of Khatt. The trees are all *Acacia tortilis*. Photo credit: Gary Feulner

2.4 Geological Highlights

Geological processes—all the processes studied by earth scientists generally—ultimately control earth's geography, the oceans, the atmosphere, the cycling and recycling of various chemical and mineral components, and the feedback mechanisms among those interrelated systems. And so, geological processes ultimately control life itself.

The classical bedrock geology of the UAE, however, is seldom exposed to view, except in the mountain regions of the northeast. In addition, with respect to the terrestrial ecosystems of the UAE that are the focus of Section 2 of this volume, the bedrock geology is generally not as important as the various geographical factors discussed above. Again, the mountain regions are a limited exception. For that reason, this section presents only an abbreviated discussion of the most distinctive features of the UAE's physical geology and geological history; the general reader seeking greater detail should consult more specialized non-technical accounts (e.g. Glennie 1992, 2001; Feulner 2005; Thomas and Ellison 2014; Searle 2019).

The treatment below nevertheless attempts to introduce the most important conceptual aspects of the UAE's geological history—those that provide context for understanding the dynamic evolution of both the Arabian landscape and the

Fig. 2.44 In some places gravel terraces are well developed within the mountain front, as here in the Wadi Ghayl tributary of Wadi Wurayah. Photo credit: Gary Feulner

plants and animals to which it plays host. Figure 2.49 is a simplified geological map of the mountain regions of the UAE and northernmost Oman. Figure 2.50 presents a schematic geological cross-section of the UAE—one of the most useful tools for understanding geological structures and interpreting geological history.

The geology of the UAE is world famous for three main reasons: (1) the country's huge oil reserves; (2) the ophiolite rocks of the Hajar Mountains (extensively exposed in the UAE and Oman); and (3) the modern-day coastal sabkha of Abu Dhabi, mentioned briefly above.

2.4.1 Oil Reserves

The UAE's oil reserves have been tremendously important for the development of the modern nation, but they have not been significant for the evolution of native UAE plant and animal life. As the cross-section shows, most of the UAE (except the mountain areas) is underlain by tens of thousands of meters of relatively undisturbed sedimentary rocks. Most of those sediments were deposited in shallow seas over the past 550 million years, beginning not long before the start of the Cambrian Period, at

Fig. 2.45 On the west flank of the mountains, the gravel plains merge with the coastal plain to the north and the sand desert to the west. Seen here is Wadi Umm Al Naghool, north of Dhaid. Photo credit: Gary Feulner

about the same time when fossilizable multicellular life first began to proliferate (Fig. 2.51).

It is in those sedimentary rocks, and mainly under Abu Dhabi emirate, that the UAE's petroleum reserves now reside. Much of those reserves is believed to derive from the decomposition of microscopic marine life from the Silurian Period (ca. 444–419 million years ago) (Glennie 2001). The resulting hydrocarbons migrated slowly upward through porous strata until they were blocked by stratigraphic or structural traps. Many of the traps were created by deformation arising from salt domes rooted in the infra-Cambrian Hormuz Formation, a very thick unit that underlies much of the central and Southern Arabian Gulf (e.g., Glennie 2001); the same salt domes are responsible for most of the UAE's offshore islands. The oil reservoirs and their host rocks now lie out-of-sight, deep underground. However, some of the same strata are exposed (but without oil) and can be studied in the mountains of the Musandam peninsula (Fig. 2.52).

The cross-section also shows that the vast dune sands so prominent in the UAE landscape today, and so characteristic of Abu Dhabi's hinterland, are just a superficial overlay, geologically speaking, being no more than a maximum of about 200 m thick. Inland, they are deposited mostly atop eroded sedimentary bedrock and/or sabkha.

Fig. 2.46 Almost everywhere, the alluvial plains have been degraded by infrastructure construction and overgrazing. More recently, cutting of live trees has been added to the list of modern environmental sins. Photo credit: Gary Feulner

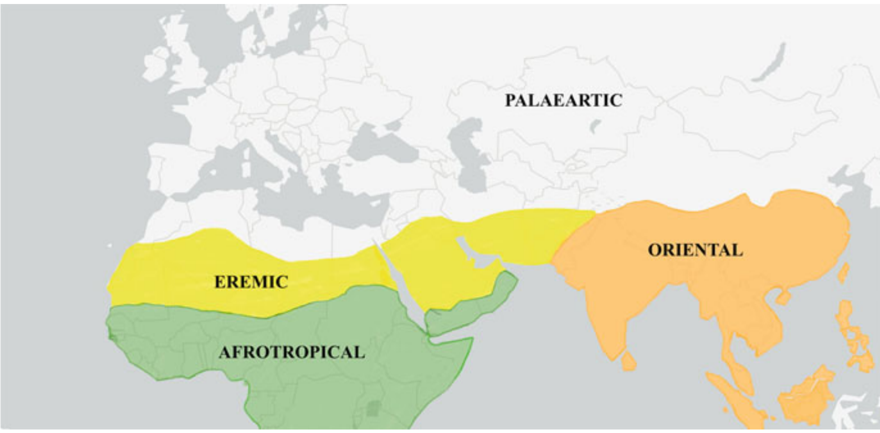


Fig. 2.47 The principal biogeographical regions of the Old World. Modified from Feulner et al. (2021) and reused with permission

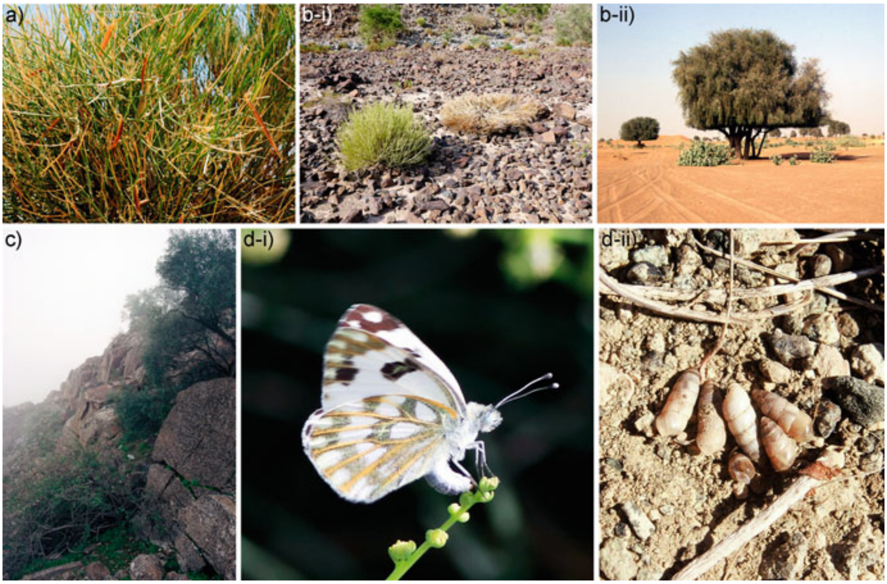


Fig. 2.48 Some examples of the multiple biogeographical components of the UAE's flora and fauna: (**a**) Afrotropical: Desert Broom (*Leptadenia pyrotechnica*), a large, leafless milkweed found across the Sahel zone of Africa; it dominates much of the sand desert of inland Dubai. (**b**) Oriental: (i) Mountain Spurge (*Euphorbia larica*), in life and in death. (ii) Ghaf tree (*Prosopis cineraria*), growing here in the bed of an intermittent sand river. The bottom of the canopy is browsed to the height of an outstretched camel's neck. (**c**) Palearctic: Wild Olive (*Olea europaea*), part of a relict population that survives in the UAE today only in a high elevation refuge. (**d**) Eremic: (i) Desert White butterfly (*Pontia glauconome*) (Pieridae). (ii) Land snail *Zootecus insularis* (Achatinidae). Both are widespread throughout the Eremic zone. Photo credits: Gary Feulner (a,b,c,d-ii), Binish Roobas (d-i)

2.4.2 Emplacement of the Ophiolite Rocks and Creation of the Hajar Mountains

The most dramatic event in the geological history of the UAE was the formation of the Hajar Mountains. The rocks that make up most of the mountain chain we see today were not originally part of Arabia. Instead, they began as part of an adjacent tectonic plate consisting of oceanic crust and underlying upper mantle from the deep ocean lying to the east, a precursor of today's Indian Ocean. During the period from about 90 to 70 million years ago, a huge slab of that oceanic plate was slowly slid over the edge of Eastern Arabia, which was beginning to descend into a subduction zone. The overriding slab was subsequently detached and uplifted, and the oceanic crust and mantle rocks, collectively called "ophiolite", are now magnificently exposed on land. They also pushed ahead of them some colorful deep ocean sediments and even remnants of coral atolls, which can be seen today in the Dibba Zone and elsewhere (Fig. 2.53). As described above, geological "windows" in the

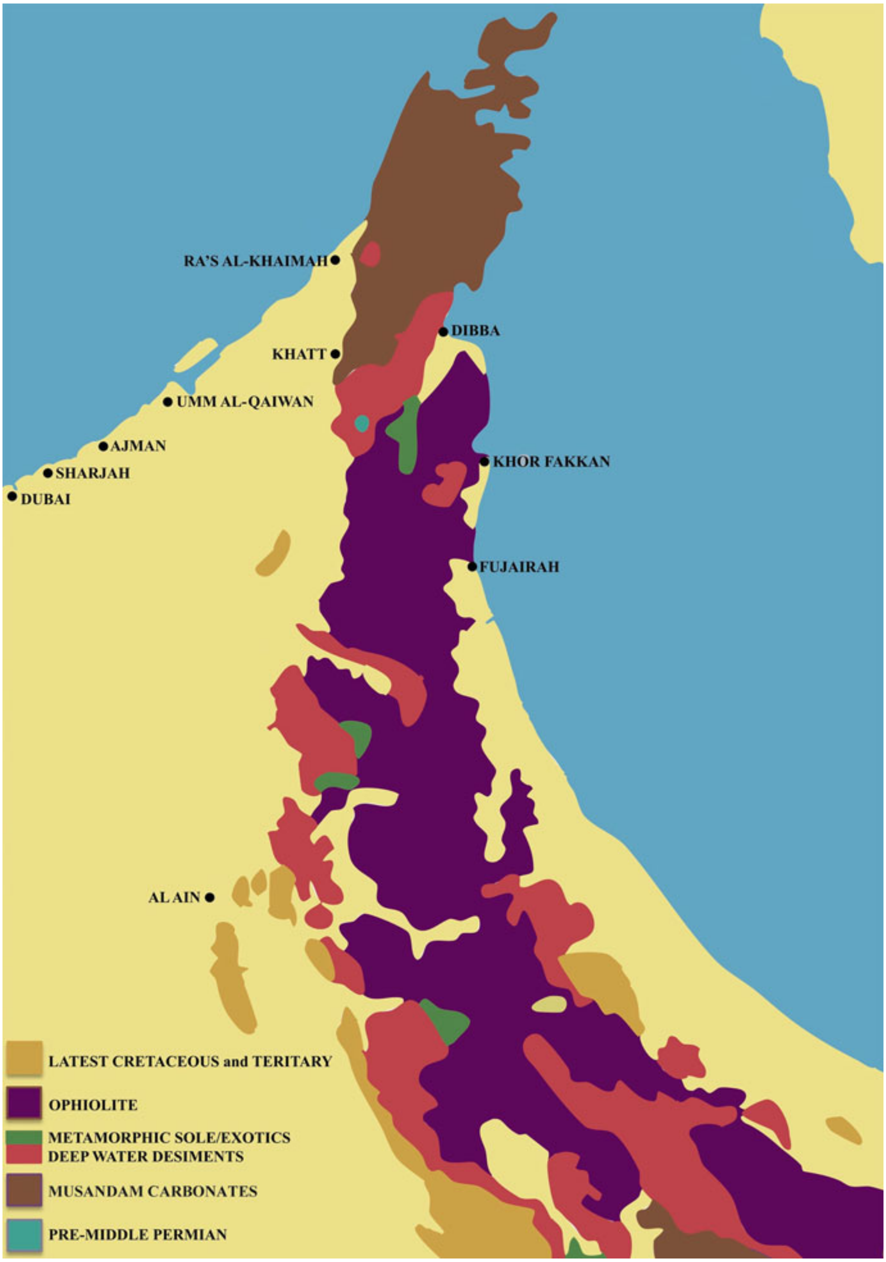


Fig. 2.49 A simplified geological map of the mountain areas of the UAE and northernmost Oman. Modified from Feulner (2005) and reused with permission

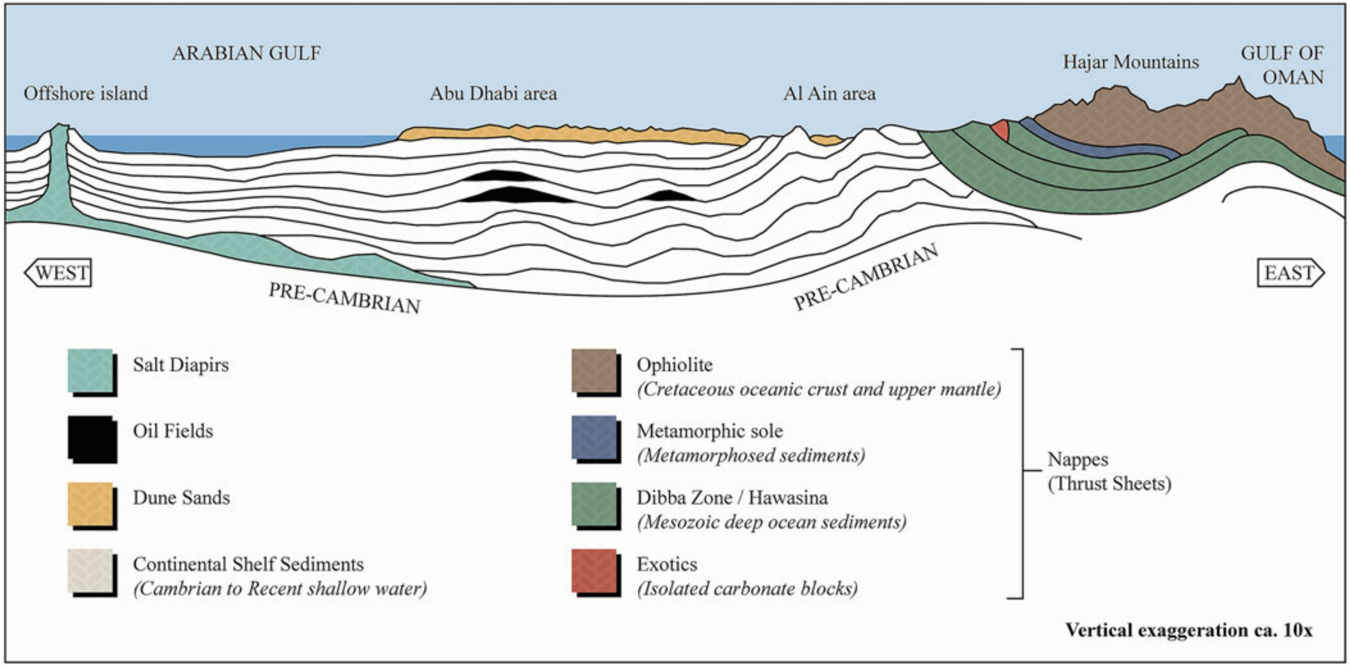


Fig. 2.50 Schematic geological cross-section of the UAE. Modified from P. Vine in Feulner (2005) and reused with permission

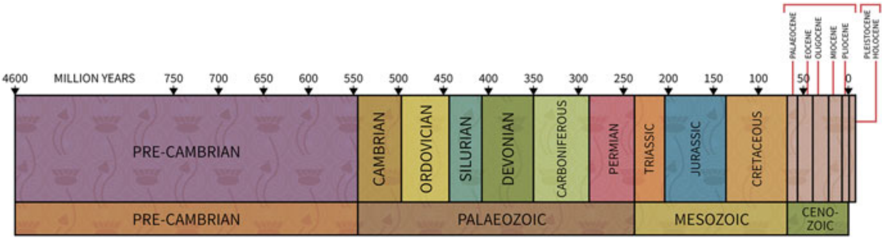


Fig. 2.51 The geological time scale. Modified from Feulner (2005) and reused with permission

Fig. 2.52 Many of the same strata that host oil reservoirs under Abu Dhabi are exposed for study (but without oil) in the mountains of the Musandam peninsula. Seen here in Wadi Naqab are the dolomitic limestones of the Ghail Formation, the uppermost member of the Permo-Triassic Ru'us Al Jibal Group. Photo credit: Gary Feulner

areas of Asimah/Tayyibah and Wadi Shis expose sedimentary rocks originally deposited on the edge of the Arabian continent that were subducted under the advancing ophiolite and metamorphosed beneath it, creating rocks unlike any others seen today in the Emirates, often silvery and metallic-looking.

Gradually, earth forces pushed the ophiolite rocks and associated sediments further and further over the edge of Arabia, then raised them up, and slowly raised the whole of Arabia as well, all as part of processes which continue today.

Fig. 2.53 In Wadi Khabb, in the south of the Ru'us Al Jibal, colorful deep ocean sediments (right) that were originally deposited far to the east have been thrust over pale grey carbonates (left) deposited on the Arabian continental shelf. Photo credit: Gary Feulner

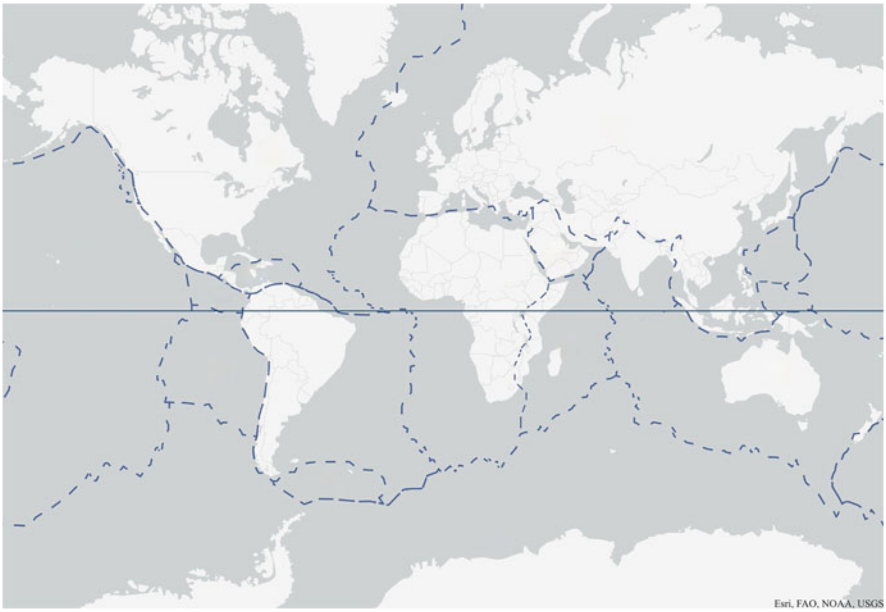


Fig. 2.54 Major tectonic plates of the modern earth

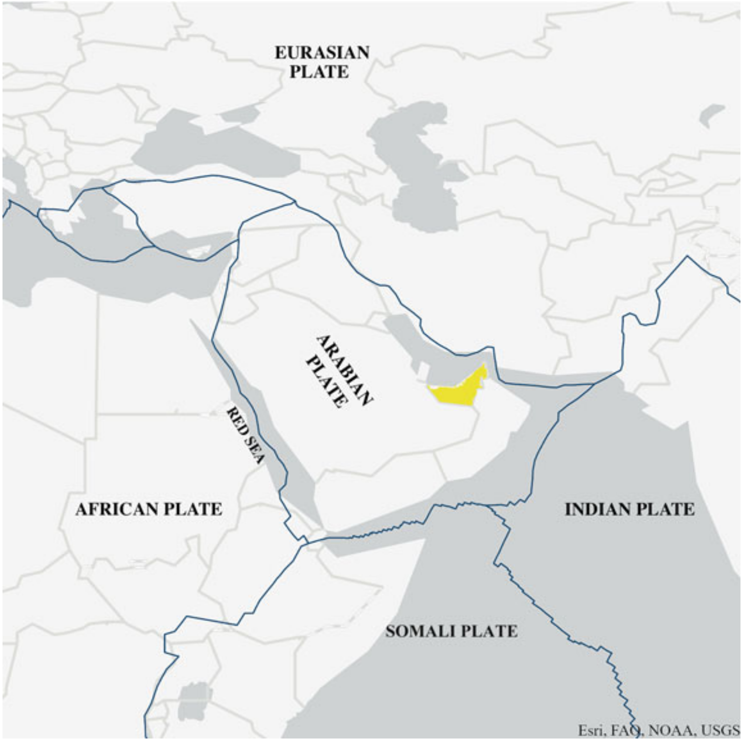


Fig. 2.55 Tectonic plate boundaries surrounding Arabia

2.5 Plate Tectonics

Underlying the emplacement of the ophiolite rocks and the formation of the Hajar Mountains is the system of earth movements called "plate tectonics" (Figs. 2.54, 2.55, and 2.56). Plate tectonics shuffles and recycles land masses and ocean basins. It is a continuing process that remains active today and it is a major unifying concept for geological science.

In Arabia, plate tectonics explains not only the formation of the Hajar Mountains, but also important regional phenomena such as (1) the opening of the Red Sea, which split Arabia from Africa and raised up the whole of Arabia above sea level; and (2) the formation of the Zagros Mountains in Iran (along with their associated earthquakes), including, as a by-product, the formation of the shallow Arabian Gulf (discussed briefly below). More broadly, plate tectonics explains the continuing collision of Afro-Arabia with Eurasia, evident on land from the Levant to Iran, but also in progress across the whole of the Mediterranean region.

The ophiolite rocks of the Hajar Mountains in the UAE and Oman are the most extensive and most complete exposures of ophiolite in the world. They have been

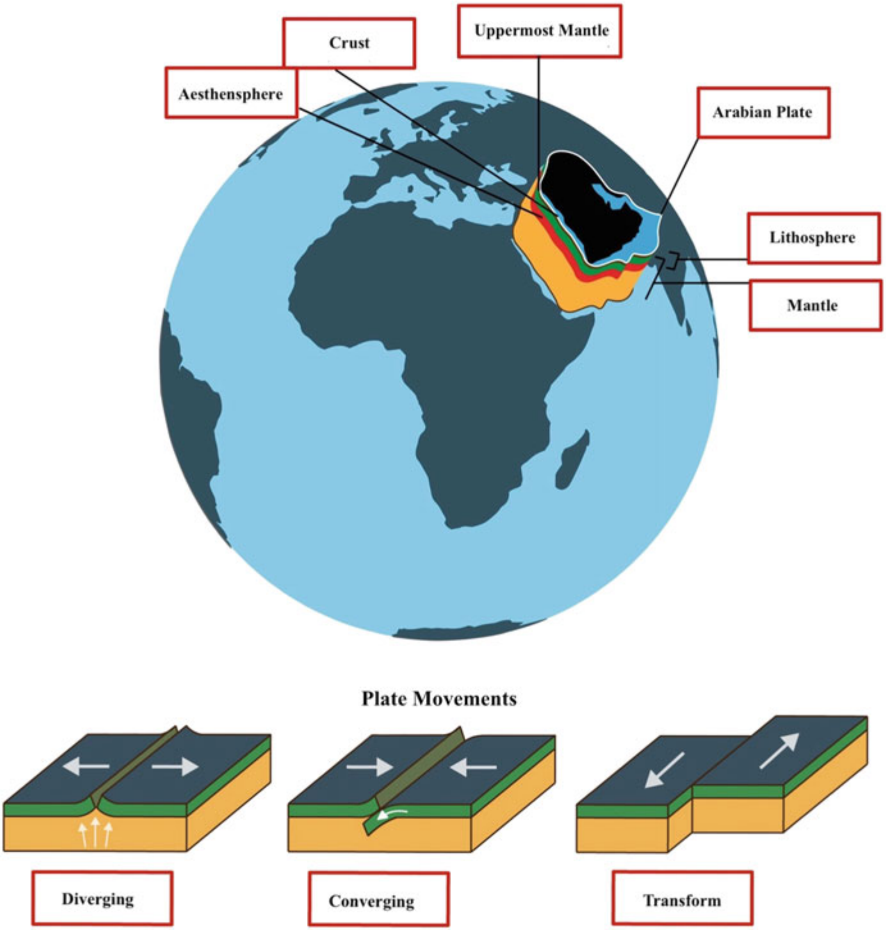


Fig. 2.56 Basic structure of the earth's interior and types of relative motion between plates

intensively studied and have helped geologists better understand many aspects of plate tectonic processes.

Of special interest to naturalists, the history of plate tectonic movements helps to explain the distribution of many plants and animals, both in the geological record and today. Two examples relevant to Arabia will help to illustrate the point.

First, the collision of Afro-Arabia with Asia in the Oligo-Miocene (beginning roughly 30 million years ago) introduced Asian freshwater fish groups to Arabia, first walking catfish (Clariidae) and bagrid catfish (Bagridae) and later, by the mid-Miocene (ca. 18 million years ago), Asian cyprinids (Cyprinidae) (Freyhof et al. 2020). The catfish species eventually succumbed to the arid and hyper-arid conditions that later beset Arabia, but the Asian cyprinids, particularly the genus *Garra* (sub-family Labeoninae), have prospered and diversified not only in the arid

Fig. 2.57 Successful radiations between Asia and Africa, via Arabia: (**a**) *Garra barreimiae*: Fossils show that the Asian cyprinid ancestors of the UAE's wadi fish, *Garra barreimiae*, reached Arabia by about 18 million years ago, not long after its collision with Eurasia. They have also successfully colonized Africa. (**b**) *Eusparassus laevatus*: The stone huntsman spider genus *Eusparassus* is considered most likely to have originated in Namibia, but it has radiated throughout Africa and today includes a number of species centered in the near East and Central Asia. *E. laevatus*, a denizen of UAE wadis, is found in East and South Arabia and in the Afar region of Northeast Africa (Moradmand 2013). Photo credits: Gary Feulner

mountains of Arabia but also in many environments on the African mainland (Levin et al. 2021) (see Chap. 21) (Fig. 2.57).

Second, and of greater significance, the collision turned Arabia into a literal crossroads for the exchange of terrestrial megafauna between Africa and Asia, with results that we take for granted today. In particular, it was during the Miocene that even-toed hoofed mammal like pigs, deer, antelope and giraffe first moved into Africa from Eurasia, while members of the elephant family and apes and Old World monkeys spread in the opposite direction (Stewart 2005).

Geological and oceanographic studies have shown that the Arabian Gulf is a relatively recent geographical feature, geologically speaking, and probably an ephemeral one (McKinnon 1990). It is not an ocean basin, but only a very shallow downwarping of the continental crust of the Arabian plate, incidental to the deformation and uplift of the Zagros Mountains at the plate boundary with Eurasia. The maximum depth of the Gulf is only 90 m—less than two-thirds the height of the tallest dunes in the interior of Abu Dhabi and only one-quarter the length of the largest oil tanker vessels currently in service. The average depth is only 30 m.

Moreover, the Gulf has been largely emptied on a number of occasions during at least the past half million years (McKinnon 1990; Glennie 1991, 1996, 2001; Sanlaville 1992, 1998; Goodall 1994; Parker 2009), as global sea levels have fallen by 100-plus meters in response to repeated cycles of glaciation ("Ice Ages") in the northern hemisphere. At such times the area of today's Gulf is thought to have been a marshy extension of the Tigris-Euphrates-Karun river system that flows from the north and drains most of Iraq and Syria, and parts of Turkey and Iran, perhaps similar to the Shatt al-Arab where those three rivers meet today, with anastomozing channels and intermittent freshwater lakes (Parker et al. 2004; Cuttler et al. 2011). Thus the Gulf region is not considered to have been a very significant physical barrier to most terrestrial plants and animals.

Most recently, the Gulf was fully dry at the peak of the last glacial maximum at about 17,000 to 18,000 years ago (see Chap. 4). As global sea level rose thereafter, the Gulf began to fill at about 16,000 years ago, was still largely empty at 12,000 years ago, and reached its current level (and a meter or two more) by about 6000 years ago (Lambeck 1996; Uchupi et al. 1999). All of these historical geological and geographical changes must be taken into account, as well as the vicissitudes of paleoclimate (e.g., Parker 2009; Parker et al. 2004, 2016; Parton et al. 2015) (see also Chap. 3), in order to fully understand the mix of flora and fauna that we see in the UAE today.

2.6 Conclusions

The UAE packs a great deal of geographical and biological diversity into its modest physical area. The coastal areas are dotted with lagoons, mangrove forests and world famous sabkha. The sand deserts form a vast sea that grades from mega-dunes in the south, on the edge of the Empty Quarter, to the low, shrub-covered dunes of the coast and the *ghaf* covered dune hills of the northern emirates. The mountains are like a tropical reef at the margin of the sand sea, creating and concealing a wealth of microenvironments that can only really be discovered by investigation on foot. The potential biodiversity of the UAE is enhanced by its position at the junction of the three major biogeographical regions of the Old World, and it has demonstrably received contributions from each.

The most fundamental geological influences on the present day natural history of the UAE include three which are consequences of regional plate tectonic movements: (1) the opening of the Red Sea beginning ca. 35 million years ago, splitting Arabia from Africa and slowly raising up the whole of Arabia above sea level; (2) the plate tectonic collision of Afro-Arabia with Eurasia beginning ca. 30 million years ago, which facilitated the exchange of flora and fauna between the two; and (3) the formation of the Zagros Mountains in Iran, including, as a by-product, the formation of the shallow Arabian Gulf. A fourth fundamental influence is the regional response to repeated cycles of glaciation ("Ice Ages") in the northern hemisphere over the past half million years or more: the alternation of cooler and hyper-arid climatic conditions in Eastern Arabia with warmer, humid ones, coupled with the repeated emptying and filling of the Arabian Gulf, as global sea levels fell and rebounded with the waxing and waning of the far-away glaciers.

2.7 Recommended Reading

Feulner (2005), now available online, is a well-received and often dramatically illustrated popular introduction to many of the diverse environments of the UAE and the processes that created and maintain them. Featured discussions include the early plate tectonic wanderings of Arabia, the genesis of the country's petroleum reserves, the growth of salt domes, the formation and erosion of the mountain regions, sand dune formation and desert oases, sabkha environments, and a simple guide to Hajar Mountain structural units and rock types.

Glennie (2001) is a wide-ranging but more technical account of the geological and geographical evolution of the country, written for the scientifically literate layman. It includes discussion of the early plate tectonic movements of Arabia, the UAE's petroleum deposits, salt domes, sand dune and sabkha formation, and the presence of riverine environments in the Miocene of western Abu Dhabi. An in-depth discussion of the plate-tectonic events leading to the emplacement of the ophiolite is informed in part by Glennie's professional acquaintance with neighboring areas of the Near East. Also discussed in detail are the climatic and sea level changes of the Pleistocene and Holocene.

Many of the extensive photos in Searle (2019) will be nostalgic for old-timers who recall the UAE and Oman from the 1970s and 1980s, but the text assumes a fair level of geological sophistication on the part of the reader.

Thomas and Ellison (2014) is an elegant and informative trophy volume produced by the British Geological Survey (BGS) team that undertook the geological mapping of the UAE in the 2000s. The BGS also produced a series of geological maps and corresponding explanatory booklets (e.g. Phillips et al. 2006). Not surprisingly, the BGS texts also assume that the reader will have an above average level of prior geological understanding. The BGS publications are available from the UAE Ministry of Energy, Department of Geology and Mineral Resources, in Abu Dhabi.

References

Anacker BL (2011) Phylogenetic patterns of endemism and diversity. In: Harrison S, Rajakaruna N (eds) Serpentine: the evolution and ecology of a model system. University of California Press, pp 49–70

Borreguero M, Jeannin P-Y (1990) Emirates Arabes unis expedition 1990. Cavernes 2:1–80

Bretzke K, Armitage SJ, Parker AG, Walkington H, Uerpmann H-P (2013) The environmental context of Paleolithic settlement at Jebel Faya, Emirate Sharjah, UAE. Quat Int: The Middle Palaeolithic in the Desert 300:83–93

Cuttler R, Tetlow E, Al-Naimi F (2011) Assessing the value of palaeoenvironmental data and geomorphological processes for understanding Late Quaternary population dynamics in Qatar. Proc Seminar Arab Stud 41:47–60

Emirates Wildlife Society–WWF (2006) Establishment of a mountain protected area in Wadi Wurayah, Fujairah Emirate, United Arab Emirates. EWS-WWF, Dubai, UAE, pp 1–83

Feulner GR (1998) Wadi fish of the UAE. Tribulus 8(2):16–22

Feulner GR (2005) Geological overview. In: Hellyer P, Aspinall S (eds) The Emirates – a natural history. Trident Press, London, pp 41–62
Feulner GR (2006) Rainfall and climate records from Sharjah Airport: Historical data for the study of recent climatic periodicity in the UAE. Tribulus 16(1):3–9
Feulner GR (2011) The flora of the Ru'us al-Jibal – the mountains of the Musandam Peninsula: an annotated checklist and selected observations. Tribulus 19:4–153
Feulner GR, Green SA (2003) Terrestrial molluscs of the United Arab Emirates. Mitteilungen der Deutschen Malakologischen Gesellschaft 69/70:23–34
Feulner GR, Roobas BR, Hitchings V, Otto HHH, Campbell O, Roberts HGB, Hornby RJ, Howarth B (2021) Butterflies of the United Arab Emirates including northern Oman. Motivate Publishing, Dubai
Freyhof J, Els J, Feulner GR, Hamidan NA, Krupp F (2020) Freshwater fishes of the Arabian Peninsula. Motivate Publishing, Dubai
Glennie KW (1991) Sand dunes in the Emirates. Tribulus 1(1):14–17
Glennie KW (1992) Plate tectonics & the Oman mountains. Tribulus 2(2):11–21
Glennie KW (1996) Geology of Abu Dhabi. In: Osborne PE (ed) Desert ecology of Abu Dhabi. Pisces Publications, Newbury, pp 16–35
Glennie KW (2001) Evolution of the Emirates' land surface: an introduction. In: Ghareeb E, Al Abed I (eds) Perspectives on the United Arab Emirates. Trident Press, London. (1997). Reprinted in Al Abed I, Hellyer P (eds) United Arab Emirates: a new perspective. Trident Press, London, pp 9–27
Glennie KW, Boeuf MGA, Hughes-Clarke MW, Moody-Stuart M, Pilaar WFH, Reinhardt BM (1974) Geology of the Oman Mountains. Verhandelingen Koninklijke Nederland Geologisch Mijnboukundig Genootschap 31:1–423 + figures (3 parts)
Goodall TM (1994) The Sabkhat Matti – a forgotten wadi system? Tribulus 4(2):10–13
Harrison SP, Kruckeberg AR (2008) Garden on the rocks. Nat Hist 117(4):40–44
Hill A (2021) Climate change is making UAE hotter – a trend that will continue. In: The National. https://www.thenationalnews.com/uae/environment/climate-change-is-making-uae-hotter-a-trend-that-will-continue-1.1249027. Accessed 10 Jul 2022
Judas J (2015) A checklist of the flora and fauna of Wadi Wurayah National Park (unpublished draft)
Kwarteng AY, Dorvlo AS, Vijaya Kumar GT (2009) Analysis of a 27-year rainfall data (1977–2003) in the Sultanate of Oman. Int J Climatol 29:605–617. https://doi.org/10.1002/joc.1727
Lambeck K (1996) Shoreline reconstructions for the Persian Gulf since the last glacial maximum. Earth Planet Sci Lett 142:43–57
Larsen TB (1984) The zoogeographical composition and distribution of the Arabian butterflies (Lepidoptera; Rhopalocera). Jour Biogeo 11:119–158
Levin B, Simonov E, Franchini P, Mugue N, Golubtsov A, Meyer A (2021) Adaptive radiation and burst speciation of hillstream fish *Garra* in an African river. bioRxiv https://doi.org/10.1101/2021.05.04.442598. Accessed 4 May 2021
McKinnon M (1990) Arabia: sand, sea, sky. BBC Books, London, pp 1–224
Moradmand M (2013) The stone huntsman spider genus *Eusparassus* (Araneae: Sparassidae): systematics and zoogeography with revision of African and Arabian species. Zootaxa 3675 (1):1–108. https://doi.org/10.11646/zootaxa.3675.1.1
Parker AG (2009) Chapter 3: Pleistocene climate change in Arabia: developing a framework for hominin dispersal over the last 350 ka. In: Petraglia MD, Rose JI (eds) The evolution of human populations in Arabia, vertebrate paleobiology and paleoanthropology. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-2719-1_3
Parker A, Eckersley L, Smith MM, Goudie AS, Stokes S, White K, Hodson MJ (2004) Holocene vegetation dynamics in the northeastern Rub' al-Khali desert, Arabian Peninsula: a pollen, phytolith and carbon isotope study. J Quat Sci 19:665–676

Parker AG, Preston GW, Parton A, Walkington H, Jardine PE, Leng MJ, Hodson MJ (2016) Low-latitude Holocene hydroclimate derived from lake sediment flux and geochemistry. J Quat Sci 31(4):286–299
Parton A, Farrant AR, Leng MJ, Telfer MW, Groucutt HS, Petraglia MD, Parker AG (2015) Alluvial fan records from southeast Arabia reveal multiple windows for human dispersal. Geology 43(4):95–98
Phillips ER, Ellison RA, Farrant AR, Goodenough KM, Arkley SLB, Styles MT (2006) Geology of the Dibba 1:50,000 map sheet, 50-2, United Arab Emirates. British Geological Survey, Nottingham
Sanlaville P (1992) Changements Climatiques dans la Péninsule Arabique durant le Pléistocène Supérieur et L'Holocène. Paléorient 18(1):5–25
Sanlaville P (1998) Les changements dans l'environnement au Moyen-Orient de 2,000 BP a 6,000 BP. Paléorient 23(2):249–262
Scott-Jackson J, Scott-Jackson W, Rose J, Jasim S (2008) Investigating Upper Pleistocene stone tools from Sharjah, UAE: Interim report. Proc Seminar Arab Stud 38:43–54
Searle M (2019) Geology of the Oman Mountains, Eastern Arabia. Springer Nature, Dordrecht, pp 1–475
Stewart JR (2005) Miocene geology and fossils of Abu Dhabi. In: Beech M, Hellyer P (eds) Abu Dhabi 8 million years ago: late Miocene fossils from the western region. Abu Dhabi Islands Archaeological Survey (ADIAS), Abu Dhabi, pp 1–68
Thomas RJ, Ellison RA (2014) Geological evolution of the United Arab Emirates. Department of Geology and Mineral Resources, UAE Ministry of Energy, Abu Dhabi
Tourenq C, Brook M, Knuteson S, Shuriqi MK, Sawaf M, Perry L (2011) Hydrogeology of Wadi Wurayah, United Arab Emirates, and its importance for biodiversity and local communities. Hydrol Sci J 56(8):1407–1422. https://doi.org/10.1080/02626667.2011.631139
Uchupi E, Swift SA, Ross DA (1999) Late quaternary stratigraphy, palaeoclimate and neotectonism of the Persian (Arabian) Gulf region. Mar Geol 160:1–23
United Arab Emirates University (1993) The national atlas of the United Arab Emirates. United Arab Emirates University, Al Ain
Valett HM (1991) The role of the hyporheic zone in the structure and function of a desert stream ecosystem. Dissertation, Arizona State University
van Harten A (ed) (2008) Arthropod fauna of the United Arab Emirates, vol 1. Dar Al Ummah, Abu Dhabi, pp 1–754
van Harten A (ed) (2009) Arthropod fauna of the United Arab Emirates, vol 2. Dar Al Ummah, Abu Dhabi, pp 1–786
van Harten A (ed) (2010) Arthropod fauna of the United Arab Emirates, vol 3. Dar Al Ummah, Abu Dhabi, pp 1–700
van Harten A (ed) (2011) Arthropod fauna of the United Arab Emirates, vol 4. Dar Al Ummah, Abu Dhabi, pp 1–832
van Harten A (ed) (2014) Arthropod fauna of the United Arab Emirates, vol 5. Department of the President's Affairs, Abu Dhabi, pp 1–744
van Harten A (ed) (2017) Arthropod fauna of the United Arab Emirates, vol 6. Department of the President's Affairs, Abu Dhabi, pp 1–775
Zander A, Bruckner H (2005) Chronology and evolution of submerged mangrove swamps buried in the subsoil of Dubai. Tribulus 15(2):10–16

Chapter 3
Climate of the United Arab Emirates: Present, Past and Impacts on Life

Francesco Paparella and John A. Burt

3.1 The UAE Climate in the Global Context

The UAE, as in most of the Arabian peninsula, is characterized by a hot desert climate: "BWh" in the Köppen climate classification system (Peel et al. 2007). BWh regions are the most common types of land area on earth, covering 14.2% of the global land surface. They straddle either the northern or the southern tropics (~30° N or S), and are characterized by extreme aridity and annual average temperatures above 18 °C. The whimsical name "lands of the empty bucket" gives an intuitive characterization of these arid climates: a bucket left outdoors is virtually never found to be full of water, because year-round evaporation exceeds precipitation (Warner 2009, ch. 2).

The hot desert climate origin must be traced back to the features of the large-scale circulation of the atmosphere. In the tropical belt the circulation is dominated by two enormous convection cells, one in each hemisphere, named after the eighteenth century meteorologist George Hadley (Fig. 3.1). Warm, moist air rises in a relatively narrow belt called "intertropical convergence zone" (ITCZ) close to the equator, rising to the bottom of the stratosphere (ca. 15 km high). As it travels upward, its

F. Paparella (✉)
Arabian Center for Climate and Environmental Sciences (ACCESS), New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

Center on Stability, Instability and Turbulence (SITE), New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
e-mail: Francesco.Paparella@nyu.edu

J. A. Burt
Arabian Center for Climate and Environmental Sciences (ACCESS), New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

Water Research Center (WRC), New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_3

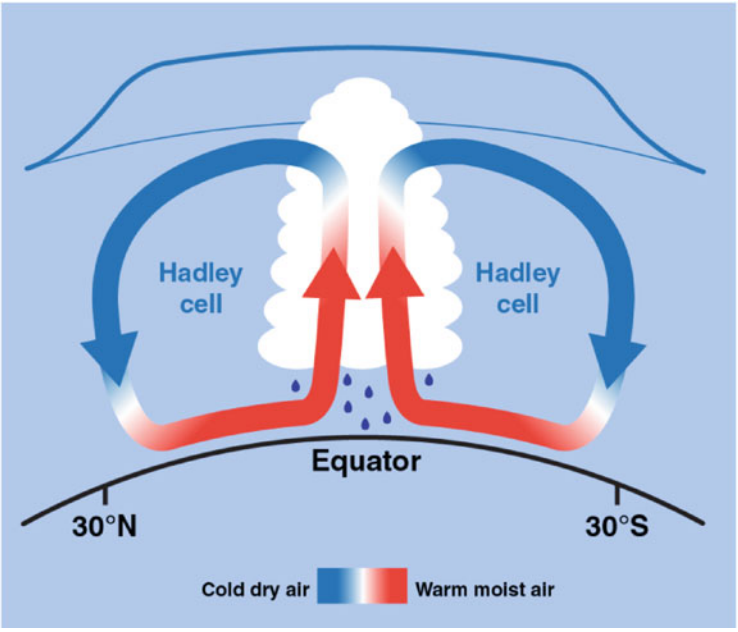


Fig. 3.1 Schematic diagram depicting the Hadley circulation in spring and autumn, when the northern and southern cells are roughly symmetric. The intertropical convergence zone (ITCZ) is the stormy area where warm, moist air uplifts. Hot desert areas occur below the descending branch of each cell. NOAA image, from scijinks.gov/trade-winds/ (Public Domain)

moisture condenses into water droplets, forming abundant clouds and storms that sustain the equatorial rainforests. Once aloft, the now dry air masses bisect and travel either northward or southward to about 30° of latitude, where they descend back to the surface, becoming warmer in the process. The descent of this dry air mass that had lost much of its moisture in the ascending phase is called "subsidence" and it is the main cause for the existence of hot desert regions. In fact, any moisture rising from the surface becomes diluted into the warm, dry, subsiding air masses, in a process that severely hampers cloud formation, and nearly eliminates it when it happens over land, where ground-level moisture is not particularly abundant. As a result, under an area of subsidence there is little to no precipitation, and, lacking the shade of clouds, the near totality of the incoming solar radiation reaches the soil, promoting evaporation (Warner 2009, ch. 2). The presence of such conditions result in vegetation and animal assemblages that are low in diversity, often highly constrained to particular microenvironments, and characterized by unique adaptations to support their continued survival under extreme aridity and temperatures (Chaps. 5 and 13).

The shape and strength of the Hadley convection cells follows a seasonal cycle: in winter the northern hemisphere cell is weaker and the narrow band where warm, moist air is uplifted is located to the south of the Equator. The opposite occurs in the summer. This seasonal cycle is highly distorted and enhanced where there is a

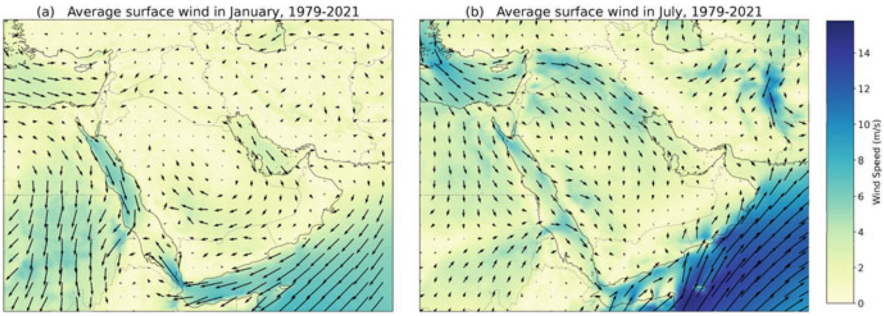


Fig. 3.2 Climatological average (1979–2021) of the surface wind vector over the Middle East region. Panel a, left: month of January. Panel b, right: month of July. Data are from the ERA5 reanalysis, copyright 2023 European Centre for Medium-Range Weather Forecasts (ECMWF); this data is published under a Creative Commons Attribution 4.0 International (CC BY 4.0)

North-South asymmetry in the distribution of land masses, most notably in the case of Asia and the Indian Ocean. Because land warms and cools more readily than the ocean, during the summer the ITCZ migrates much further north, over the Indian subcontinent and the Indochinese Peninsula, and regresses south of the Equator over the Indian Ocean during the winter. This extreme seasonal shift of the ITCZ is the Indian Monsoon, and the associated summer rainfall maintains Southern Asia lush and humid, even though it lies at the same latitudes as the Sahara desert.

The seasonal shift of the ITCZ is the main determinant of the seasonal climate cycle of the Arabian peninsula. During the winter, the subsidence of air produces a persistent region of high pressure in the middle of the peninsula that organizes the dominant winds in an anticyclonic (that is, rotating clockwise) pattern (Fig. 3.2a). Mid-latitude winter storms forming on the Mediterranean are capable of bringing some clouds and rain to the northernmost part of that region and the Mediterranean Levant (Kushnir et al. 2017). Sometimes, the high pressure area in Arabia weakens and the occasional Mediterranean storm is able to penetrate further into the Arabian peninsula. These are the main sources of winter rainfall for the inner part of the Arabian peninsula. Very rarely, storms of this sort are able to reach the UAE. Those rare storms, which are associated with the strongest Kaus-Shamal winds (see below), are powerful ones, and when they occur, they bring bursts of very heavy rainfall, resulting in widespread flooding (Membery 1997). Such rainfall events can be important for enhancing germination of annual plant seedbanks, leading to short-lived but widespread blooms of vegetation in the wake of storms (Chap. 5). Most of the (little) rain that the UAE receives is triggered by the presence of the Hajar mountains. Winds may occasionally push and uplift moist air over the mountain slopes, which then condenses, causing storms and rain. Such rainfall differences, in part, support the unique floral and faunal communities that characterize the Hajar mountain range (Chaps. 6 and 13), as well as the vegetation of the alluvial plains that specialize on tapping into the underground waters flowing subsurface from the mountains following rains (Chap. 5).

During the summer, the ITCZ brushes the southern part of the Arabian Peninsula, and it can be recognized as a narrow belt of very low surface wind (associated with upward air motion) running from the Strait of Bab el Mandeb in the south of the Red Sea to the Strait of Hormuz at the entrance to the Arabian Gulf (Fig. 3.2b). This is connected with a low pressure area sitting over the vast expanse of the *Rub' al Khali* (Fonseca et al. 2022), known in English as the "Empty Quarter": a hyper-arid sand desert that occupies most of the eastern part of Saudi Arabia and of the southern UAE. The low pressure draws-in dry air from all of the northern Arabian peninsula, but moist air coming from the Indian Ocean is deviated by Earth's rotation in north-easterly direction (due to Coriolis forces), flowing towards India in a fast stream of air known as the "Somali Jet" (a portion of which is clearly visible in the lower-right corner of Fig. 3.2b). Only the south-western tip of the Arabian Peninsula, roughly coinciding with modern-day Yemen, is systematically reached by monsoonal humid air that, thanks also to the favorable topography, every summer brings rain well in excess of 200 mm/year, peaking above 400 mm/year in some places. These rain levels far exceed those found anywhere else in the Arabian Peninsula (Almazroui et al. 2012) and justify the name that the ancient Romans gave to this southern region: *Arabia Felix*: 'Fertile Arabia'. Most of Oman and the UAE only occasionally experience summer rain of monsoonal origin. Other than in Yemen and in some portions of southern Oman, the total amount of summer rain in the Arabian peninsula is much lower than that of winter rain (Jing et al. 2020).

3.2 Climate of the Past

The changing breadth of the seasonal shifts in the position of the ITCZ have been the main factor shaping the climate of North Africa and of the Arabian Peninsula during the Quaternary Period (ca. the past 2.6 million years). It is well known that changes in insolation (that is, sunlight intensity) are determined by changes in Earth's orbital parameters (ellipticity of the orbit, inclination of the Earth's rotation axis) which drive the expansion and retreat of ice sheets at high latitudes. Those same changes also determine the strength and latitudinal extent of the monsoonal rains in Africa, Arabia and India. Stronger insolation during the summer leads to larger seasonal shifts in the position of the ITCZ.

After the end of the last glacial phase, when summer insolation was at its maximum, the ITCZ occurred much further north than in the present day (Kutzbach 1981). Therefore, during summer, abundant rainfall would reach areas that today are arid. While North Africa was very dry during the last glacial maximum, between approximately 11,500 YBP and 5500 YBP, the Sahara was not a desert, but rather a fertile, humid savannah, which sustained numerous neolithic civilizations (Bard 2013).

During that period, the sea was slowly rising to the current-day level as the polar ice sheets melted, flooding into the riverine basin which today is the Arabian Gulf (Chap. 4), and the Somali jet blew much further north over the Arabian peninsula, rather than offshore of the Oman coastline (Fleitmann et al. 2007). Abundant summer monsoonal rainfall would have been common in the southern half of the peninsula, including all of modern-day UAE, while Mediterranean, wet-winter conditions would prevail in the northern half (Lüning and Vahrenholt 2019). This was a period of time known as the 'climatic optimum' when early civilization was established in Mesopotamia, and when early maritime trade networks were established throughout the Arabian Gulf region, including at many early villages along the UAE's Gulf coast (Kennett and Kennett 2006; Uerpmann and Uerpmann 1996; Charpentier and Mery 2008; Beech et al. 2000). The UAE at this time had savanna-like grasslands and dense shrubbery across much of its extent (Kallweit 2003; Rose 2022), and it has been suggested that today's *ghaf* stands are remnants of much more widespread systems that occurred during this humid period (Chap. 5).

Both the onset and the end of the African Humid Period (i.e. the 'climatic optimum' that ended approximately 5500 YBP) appear to have been abrupt, even though its astronomical causes undergo a very gradual change (deMenocal et al. 2000). Unraveling the causes of such an abrupt climate shift is an ongoing puzzle that has not yet been completely resolved. It has long been known that changes in the vegetation cover feed-back on the strength and the extent of the Hadley circulation by affecting the fraction of sunlight that is reflected back into space rather than absorbed by the ground (Charney 1975). It has also been suggested that the subsidence of air over western Sahara and the Mediterranean may be linked to the strength of the Asian monsoon, in a counterintuitive desert-monsoon feedback (Rodwell and Hoskins 1996). Other feed-back mechanisms include the the mutual influence of vegetation and of the hydrological cycle, and of the atmospheric and oceanic circulations on each other (Claussen et al. 1999). The overall picture that emerges of recent climate shifts is that North Africa and the Arabian peninsula may be found in either of two states: desert or savannah. The presence of each state creates conditions favorable to its own existence and persistence. The state, therefore, persists for a while, even in the face of astronomical conditions becoming unfavorable, until it finally suddenly gives way to the other state. This relatively sudden shift to today's arid conditions ca. 6000 to 5000 YBP is known as the 'Dark Millenium', when archaeological evidence suggests a broad collapse of early pastoral societies along the UAE's Arabian Gulf coast and a return to nomadism and a mass migration of people to more benign environmental refugia on the Oman coast (Rose 2022) (see also Chap. 22); this period led to the onset of the arid conditions that persist to this day and continue to shape local ecology.

3.3 The Shamal and Other Winds

The dominant, large-scale wind over the Arabian Gulf blows from north-west to south-east (Fig. 3.2a,b). When it reaches speeds capable of dominating over the local breezes this wind becomes known as *Shamal* (Arabic for north). It is convenient to distinguish between a summer and a winter Shamals: even though both kinds of wind blow in the same direction, their origin and nature is distinct.

The summer shamal originates in the Tigris and Euphrates valley, where it blows stronger, and gradually weakens as it moves towards the UAE (Fig. 3.2b). It may be interpreted as the return path of air circulating in the Northern Hadley Cell subsiding over the Mediterranean Levant and flowing towards the summer low pressure area residing over the *Rub' al Khali*. The Zagros mountains in Iran help guide this air stream over the Gulf and the east coast of the Arabian peninsula (Membery 1983). The summer Shamal is sometimes called the "wind of 120 days" (Yu et al. 2016) because of its persistent nature. However, individual Shamal events of greater strength than the average are recognizable during the course of a single summer. Because the summer Shamal is linked to the position of the ITCZ, which is itself modulated by several global-scale cycles, in some years the summer Shamal is stronger than in others (Al Senafi and Anis 2015). The summer Shamal is also a main contributor to the regulation of the Arabian Gulf's sea temperature, because it induces strong evaporative cooling, which, in the Abu Dhabi waters, may reach 400 W/m^2 (Paparella et al. 2019; see also Chap. 4). Such shamal-driven cooling can be critically important for marine organisms in summer, as they can lead to temperature declines of up to 2 °C that can persist for over a week (Paparella et al. 2019). In the absence of summer shamals, water temperatures may rise to levels that exceed the lethal limits of marine fauna, such as during the calm summer of 2017 when sea temperatures reached 37 °C and caused the loss of 73% of all coral in Abu Dhabi (Burt et al. 2019). Finally, strong summer Shamal events can cause large-scale dust storms. Iraq and Kuwait are most affected by these, but the dust-loaded air can easily reach the UAE shores, severely deteriorating the air quality for several days in a row (Bou Karam Francis et al. 2017). Such dust storms have been suggested to be important nutrient fertilizers (particularly of iron) that enhance phytoplankton productivity in the Gulf (Moradi and Moradi 2020), although they may also exacerbate harmful algal blooms (Hamza 2021).

During winter, the establishment of a region of high pressure in the center of the Arabian peninsula produces a clockwise (anti-cyclonic) circulation that, over the Gulf, leads to dominant winds blowing from north-west to south-east (Fig. 3.2a). These, however, are generally weak and fluctuating. The actual winter Shamal events are relatively rare, generally occurring two or three times per year, between November to March. They each typically last 3–5 days, during which the wind speed over the Gulf exceeds gale force (more than 50 km/h). A winter Shamal event is triggered by the formation of a low pressure over the Mediterranean Levant. The low pressure, as it moves eastward over the southern Tigris-Euphrates valley, attracts air from the Gulf, which takes the form of a wind from the south east, named the *Kaus* wind locally, from Farsi for 'south' (Reynolds 2002). The strength of the Kaus varies greatly, ranging from nearly zero to gale-force winds, and may be associated with rain or dust storms. The low pressure then moves over the Iranian Zagros mountains, opposite to the high pressure residing over Saudi Arabia. This pushes a cold front over the Gulf: a tongue of cold air which propagates from north-west to south-east, sandwiched between the high and the low pressure. In the wake of the cold front, a jet of gale-force winds, the actual winter Shamal, persists for a few days before weakening and dissipating when the low pressure over the Zagros mountains finally disappears (Perrone 1979). The extreme cold carried by some winter shamals can have rare but significant biological consequences, such as leading to cold-induced coral bleaching and mass mortality on reefs in the southern Gulf (Shinn 1976; Coles and Fadlallah 1991).

Outside of shamal events, winds on the UAE coastline are more typically dominated by daily land-sea breeze cycles. The basic mechanism is well-known: air rising over hot afternoon land draws-in cooler air from the sea, giving a so-called seabreeze each afternoon that persists until sunset. Late at night, when land becomes colder than the sea, the flow reverses, resulting in a slight landbreeze that moves offshore during the early morning hours. In the UAE this basic mechanism is present, but with a literal twist. Air masses pushed in any given direction, because of Earth's rotation, don't keep traveling in that same direction, but deviate to their right, so that, if nothing else intervenes, the air mass travels a full circle, performing what is called an *inertial oscillation*. At the latitudes of the Gulf, the circle closes in about 1 day. There's thus the potential for resonance between the daily land-sea breeze and the inertial oscillations (Fearon et al. 2020). As a result, the direction of the breeze on the UAE coastline typically performs a full 360° turn every 24 h (Fig. 3.3, top panel). The wind speed still shows the usual modulation of a land-sea breeze: it picks up speed early in the morning and late in the afternoon, and subsides in the middle of the day and of the night (Fig. 3.3, bottom panel) but the wind direction rotates, rather than reverse its course (Paparella et al. 2019). Little is known of the biological importance of the daily land-sea breeze cycles in terrestrial systems, but they can be highly important for turning over waters in lagoon systems, modulating temperatures (Mohamed et al. 2005).

Convective storms occur when warm, humid air is, within hours, uplifted from near the surface to heights of several kilometers, triggering condensation and rain. Rain-cooled air falls to the surface, replacing the uplifted warm air, producing cold, strong surface winds in front of the storm. Squalls of this sort are commonly observed in association with mid-latitude thunderstorms, where they generally precede by a few tens of minutes the arrival of the rain, but are otherwise inconsequential except to sailors. Desert storms also have cold squalls that precede their arrival, but in a dry, sandy environment they cause dangerous dust storms called '*haboobs*' (from the Arabic for 'blowing') that suddenly reduce visibility and bring unhealthy air. In the UAE haboobs generally are caused by storms originating from warm, humid air coming from the Sea of Oman, uplifted over the slopes of the Hajar mountains, which are able to cross the mountains where they drop rain that results in the cooling front and move into the flatlands overlooking the Gulf coast. More rarely, haboob-forming storms originate from the Empty Quarter, entering the UAE from its southern border (Miller et al. 2008).

Tropical cyclones are the most powerful storms on the planet. Those originating in the Atlantic are known as hurricanes, and those originating in the Asian Pacific are known as typhoons. The Arabian Sea can become warm enough to trigger the formation of tropical storms and tropical cyclones. They generally form near the

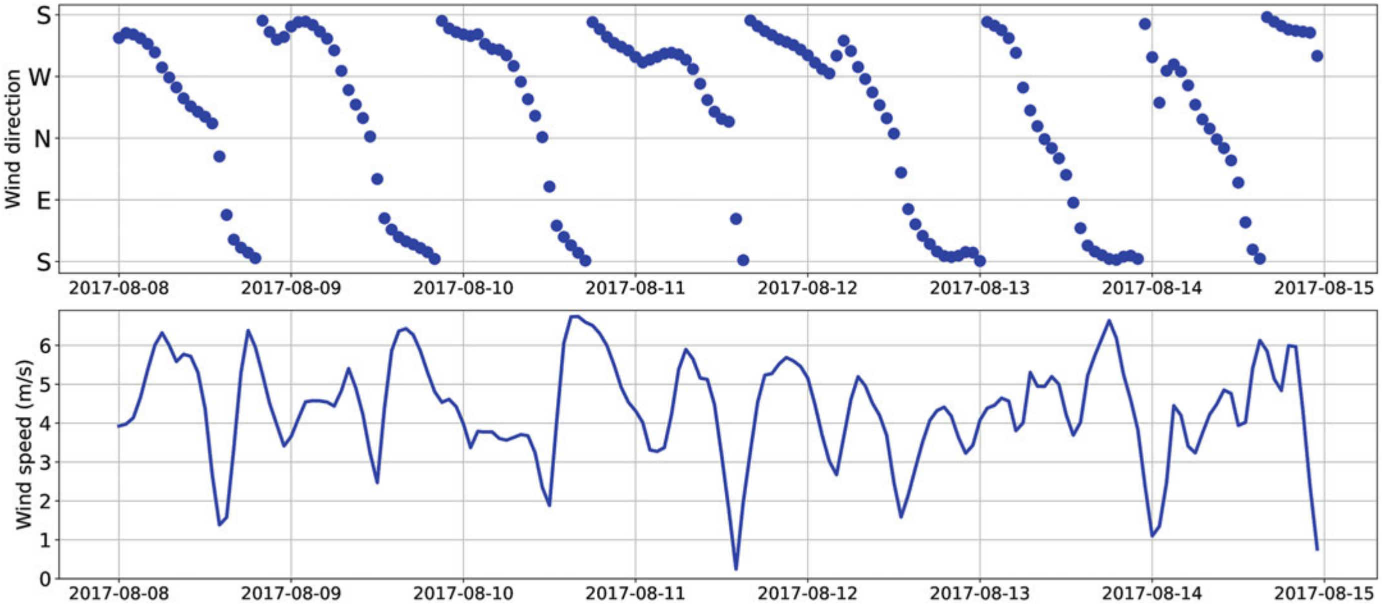


Fig. 3.3 Rotating summer coastal breezes off the Abu Dhabi coast (25.75 N, 54.25 E). Top panel: wind direction. Bottom panel: wind speed. Data are from the ERA5 reanalysis, copyright 2023 European Centre for Medium-Range Weather Forecasts (ECMWF); this data is published under a Creative Commons Attribution 4.0 International (CC BY 4.0)

Laccadive islands, west of the southernmost tip of India, and travel north-westward, with the potential for making landfall anywhere from Somalia to Pakistan. Curiously, tropical cyclones are relatively rare in this region in July, August and September, when the strong Somali jet induces upwelling of cold, deep water along the Somali and Omani coast, thus reducing the ocean water temperature, which, in turn, hampers the formation of tropical storms. Regionally, most tropical cyclones form in May and June, and in October and November. About one third of the storms forming in the Arabian Sea eventually reach the Sea of Oman, making landfall on average once every 3 years. These bring high seas and flooding rain that can easily exceed 200 mm for a single event (Membery 1998). The tropical cyclone Gonu, in June 2007, is so far the strongest tropical cyclone on record in the Arabian Sea. It reached the Sea of Oman, generating waves higher than 9 m, and causing extensive coastal damage in Oman, Iran and on the UAE east coast (Dibajnia et al. 2010). Such storms can cause significant damage to coral reefs, as occurred during Cyclone Gonu when over 50% of branching and table corals were lost from coral reefs on the Fujairah coast (Foster et al. 2011, ch. 11). However, they can also provide unexpected environmental benefits, acting as a significant source of rainfall to recharge groundwater aquifers by bringing precipitation in 24 h that can more than double the amount that typically falls in an entire year (Al Khatry and Helmi 2008; Abdalla and Al-Abri 2011).

3.4 Can We Glimpse UAE's Future Climate?

The Eastern Mediterranean and Middle-East region is warming at a rate of 0.45 °C/decade (Zittis et al. 2022). This is 1.66 times higher than the global average (0.27 °C/decade), and slightly more than the average temperature increase on land between ±40° latitude, which is 1.5 higher than the global average (Sutton et al. 2007).

The warming trend is projected by the IPCC to continue with an end-of-century increase over the Gulf region of 1.3 °C from the present-day average in the optimistic SSP1-2.6 scenario, and an increase of 4.7 °C from the present-day average in the pessimistic SSP1-8.5 scenario (Gutierrez et al. 2021). Neither scenario should be considered as particularly likely to occur, and we'll probably witness temperature increases intermediate between these two extremes (Hausfather and Peters 2020).

The impacts of increasing temperature are likely to be most extreme for ectothermic (cold-blooded) animals that have difficulty in maintaining core body temperatures. This is particularly true of marine fauna, which are unable to escape extreme water temperatures using behavioral strategies that can be used by animals on land (burrowing, shading, etc.; see Chaps. 14 and 16). Recurrent coral bleaching events are unfortunately already common on the UAE's Gulf coast (Riegl et al. 2018), and have begun to occur on the east coast in recent years (J.Burt, unpubl. data, ch. 11). Currently, ectothermic Hawksbill turtles undertake migration to offshore environments to avoid extreme inshore summer temperatures (Marshall et al. 2020), therefore the projected increased temperatures represent a threat to these important thermal refugia.

For other parameters future trends are not so clear. Some studies find a slight (and weakly significant) decrease in wind speed over the past 40 years (Paparella et al. 2022), while others project a 10% increase by the end of the century (Feron et al. 2021).

Most uncertain of all is the future amount of rainfall. The most recent IPCC models project an increase of rainfall over the Arabian peninsula of 5% in the SSP1-2.6 scenario and of 25% in the SSP5-8.5 scenario. These are, however, multi-model averages. The IPCC models actually disagree among each other, and the individual models project rainfall changes ranging from −21% to +196% for the SSP5-8.5 scenario (−17% to +93% for the SSP1-2.6 scenario). This range is much wider than the natural variability of the climate system and signals an intrinsic inability of current climate models to produce reliable scenarios at regional and local scales, particularly in some locations, such as the Gulf region (Zittis et al. 2022). Future rainfall in the UAE will be determined by a complex interplay between shifts of the ITCZ, interactions of the large-scale atmospheric circulation with the Hajar mountains (Jing et al. 2020), and subtle feedbacks between uplift of dust and cloud formation (Francis et al. 2021). Most of these processes are poorly represented (or not represented at all) in global climate models, which calls for renewed efforts in regional-scale climate modeling.

3.5 Atlas of UAE Climatology: 1979–2021

Climate is defined by the World Meteorological Organization as the average meteorological conditions across a period of three decades or longer, allowing a smoothing out of short-term variability. We conclude this chapter with a series of maps of key climatic parameters for the period 1979–2021, as captured in the ERA5 reanalysis (Hersbach et al. 2020), in order to provide a comprehensive and current description of the national climate. The ERA5 is the most extensive collection of global meteorological and climate data currently available, assimilated in a state-of-the-art model of the Earth's atmosphere, and released with a horizontal resolution of about 30 km. From the same dataset we also present the monthly statistics of temperature, wind and rainfall data at the location of 10 UAE cities.

Unsurprisingly for anyone who has spent time in the Emirates, there is great variation in temperature between seasons across the nation, but there is also significant variability across locations (Fig. 3.4). Daily and seasonal temperature fluctuations are larger in the desert interior of the UAE, and are less pronounced along the coastline where coastal waters can dampen temperature fluctuations (Fig. 3.4).

In addition to seasonal temperature fluctuations, we are also experiencing a warming trend, presumably as a localized response to global climate change. The July maxima in the decade between 1979 and 1988 were about one degree cooler at any given location in the UAE than in the most recent decade of 2012 to 2021,

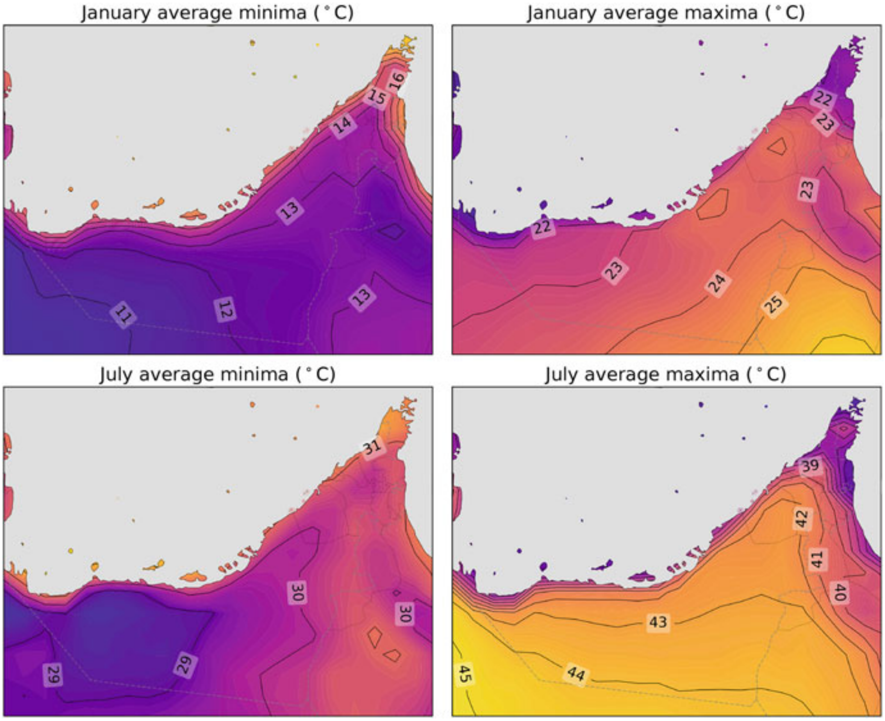


Fig. 3.4 Average daily minimum temperature (left panels) and maximum temperature (right panels) in January (top panels) and July (bottom panels). Data are from the ERA5 reanalysis, copyright 2023 European Centre for Medium-Range Weather Forecasts (ECMWF); this data is published under a Creative Commons Attribution 4.0 International (CC BY 4.0)

except on the Musandam peninsula, where there has not been any significant trend (Fig. 3.5). While a 1 °C temperature increase in a three decade period may not sound significant to many people in the general public, this is faster than is happening on a global average (Zittis et al. 2022), and is rapidly approaching the 1.5 °C that is considered a critical threshold beyond which substantial impacts to ecosystems, human health and economies are projected to occur (Masson-Delmotte et al. 2018). The UAE is already experiencing recurrent marine heat waves that have substantially degraded its coral reefs, for example (see Chap. 11), and the increased temperature is presumably also enhancing evaporation on land, reducing water availability for terrestrial vegetation and exacerbating ongoing desertification (see Chap. 5). The consequences of even further 'modest' increases in temperature are dire, particularly given that many organisms in the UAE are already living at the physiological limits of temperature exposure.

In addition to temperature, precipitation is one of the main factors structuring the occurrence and distribution of organisms in the UAE. Precipitation in the Emirates is extremely variable from year to year, with a few rainy years interspersed between dryer ones. It is highly seasonal, with virtually all rainfall occurring in winter and in

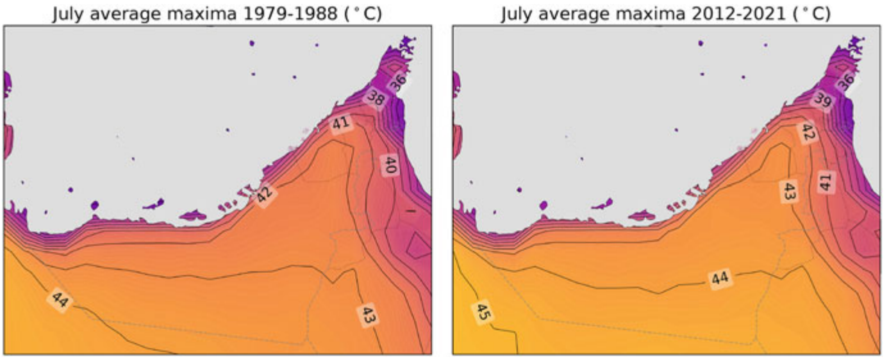


Fig. 3.5 Average daily maximum temperature in the decade 1979–1988 (left) and in the decade 2012–2021 (right). Data are from the ERA5 reanalysis, copyright 2023 European Centre for Medium-Range Weather Forecasts (ECMWF); this data is published under a Creative Commons Attribution 4.0 International (CC BY 4.0)

early spring (Fig. 3.6). It varies spatially as well, with the majority of precipitation occurring in the vicinity of the Hajar mountain range on the eastern side of the nation Figs. 3.7–3.11. These spatial differences in rainfall, in combination with the local geology and geography, are a primary factor driving variation in vegetation assemblages around the Emirates (Chap. 5). While the absolute amount of rain varies between locations across the UAE, March is typically as rainy as the winter months in most locations (for the monthly statistics of rainfall at selected UAE locations, see below Figs. 3.12–3.21). Very little rainfall occurs from May to October, regardless of location (Fig. 3.6). This seasonal variation in rain drives the ebb-and-flow of annual plant life cycles, with most emerging following the spring rains to rapidly produce seeds and die off with the onset of summer (Chap. 13). Perennial plants, in contrast, have developed unique adaptations to help them persist through the extreme aridity of the summer months (e.g. drought tolerance, drought avoidance and succulence; see Chap. 13).

The long-term comparison of precipitation in the decade between 1979–1988 versus the more recent decade between 2012–2021 is disheartening: in most of the UAE the amount of rainfall in the winter months has more than halved (Fig. 3.7). On the Hajar mountains and on the Musandam peninsula the rainfall decline has been less extreme, but even there a decrease is quite evident. The biological implications of such radical reductions of an already limited water supply cannot be understated. Most arid region vegetation exists in a fairly fragile balance with local water supply, and such reductions can result in dramatic reductions in vegetation cover, restructuring of community composition, and exacerbation of desertification, potentially causing phase-shifts that lead to degraded stable states where recovery is near impossible. This is particularly important for highly localized and unique vegetation communities as they are unlikely to be able to migrate to other areas due to highly restrictive habitat requirements (see Chap. 5). As this vegetation also serves as food, shelter and habitat for the remainder of the food web, the knock-on implications of

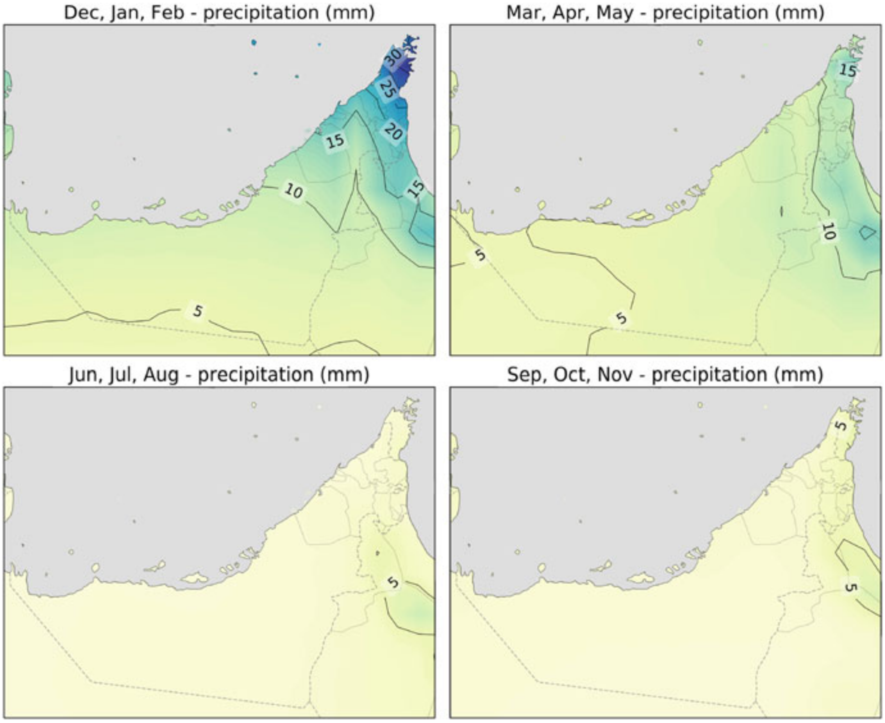


Fig. 3.6 Maps of seasonal rainfall expressed as mean precipitation (mm) over 1 month. Data are from the ERA5 reanalysis, copyright 2023 European Centre for Medium-Range Weather Forecasts (ECMWF); this data is published under a Creative Commons Attribution 4.0 International (CC BY 4.0)

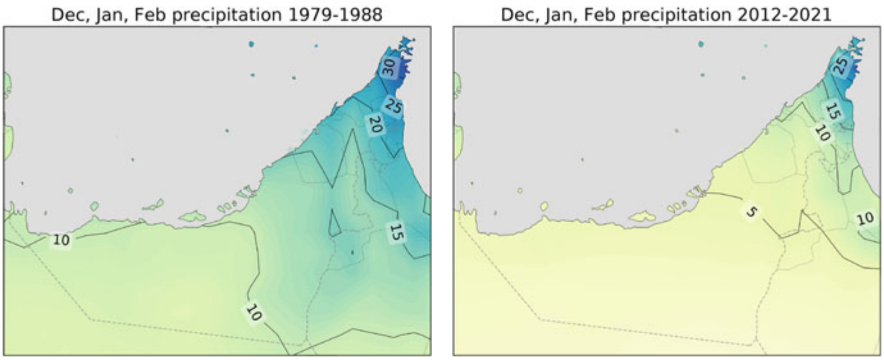


Fig. 3.7 Winter average monthly precipitation in the decade 1979–1988 (left) and in the decade 2012–2021 (right). Data are from the ERA5 reanalysis, copyright 2023 European Centre for Medium-Range Weather Forecasts (ECMWF); this data is published under a Creative Commons Attribution 4.0 International (CC BY 4.0)

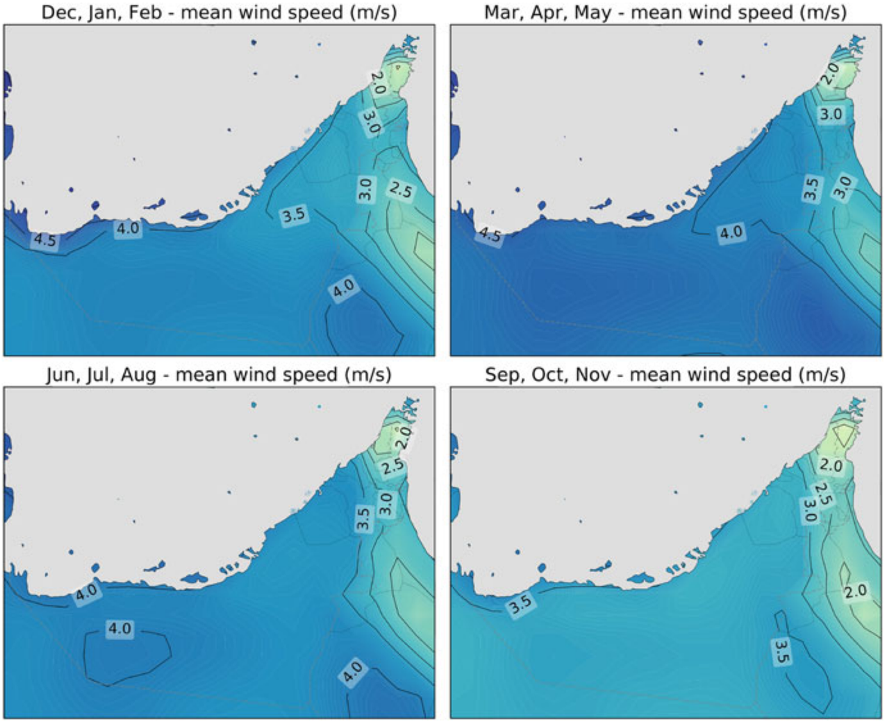


Fig. 3.8 Seasonal mean wind speed (m/s). Note that here and in Fig. 3.9 we report the average of the wind speed. This differs from Fig. 3.2, which shows the average of the wind vector (thus in Fig. 3.2 a low average wind may be the result of an alternation of winds blowing in opposite directions, while here low values indicate a persistent lack of wind). Data are from the ERA5 reanalysis, copyright 2023 European Centre for Medium-Range Weather Forecasts (ECMWF); this data is published under a Creative Commons Attribution 4.0 International (CC BY 4.0)

such substantial reductions in precipitation since the 1980s to the biodiversity of the UAE are alarming.

Although the occurrence of seasonally extreme winds such as winter 'shamal' events and early summer 'cyclones' would hint at a high degree of seasonality in the wind climate of the UAE, this is not the case. As shown in Fig. 3.8, the average wind speed is only slightly higher during the spring, and just slightly lower during the autumn, compared to the year as a whole. This is because the extreme events, such as a shamal-driven storm, are typically very short in duration (ca. 3 days), and occur only occasionally, with the wind climate much more typically characterized by near-calm or breeze conditions, resulting in the limited seasonal variability observed in Fig. 3.8. In terms of spatial differences, the complicated topography of the Hajar mountains and of the Musandam peninsula acts to reduce the surface wind speed in that area. Winds are substantially higher in the more unobstructed Empty Quarter, where winds are typically more than double that occurring in the northern Hajar

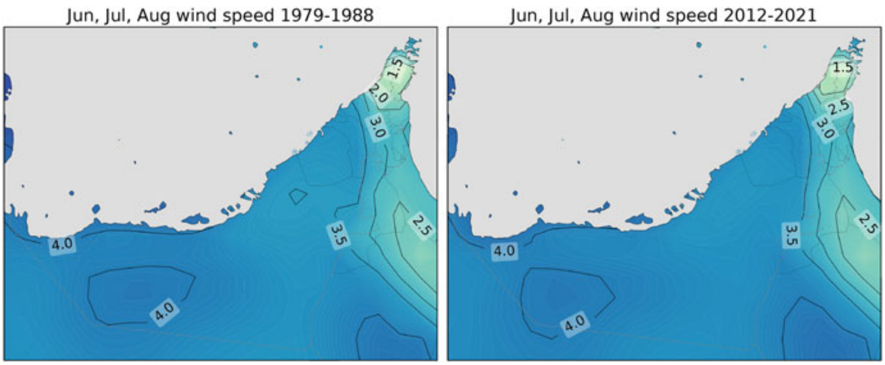


Fig. 3.9 Average summer wind speed (m/s) in the decade 1979–1988 (left) and in the decade 2012–2021 (right). Data are from the ERA5 reanalysis, copyright 2023 European Centre for Medium-Range Weather Forecasts (ECMWF); this data is published under a Creative Commons Attribution 4.0 International (CC BY 4.0)

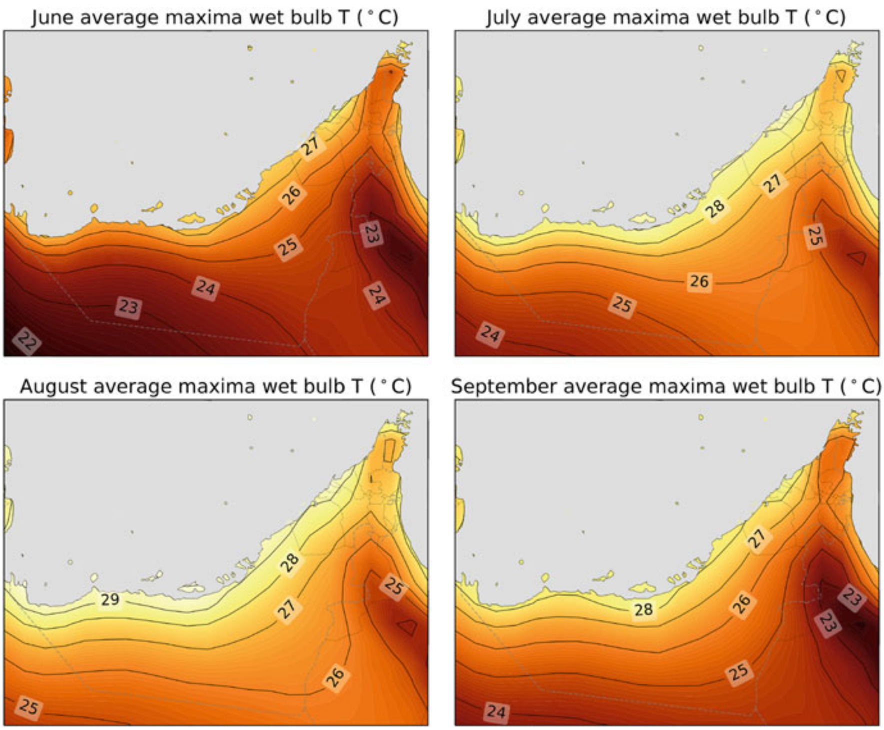


Fig. 3.10 Monthly average of the daily maximum wet bulb temperature (centigrade) in June, July, August and September. Data are from the ERA5 reanalysis, copyright 2023 European Centre for Medium-Range Weather Forecasts (ECMWF); this data is published under a Creative Commons Attribution 4.0 International (CC BY 4.0)

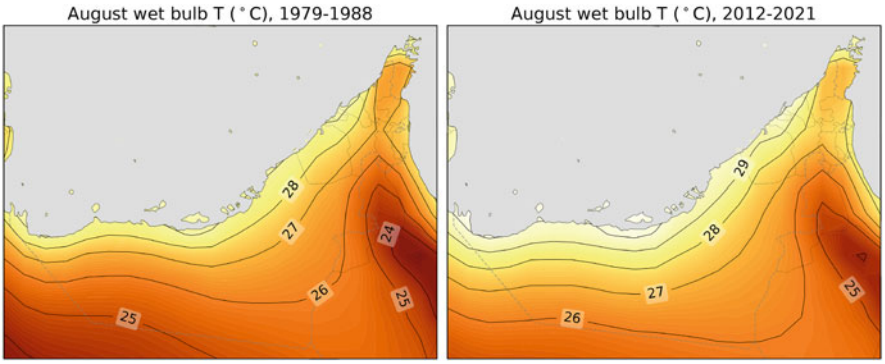


Fig. 3.11 Average of the daily maximum wet-bulb temperature in August in the decade 1979–1988 and in the decade 2012–2021. Data are from the ERA5 reanalysis, copyright 2023 European Centre for Medium-Range Weather Forecasts (ECMWF); this data is published under a Creative Commons Attribution 4.0 International (CC BY 4.0)

mountains (Fig. 3.8). No appreciable changes in average wind speed have occurred in the last 40 years at any location in the UAE (Fig. 3.9).

Wet-bulb temperature is the temperature of a thermometer whose heat-sensing device is wrapped in a water-soaked cloth and exposed to strong wind. As a result of the evaporative cooling, the wet-bulb temperature is always lower than the actual air temperature. The difference between the two temperatures is a measure of the humidity content of the air. For the same air temperature, dry conditions yield a lower wet-bulb temperature than when the air is very humid. This seemingly arcane quantity is of great usefulness for quantifying the discomfort experienced by humans exposed to a hot environment. The more the wet bulb temperature increases, the less a human body is capable of losing heat by sweating. The physiological limit of the wet bulb temperature for humans is considered to be 35 °C. An environment where the wet bulb temperature is above that threshold is considered life-threatening.

Recently it has been suggested that some regions near the Arabian Sea may experience wet-bulb temperatures close to 35 °C as a result of climate change (Pal and Eltahir 2016; Raymond et al. 2020). Our analyses show that in the UAE the wet-bulb temperature has historically been substantially higher along the coastline than in the dryer interior, reflecting the strong influence of evaporation from the Arabian Gulf and Gulf of Oman for coastal humidity. In Abu Dhabi, during August, it is on average higher than 29 °C (Fig. 3.10). While this is still sufficiently below the physiological threshold to avoid human health alarm, the trend does not bode well: in the last 40 years the wet bulb temperature in the UAE coastal regions has increased by one degree (Fig. 3.11), suggesting that the dire human health impact projections of Pal and Eltahir (2016) are reasonable. What implications this has for the native fauna (or flora) of the UAE remains largely unknown, although heat stress impacts on domesticated livestock appear to be a significant cause for concern (Carnovale and Phillips 2020), and are likely equally an issue for natural populations.

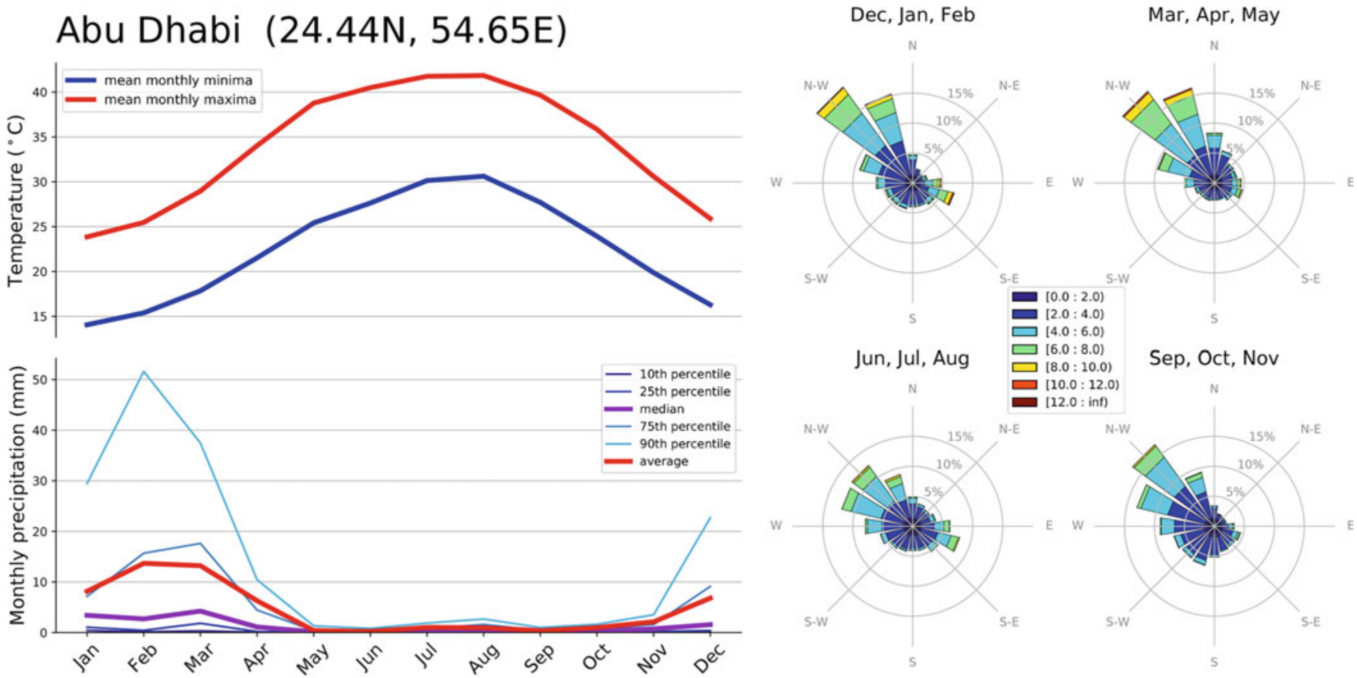


Fig. 3.12 Climatological statistics of Abu Dhabi. Top left panel: mean monthly maximum and minimum temperature. Bottom left panel: statistics of monthly precipitation. Right panels: seasonal wind roses showing the direction from which the wind blows; the width of the colored bars is proportional to the likelihood of occurrence of a given wind speed (in m/s, as given by the central legend). Data are from the ERA5 reanalysis, copyright 2023 European Centre for Medium-Range Weather Forecasts (ECMWF); this data is published under a Creative Commons Attribution 4.0 International (CC BY 4.0)

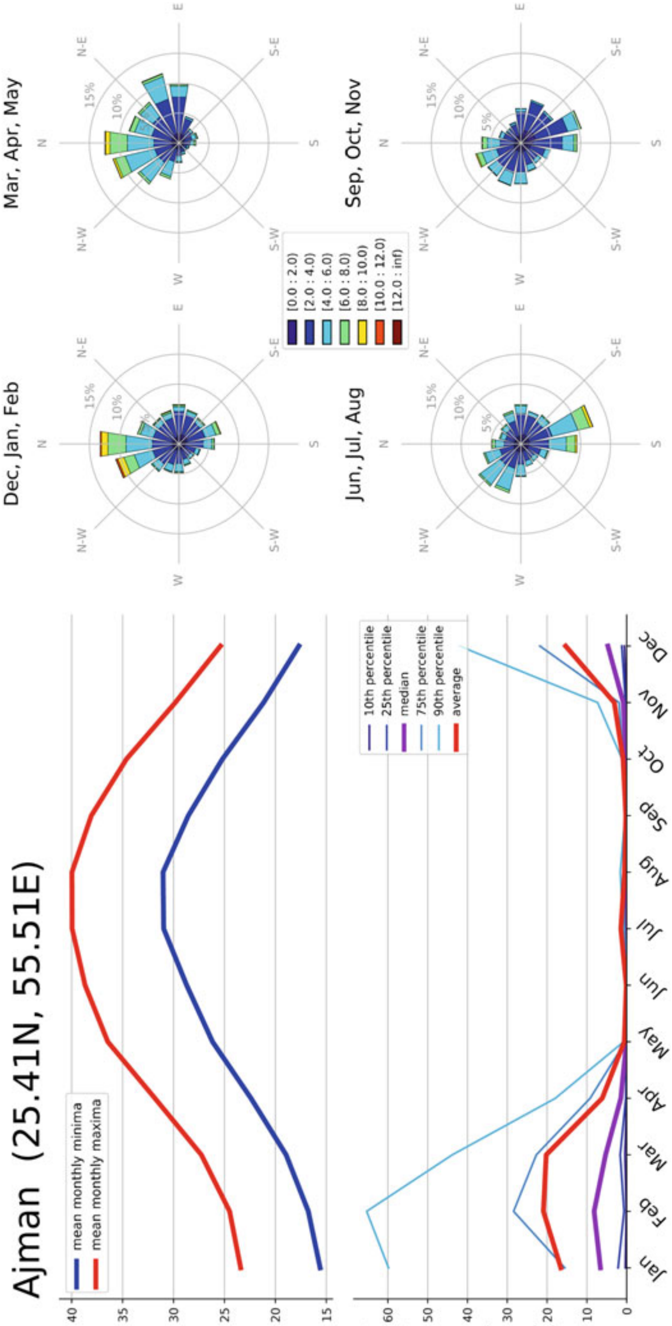


Fig. 3.13 Climatological statistics of Ajman. See legend of Fig. 3.12

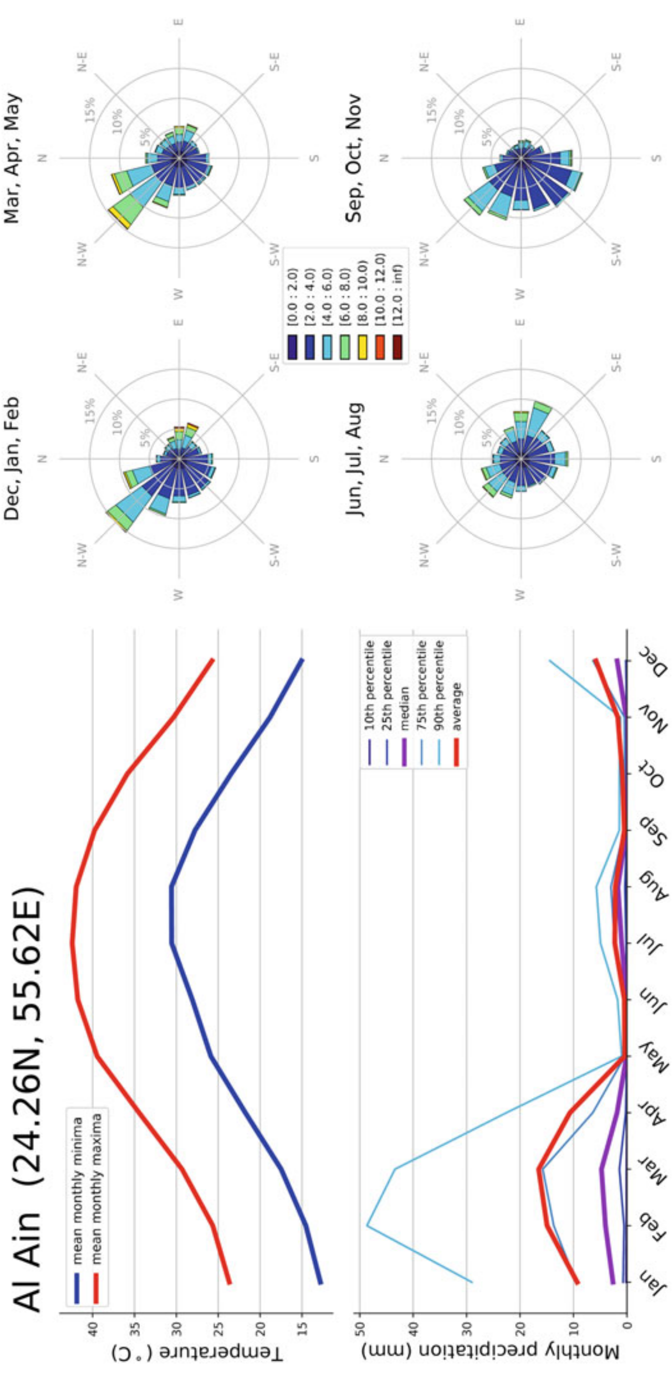


Fig. 3.14 Climatological statistics of Al Ain. See legend of Fig. 3.12

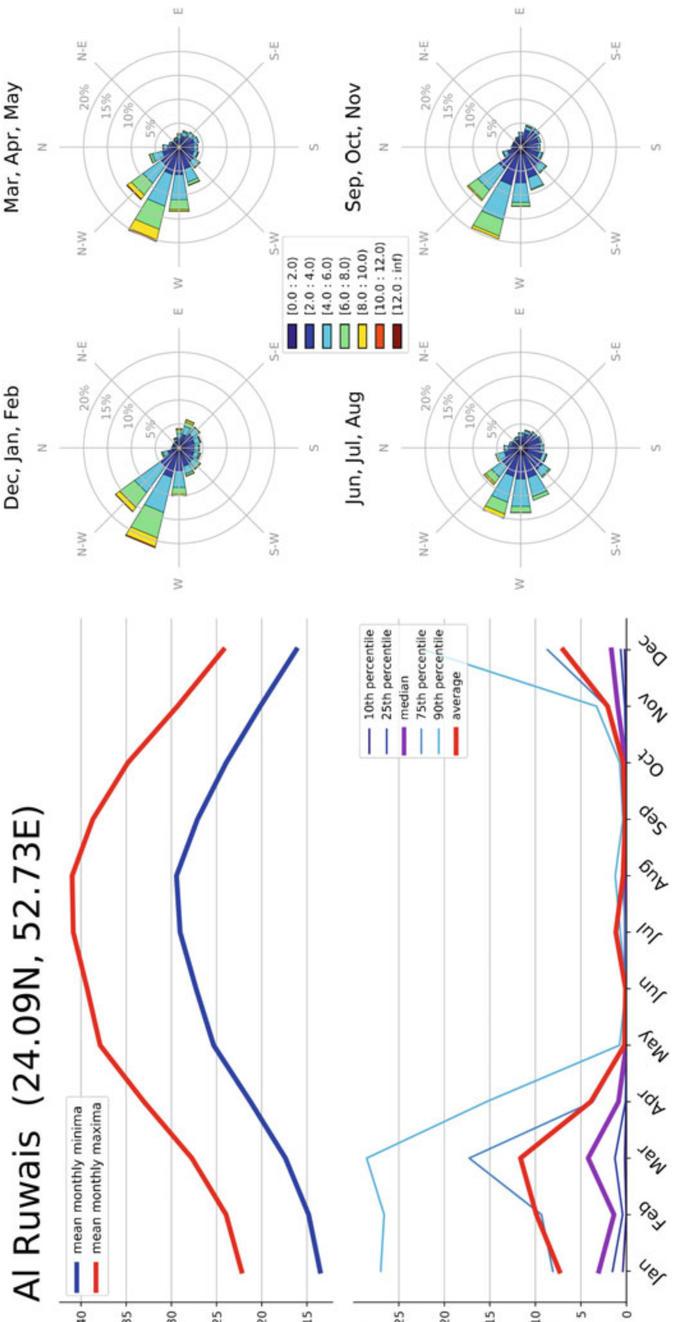


Fig. 3.15 Climatological statistics of Al Ruwais. See legend of Fig. 3.12

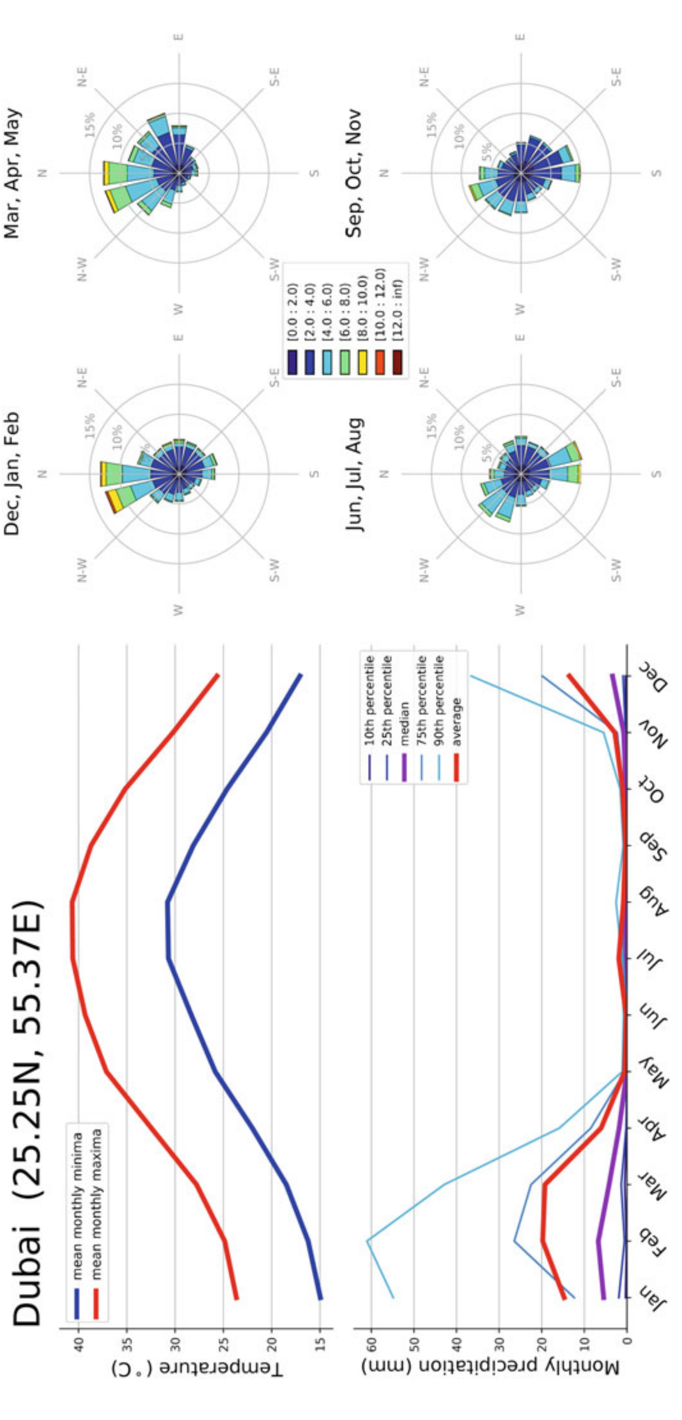


Fig. 3.16 Climatological statistics of Dubai. See legend of Fig. 3.12

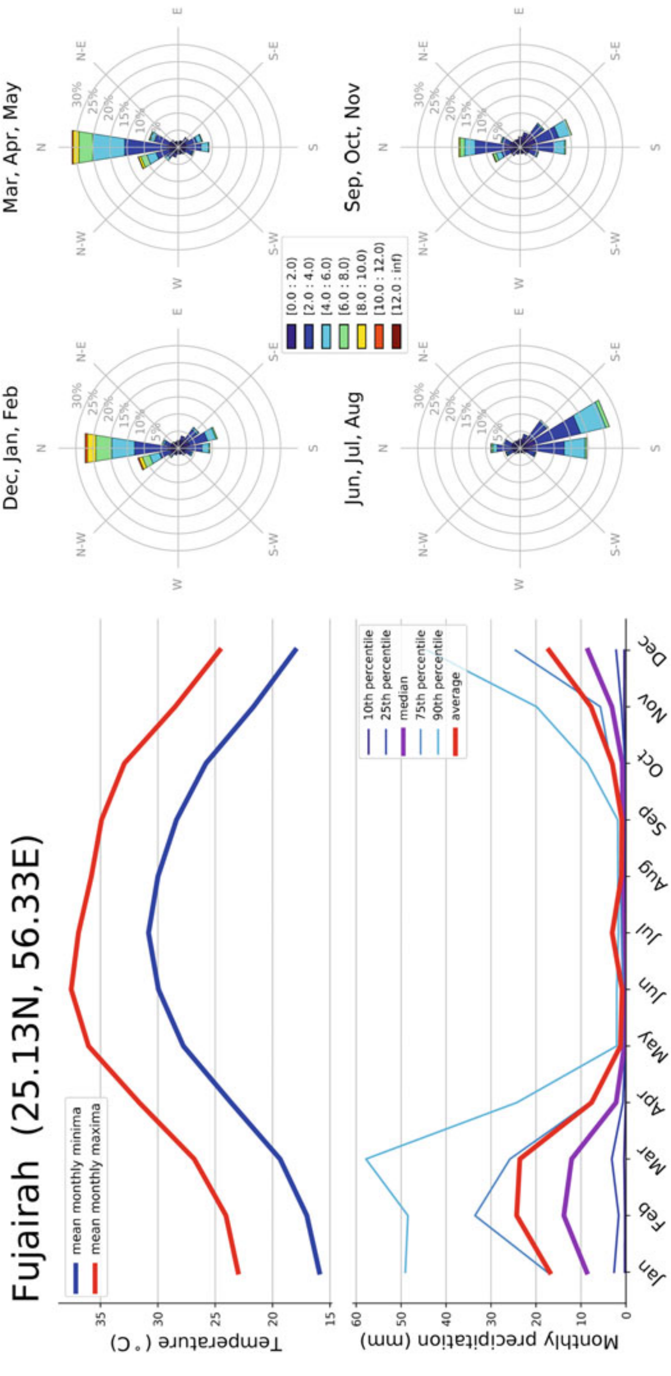


Fig. 3.17 Climatological statistics of Fujairah. See legend of Fig. 3.12

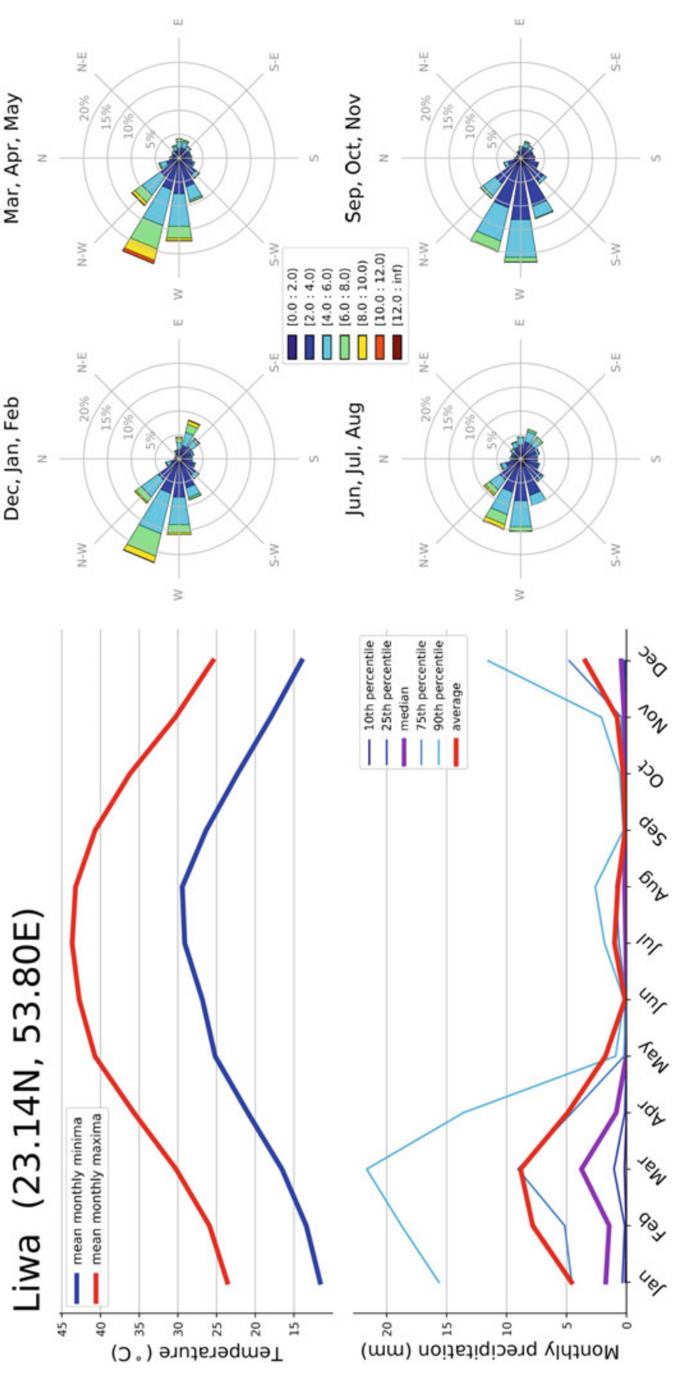


Fig. 3.18 Climatological statistics of Liwa. See legend of Fig. 3.12

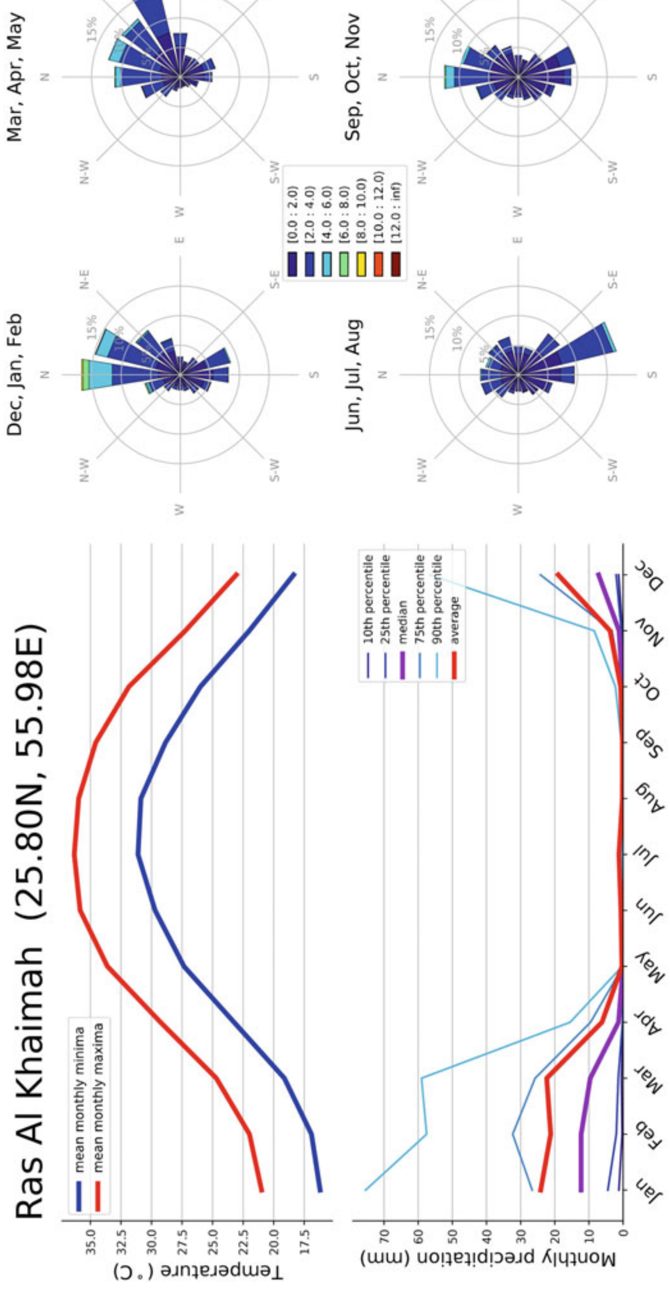


Fig. 3.19 Climatological statistics of Ras Al Kaimah. See legend of Fig. 3.12

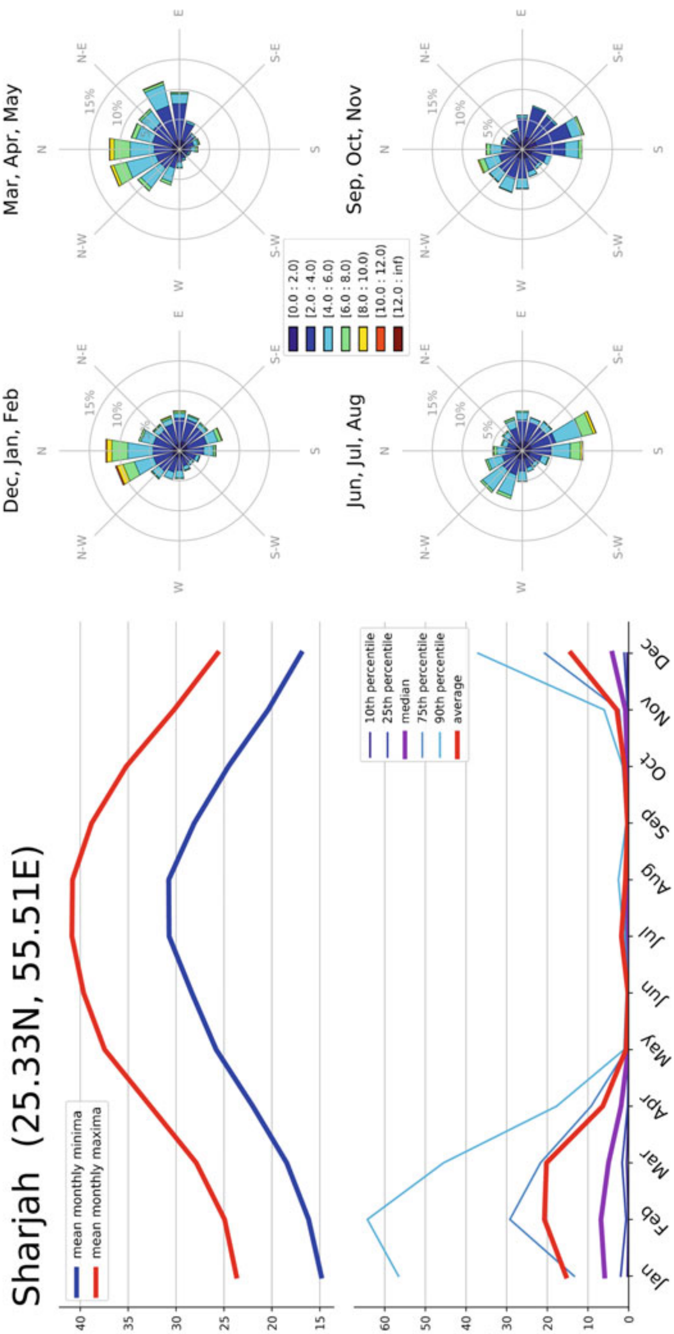


Fig. 3.20 Climatological statistics of Sharjah. See legend of Fig. 3.12

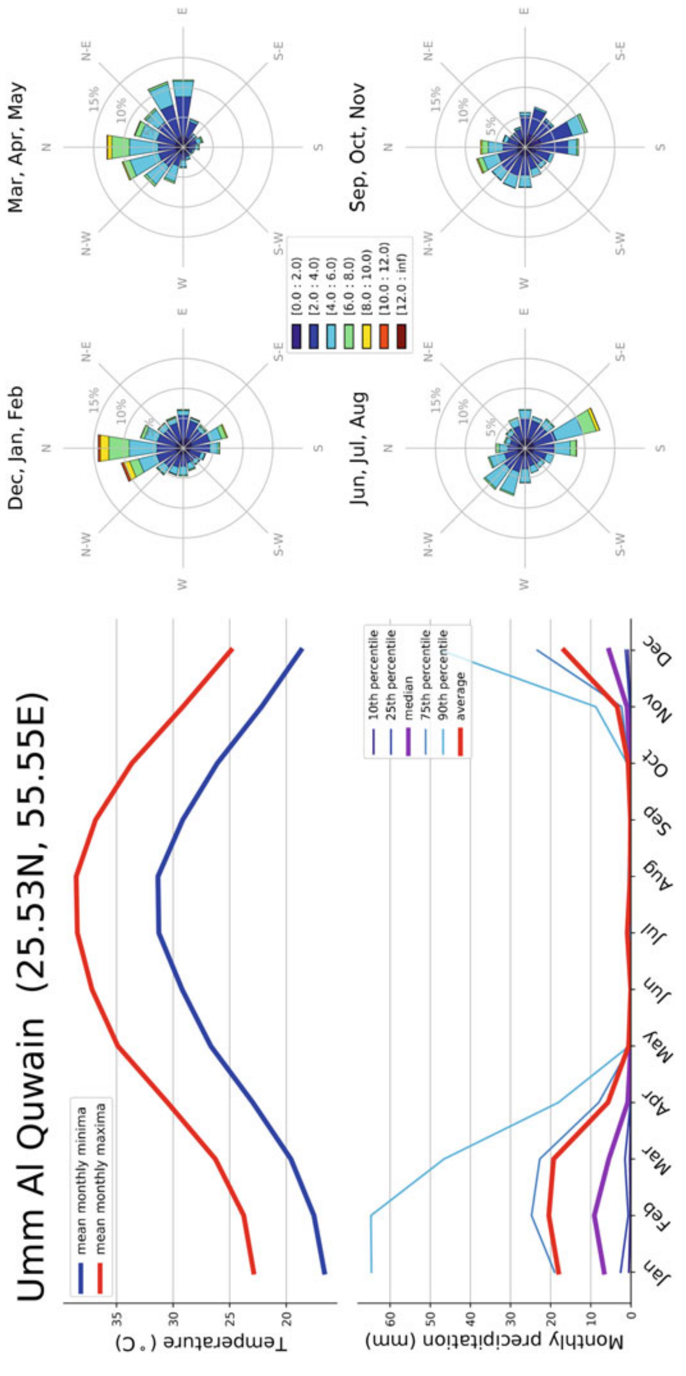


Fig. 3.21 Climatological statistics of Umm Al Quwain. See legend of Fig. 3.12

3.6 Conclusions

In summary, the climate of the UAE is a highly peculiar one. It is a harsh desert, but it is strongly affected by the Indian monsoon, which in a past age made this a green land. It lies on the southern shores of an internal sea, the Arabian Gulf, that channels the dominant winds and through which it feels the influence of the Mediterranean Levant. The large-scale dynamics that broadly determine UAE's climate are adjusted and corrected by local features, mainly the presence of the Hajar Mountains, which trigger most of the scarce rainfall descending on this land. Along with the underlying geology, these climate features are a primary features driving vegetation patterns across the Emirates, and indirectly structuring the animal food web upon which they subsist.

In spite of its interesting features, many details of the UAE climate are still poorly understood. The mutual interaction between dust and rainfall, how the UAE climate will evolve in a globally warming world, and the feed-backs of local climate changes to the UAE ecosystems are examples of topics where more research is needed.

3.7 Recommended Readings

A good introduction to the meteorology and climatology of deserts and arid regions is given by Warner (2009). A technical, but still accessible, review of the climate of the Middle East, with a special focus on the projected climate change may be found in Zittis et al. (2022). Pal and Eltahir (2016) focus on the overlooked threat constituted by the combination of rising temperatures and high humidity, which may lead to unbearable outdoor conditions. Finally, deMenocal et al. (2000) and Lüning and Vahrenholt (2019) give detailed reviews on how climate shaped the civilizations of the earliest inhabitants of the Arabian Peninsula.

References

Abdalla O, Al-Abri R (2011) Groundwater recharge in arid areas induced by tropical cyclones: lessons learned from Gonu 2007 in Sultanate of Oman. Environ Earth Sci 63:229–239. https://doi.org/10.1007/s12665-010-0688-y

Al Khatry A, Helmi T (2008) The effect of Gonu cyclone on recharging groundwater aquifers—sultanate of Oman. The First International Conference on Water Resources and Climate Change in the MENA Region Muscat, the Sultanate of Oman:2–4

Almazroui M, Nazrul Islam M, Athar H, Jones PD, Rahman MA (2012) Recent climate change in the Arabian Peninsula: annual rainfall and temperature analysis of Saudi Arabia for 1978–2009. Int J Climatol 32(6):953–966. https://doi.org/10.1002/joc.3446

Al Senafi F, Anis A (2015) Shamals and climate variability in the Northern Arabian/Persian Gulf from 1973 to 2012. Int J Climatol 35(15):4509–4528

Bard E (2013) Out of the African humid period. Science 342(6160):808–809

Beech M, Elders J, Shepherd E (2000) Reconsidering the Ubaid of the Southern Gulf: new results from excavations on Dalma Island, UAE. Proc Semin Arabian Stud 30:41–47

Bou Karam Francis D, Flamant C, Chaboureau J-P, Banks J, Cuesta J, Brindley H, Oolman L (2017) Dust emission and transport over Iraq associated with the summer Shamal winds. Aeolian Res 24:15–31. https://doi.org/10.1016/j.aeolia.2016.11.001

Burt J, Paparella F, Al-Mansoori N, Al-Mansoori A, Al-Jailani H (2019) Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. Coral Reefs 38:567–589. https://doi.org/10.1007/s00338-019-01767-y

Carnovale F, Phillips CJC (2020) The effects of heat stress on sheep welfare during live export voyages from Australia to the Middle East. Animals 10:694. https://doi.org/10.3390/ani10040694

Charney JG (1975) Dynamics of deserts and drought in the Sahel. Q J R Meteorol Soc 101(428): 193–202

Charpentier V, Mery S (2008) A Neolithic settlement near the Strait of Hormuz: Akab Island, United Arab Emirates. Proc Semin Arabian Stud 38:117–136

Claussen M, Kubatzki C, Brovkin V, Ganopolski A, Hoelzmann P, Pachur HJ (1999) Simulation of an abrupt change in Saharan vegetation in the mid-Holocene. Geophys Res Lett 26(14): 2037–2040. https://doi.org/10.1029/1999GL900494

Coles SL, Fadlallah YH (1991) Reef coral survival and mortality at low temperatures in the Arabian Gulf: new species-specific lower temperature limits. Coral Reefs 9(4):231–237. https://doi.org/10.1007/BF00290427

deMenocal P, Ortiz J, Guilderson T, Adkins J, Sarnthein M, Baker L, Yarusinsky M (2000) Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing. Quat Sci Rev 19(1–5):347–361. https://doi.org/10.1016/S0277-3791(99)00081-5

Dibajnia M, Soltanpour M, Nairn R, Allahyar M (2010) Cyclone Gonu: the most intense tropical cyclone on record in the Arabian Sea. In: Charabi Y (ed) Indian ocean tropical cyclones and climate change. Springer, Dordrecht, pp 149–157. https://doi.org/10.1007/978-90-481-3109-9_19

Fearon G, Herbette S, Veitch J, Cambon G, Lucas AJ, Lemarié F, Vichi M (2020) Enhanced vertical mixing in coastal upwelling systems driven by diurnal-inertial resonance: numerical experiments. J Geophys Res Oceans 125(9):e2020JC016208. https://doi.org/10.1029/2020JC016208

Feron S, Cordero RR, Damiani A, Jackson RB (2021) Climate change extremes and photovoltaic power output. Nat Sustain 4(3):270–276. https://doi.org/10.1038/s41893-020-00643-w

Fleitmann D, Burns SJ, Mangini A, Mudelsee M, Kramers J, Villa I et al (2007) Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). Quat Sci Rev 26(1–2):170–188. https://doi.org/10.1016/j.quascirev.2006.04.012

Fonseca R, Francis D, Nelli N, Thota M (2022) Climatology of the heat low and the intertropical discontinuity in the Arabian Peninsula. Int J Climatol 42(2):1092–1117. https://doi.org/10.1002/joc.7291

Foster K, Foster G, Tourenq C, Shuriqi M (2011) Shifts in coral community structures following cyclone and red tide disturbances within the Gulf of Oman (United Arab Emirates). Mar Biol 158:955–968. https://doi.org/10.1007/s00227-010-1622-2

Francis D, Chaboureau JP, Nelli N, Cuesta J, Alshamsi N, Temimi M et al (2021) Summertime dust storms over the Arabian Peninsula and impacts on radiation, circulation, cloud development and rain. Atmos Res 250:105364. https://doi.org/10.1016/j.atmosres.2020.105364

Gutiérrez J et al (2021) Atlas. In: Masson-Delmotte V et al (eds) Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. http://interactive-atlas.ipcc.ch/

Hamza W (2021) Dust storms and its benefits to the marine life of the Arabian Gulf. In: Jawad LA (ed) The Arabian seas: biodiversity, environmental challenges and conservation measures. Springer International Publishing, Cham, pp 141–160. https://doi.org/10.1007/978-3-030-51506-5_7

Hausfather Z, Peters GP (2020) Emissions–the 'business as usual' story is misleading. Nature 577: 618–620. https://doi.org/10.1038/d41586-020-00177-3
Hersbach H, Bell B, Berrisford P, Hirahara S, Horányi A, Muñoz-Sabater J et al (2020) The ERA5 global reanalysis. Q J R Meteorol Soc 146(730):1999–2049. https://doi.org/10.1002/qj.3803
Jing X, Xue L, Yin Y, Yang J, Steinhoff DF, Monaghan A et al (2020) Convection-permitting regional climate simulations in the Arabian Gulf Region using WRF driven by bias-corrected GCM data. J Clim 33(18):7787–7815. https://doi.org/10.1175/JCLI-D-20-0155.1
Kallweit H (2003) Remarks on the Late Stone Age in the UAE. Archaeology of the United Arab Emirates. Proceedings of the First International Conference on the Archaeology of the UAE:56–64
Kennett DJ, Kennett JP (2006) Early state formation in Southern Mesopotamia: sea levels, shorelines, and climate change. J Isl Coast Arch 1:67–99. https://doi.org/10.1080/15564890600586283
Kushnir Y, Dayan U, Ziv B, Morin E (2017) Climate of the levant: phenomena and mechanisms. In: Enzel Y, Ofer BY (eds) Quaternary of the levant: environments, climate change, and humans. Cambridge University Press, Cambridge, pp 31–44. https://doi.org/10.1017/9781316106754
Kutzbach JE (1981) Monsoon climate of the early Holocene: climate experiment with the earth's orbital parameters for 9000 years ago. Science 214(4516):59–61
Lüning S, Vahrenholt F (2019) Holocene climate development of North Africa and the Arabian Peninsula. In: Bendaoud A et al (eds) The geology of the Arab world - an overview. Springer, Dordrecht, pp 507–546. https://doi.org/10.1007/978-3-319-96794-3_14
Marshall C, Cullen J, Al-Ansi M, Hamza S, Abdel-Moati M (2020) Environmental drivers of habitat Use by hawksbill turtles (*Eretmochelys imbricata*) in the Arabian Gulf (Qatar). F Mar Sci 7:549575. https://doi.org/10.3389/fmars.2020.549575
Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, and Waterfield T (2018) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157940.001
Membery DA (1983) Low level wind profiles during the Gulf Shamal. Weather 38(1):18–24. https://doi.org/10.1002/j.1477-8696.1983.tb03638.x
Membery D (1997) Unusually wet weather across Arabia. Weather 52(6):166–174. https://doi.org/10.1002/j.1477-8696.1997.tb06303.x
Membery D (1998) Famous for 15 minutes: an investigation into the causes and effects of the tropical storm that struck southern Arabia in June 1996. Weather 53(4):102–110. https://doi.org/10.1002/j.1477-8696.1998.tb03972.x
Miller SD, Kuciauskas AP, Liu M, Ji Q, Reid JS, Breed DW et al (2008) Haboob dust storms of the southern Arabian Peninsula. J Geophys Res Atmos 113(D1). https://doi.org/10.1029/2007JD008550
Mohamed KA, Odeh M, Areiqat A (2005) Environmental impact assessment on a plant located inside a lagoon. Desalination 185:45–56. https://doi.org/10.1016/j.desal.2005.03.070
Moradi M, Moradi N (2020) Correlation between concentrations of chlorophyll-a and satellite derived climatic factors in the Persian Gulf. Mar Pollut Bull 161:111728. https://doi.org/10.1016/j.marpolbul.2020.111728
Pal JS, Eltahir EA (2016) Future temperature in southwest Asia projected to exceed a threshold for human adaptability. Nat Clim Chang 6(2):197–200. https://doi.org/10.1038/nclimate283
Paparella F, Xu C, Vaughan GO, Burt JA (2019) Coral bleaching in the Persian/Arabian Gulf is modulated by summer winds. F Mar Sci 6:1–15. https://doi.org/10.3389/fmars.2019.00205

Paparella F, D'Agostino D, Burt JA (2022) Long–term, basin–scale salinity impacts from desalination in the Arabian/Persian Gulf. Sci Rep 12:20549. https://doi.org/10.1038/s41598-022-25167-5

Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci 11:1633–1644. https://doi.org/10.5194/hess-11-1633-2007

Perrone TJ (1979) Winter shamal in the Persian Gulf. Naval Environmental Prediction Research Facility, Monterey, CA

Raymond C, Matthews T, Horton RM (2020) The emergence of heat and humidity too severe for human tolerance. Sci Adv 6:eaaw1838. https://doi.org/10.1126/sciadv.aaw1838

Reynolds RM (2002) Meteorology and climate. In: Price ARG, Munawar M, Khan NY (eds) The Gulf ecosystem health and sustainability. Michigan State University Press, Ann Arbor, MI, pp 41–51. https://doi.org/10.14321/j.ctt1tm7jkg.10

Riegl B, Johnston M, Purkis S, Howells E, Burt J, Steiner SC et al (2018) Population collapse dynamics in *Acropora downingi*, an Arabian/Persian Gulf ecosystem-engineering coral, linked to rising temperature. Glob Chang Biol 24:2447–2462. https://doi.org/10.1111/gcb.14114

Rodwell MJ, Hoskins BJ (1996) Monsoons and the dynamics of deserts. Q J R Meteorol Soc 122: 1385–1404. https://doi.org/10.1002/qj.49712253408

Rose JI (2022) Lands of legend (12–6 ka) an introduction to human prehistory in Arabia: the lost world of the southern crescent. Springer International Publishing, Cham, pp 257–297. https://doi.org/10.1007/978-3-030-95667-7_11

Shinn EA (1976) Coral reef recovery in Florida and the Persian Gulf. Environ Geol 1:241–254. https://doi.org/10.1007/BF02407510

Sutton RT, Dong B, Gregory JM (2007) Land/sea warming ratio in response to climate change: IPCC AR4 model results and comparison with observations. Geophys Res Lett 34(2). https://doi.org/10.1029/2006GL028164

Uerpmann M, Uerpmann H-P (1996) Ubaid pottery in the eastern Gulf – new evidence from Umm al-Qaiwain (U.A.E.). Arab Archaeol Epigr 7:125–139. https://doi.org/10.1111/j.1600-0471.1996.tb00096.x

Warner TT (2009) Desert meteorology. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511535789

Yu Y, Notaro M, Kalashnikova OV, Garay MJ (2016) Climatology of summer shamal wind in the Middle East. J Geophys Res Atmos 121(1):289–305. https://doi.org/10.1002/2015JD024063

Zittis G, Almazroui M, Alpert P, Ciais P, Cramer W, Dahdal Y et al (2022) Climate change and weather extremes in the Eastern Mediterranean and Middle East. Rev Geophys 60: e2021RG000762. https://doi.org/10.1029/2021RG000762

Chapter 4
The Marine Environment of the Emirates

John A. Burt and Francesco Paparella

4.1 The Emirates in a Regional Marine Context

The United Arab Emirates (UAE) is bordered by two water bodies with markedly different environments. These differences are a consequence of a geological history that has resulted in the Arabian Gulf being a shallow semi-enclosed sea that is highly influenced by the regional climatic conditions, while the deep, unenclosed Sea of Oman is well buffered by its connection to the Arabian Sea and wider Indian Ocean. The UAE's east coast borders the Sea of Oman, where the continental slope rapidly increases in depth close to shore. Depths often exceed 50 m within a few km of the coast, dropping to over 1000 m depth offshore. This large depth gradient and the high degree of mixing with the wider Indian Ocean result in a marine environment on the UAE's Sea of Oman coast that is typical of a subtropical ocean and that is well buffered from the considerable environmental variability that characterizes the UAE's western coast.

In contrast, the Strait of Hormuz acts as a geographically and environmentally isolating bottleneck at the entrance of the Arabian Gulf, constricting exchange of Gulf waters with the Indian Ocean through a narrow opening (52 km wide). From an

J. A. Burt (✉)
Arabian Center for Climate and Environmental Sciences (ACCESS), New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

Water Research Center (WRC), New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
e-mail: John.Burt@nyu.edu

F. Paparella
Arabian Center for Climate and Environmental Sciences (ACCESS), New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

Center on Stability, Instability and Turbulence (SITE), New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_4

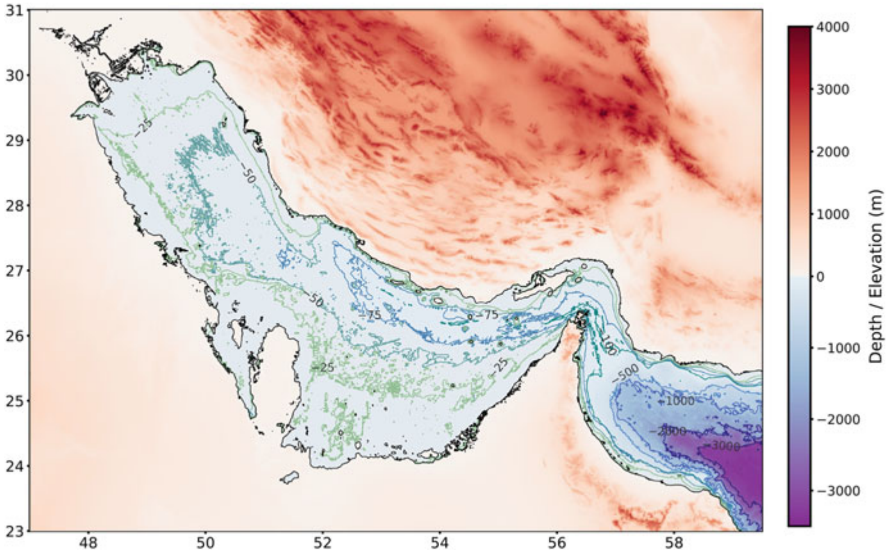


Fig. 4.1 High-resolution bathymetry and elevation of the Gulf region. Degrees of latitude and longitude are provided on the axes. Data from the GEBCO 2022 global terrain model, GEBCO Compilation Group (2021) GEBCO_2022 Grid 10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c (public domain)

oceanographic perspective, the Arabian Gulf is extremely shallow, with an average depth of 30 m and a maximum depth of just over 100 m in a narrow, elongated submarine valley parallel to the Iranian coast (Fig. 4.1). The shallowest, lowest sloping areas in the Gulf occur in the southern basin along the UAE's Abu Dhabi coast, where large areas extending many km from the mainland are less than 15 m depth (Fig. 4.1). More rapid increases in depth only occur offshore from the northern emirates (e.g. Ras Al Khaimah) where the sea-bottom slope is steeper, but even there depths typically do not exceed 30 m within 10 km of the coast. Its shallow depth and isolation from the Indian Ocean, working under the influence of regional climate, are the main conditions responsible for the highly variable and extreme environmental conditions that characterize Arabian Gulf waters.

The geographic history of this region has shaped the distinct bathymetric profiles of the Sea of Oman and the Arabian Gulf. The modern Arabian Gulf is one of the world's youngest seas, having formed only after the peak of the most recent glacial period (Sheppard et al. 1992). At the last glacial maximum sea levels were approximately 120 m lower than today, such that the entire Gulf would have been above sea level and the coastline at that time was located outide the Strait of Hormuz, offshore from modern Fujairah (Lambeck 1996). The only water occurring in the Gulf basin at that time would have been the freshwater flow of the historic Shatt-Ur River system (today's Tigris-Euphrates) that would have extended from Iraq, along the coast of Iran, before emptying into an estuary, possibly a seasonal marshland, where it flowed into the Sea of Oman (Kennett and Kennett 2006). Between 18,000 and 12,000 YBP the glacial ice sheets on the northern continents began to recede,

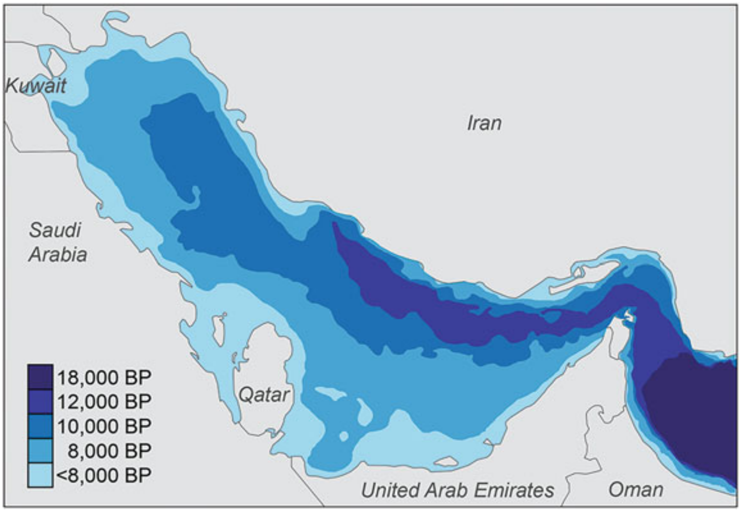


Fig. 4.2 Map illustrating the chronology of Arabian Gulf flooding following the last ice age (BP = before present). Modified from Fig. 4.2 in Smith et al. (2022) under CC-BY-4.0

causing sea levels to rise and the marine transgression to begin to flood the Gulf, initially following its lowest topography adjacent to the Iranian coast. Over the subsequent millennia, flooding extended along the Iranian coast towards the northern Gulf by 10,000 YBP before migrating slowly into the shallow southern basin by 8000 YBP, with today's modern Gulf coastline established only about 6000 YBP (Fig. 4.2; Lambeck 1996). This latter period (10,000 to 6000 YBP) was a time of greater humidity in the region known as the 'climatic optimum', and coincided with the beginning of modern human civilization in the marshlands of today's Iraq (Kennett and Kennett 2006). This period was also biologically important because marine organisms such as corals began to re-colonize the Gulf and to experience pressure from natural selection to adapt to the exceptional environmental conditions of this new and peripheral marine basin, compared with the more customary sub-tropical oceanic conditions of their Indian Ocean source populations (see below) (Smith et al. 2022).

4.2 Geographic Features of the UAE's Coasts

The major geographic feature dominating the east coast of the UAE is the Hajar Mountains which extend along the length of the UAE's Sea of Oman coast. In the northern areas of Dibba, Al Aqah and Khor Fakkan, the mountain's foothills sometimes extend directly to the shoreline with headlands piercing into the marine systems as rocky promontories; occasional hilltops also emerge as nearshore islands (e.g. Dibba Rock and 'Snoopy' Island) or barely submerged pinnacles (e.g. the

Fig. 4.3 Rocky headlands of the Hajar Mountains extend into the sea in the northern portions of the UAE's Sea of Oman coast, where they constitute an important habitat for coral reef development (inset: Table corals at Shark Island reef). Photo credits: John Burt

well-known Martini Rock diving site). The presence of these rocky habitats is critically important in providing hard-bottom habitat necessary for coral growth, and as a result well-developed coral reef ecosystems occur across much of the northern portion of the UAE's east coast (Fig. 4.3; see Chap. 11). South of Khor Fakkan and extending to the Oman border near Kalba, the Hajar Mountains are situated slightly further inland, and the coastline is characterized by gravel and sand alluvium eroded from the mountains over many millennia. Here, the nearshore environment is heavily dominated by mobile sands and rocky hard-bottom habitats do not occur, except as occasional cemented intertidal alluvial areas. The coast in this area was historically dominated by sand beaches until modern urbanization resulted in substantial alteration through construction of harbors, breakwaters and groyne fields. At the most southerly end of the UAE's east coast, at Khor Kalba, occurs the only modern lagoon system on the east coast, where an extensive mangrove forest occurs (see Chap. 7). Archaeological evidence from shell middens shows human occupation in the area extending back to the Neolithic (Lindauer et al. 2017).

Unlike the east coast, where the sands are largely derived from erosion of the Hajar Mountains, the white coastal sands of the Arabian Gulf coast are largely carbonate sands generated from the skeletons of deceased marine organisms and swept up on shore (Clarke and Keij 1973). The 600 km UAE Gulf coastline is broken into three sedimentary provinces largely based on their degree of exposure to winds and waves. The northeastern portion extends from the northern border of Ras Al Khaimah to the Dubai/Abu Dhabi border, and is characterized by fully unprotected exposure to northerly 'shamal' winds that typically blow across the entire length of the Gulf from Iraq. As a result of the open exposure of this coast, high wave energy

Fig. 4.4 Satellite image of a large longshore sand-spit system at Umm Al Quwain, which is emblematic of the high-energy wave environments that occur on exposed sandy shorelines of the UAE's Arabian Gulf coast. Historically, such systems were more common, but many have since been heavily modified or removed through coastal dredging and reclamation. Modified from Umm Al Quwain © 2023 by Google Earthview and Cnes/Spot Image, Maxar Technologies and distributed under their Terms of Use

can occur during storms, leading to the formation of large longshore sand-spit or barrier island systems. While many of these have been removed or heavily modified by dredging in recent decades (e.g. around Ras Al Khaimah; Goudie et al. 2000), Siniyah Island, the 15 km long barrier island protecting the Umm Al Quwain lagoon remains as a prime example (Fig. 4.4; see also Chap. 8). Although the coastline north of Ras al-Khaimah is overlooked by the mountains of the Musandam peninsula, those mountains are composed primarily of carbonate rocks (limestone and dolomite), so their contribution to the coastal sands is also in the form of carbonate grains.

The central portion of the Gulf coast extends from the Dubai/Abu Dhabi border west to Jebel Dhanna. In this area wave protection is provided by nearshore pearl banks and coral reefs (Fig. 4.5), resulting in the development of sandy barrier islands that, in turn, protect lagoon systems and tidal flats in their lee (Kendall and Skipwith 1969; Evans et al. 1973). For example, the capital city of Abu Dhabi sits on a barrier island that formed in the lee of a large nearshore coral reef that existed up until the 1970s, but has since been lost following the development of Mina Zayed and Lulu Island (Murray 1970). Examples that still exist today include Saadiyat Island and Dhab'iyah, both of which occur behind coral reefs. The lagoon systems that lie behind these barrier islands are typically characterized by extreme salinity and temperatures (Murray 1970), but often contain large stands of mangrove forests as well as extensive mudflats that can be important feeding grounds for resident and migratory birds (see Chap. 8). Historically, tidal channels near the barrier islands were also occupied by coral reefs, although dredging for navigation has removed

Fig. 4.5 Coral growth occurs in discontinuous areas where lithified sandstone caprock rises above the sand that typically dominates sea-bottoms along the UAE's Arabian Gulf coast. Photo credit: John Burt

most of these habitats (Kinsman 1964). While generally considered environmentally damaging, dredging can sometimes have unintended positive impacts. For example, channel construction around Abu Dhabi city reduced lagoon salinities there to levels amenable to mangrove growth, explaining their rapid expansion in recent years, particularly in areas supported by seedling afforestation programs (Embabi 1993; Friis and Burt 2020).

The western portion of the Gulf coast extends from Jebel Dhanna to the Saudi Arabian border near Al-Sila. The most westerly shoreline in this area lies is protected by the Qatar Peninsula from the northwesterly shamal winds that blow down the Gulf, and from the most severe storms. Much of the bottom is made up of fine sands and muds with occasional rocky outcrops (Purser and Evans 1973). Towards the east, the shoreline becomes more exposed and is characterized by wide, low sloping intertidal flats that grade into sabkha environments, including the Sabkha Matti, which continues far inland—one of the world's largest sabkhas (see Chap. 2), and which is protected by a high (1–3 m) storm beach. The UAE sabkha environments have been the focus of intense research by geologists over more than 50 years and represent unique geochemical and biological systems in their own right (particularly in the nearshore areas) (Böer 2002; Böer and Saenger 2006). Unfortunately, development has reduced the 150 km length of pristine sabkha coastline that occurred in the 1960s to just 54 km by the 2010s (Lokier 2013).

While the offshore environment of the northeastern portion of the UAE's Gulf coast is largely low complexity sands and muds, the central and western portion of the Gulf coast are characterized by extensive shoals and offshore islands formed above salt domes (Riegl et al. 2012). An area of 5500 km^2 of seagrass beds dominates the shallow waters of Abu Dhabi, representing three-quarters of all

Fig. 4.6 Fringing coral reefs are common on the windward northwestern face of islands in the southern Arabian Gulf. Shown here is a photo from the coral reef at Delma Island in 2016. Photo credit: John Burt. Map inset: Delma Island, modified from ESRI World Imagery layer under their Terms of Use (Esri, NASA, NGA, USGS | Esri, HERE, Garmin, Foursquare, METI/NASA, USGS | Earthstar Geographics)

seagrass in the Gulf and 3.4% of the entire global seagrass area (Erftemeijer and Shuail 2012), supporting large populations of dugongs and green turtles (Preen 2004; Pilcher et al. 2021) (see Chap. 9). Extensive coral reefs are also common and widespread in the shallow waters of Abu Dhabi and around offshore islands (Fig. 4.6), particularly on the windward (NNW) shores, although these reefs are typically low in diversity due to the extreme environmental conditions of the southern Gulf (Riegl et al. 2012; Bejarano et al. 2022). From Ras Ghanada to the northern emirates, corals have historically been restricted to lithified sandstone outcrops in a discontinuous narrow band that occurs approximately a kilometer offshore, with the remainder of the area dominated by mobile sands and muds (Grizzle et al. 2016) (Chap. 11). These sandstone 'caprock' outcrops are formed by the cementation of sand grains by dissolved calcium carbonate during periods of low wave action, with modern rock forming in just a few years (Purkis et al. 2011).

4.3 The UAE's Arabian Gulf Coast: An Extreme Marine Environment

4.3.1 Atmospheric Influences on the Arabian Gulf

The UAE is located in a region that straddles 30°N latitude known as the subtropical high pressure zone. The subtropical high pressure zone is itself part of a larger convective circulation phenomenon called the Hadley cell (see Chap. 3). Near the equator, warm air is uplifted to the upper atmosphere where it drops most of its moisture as rain, moves towards the poles, cools and sinks back to the earth's surface at 30° as extremely dry air, before being drawn back towards the Equator along the earth's surface. This results in an environment in the Emirates that is characterized by few clouds, limited rainfall, high solar insolation and high evaporation rates; in short, creating the arid terrestrial desert biome that dominates the region (Chap. 3; Boer 1997). While this has only limited impact on the marine systems of the UAE's Sea of Oman waters, which are buffered by its greater depth and substantial mixing with the Indian Ocean (see below), these atmospheric conditions exert a major influence over the marine environment of the Arabian Gulf.

4.3.2 Sea Temperatures on the Gulf Coast

Due to its shallow depth and limited exchange through the narrow Strait of Hormuz, atmospheric conditions have dramatic impacts on Gulf waters. This is particularly true of the extensive shallow southern Gulf basin that borders Abu Dhabi. Seasonal sea temperatures are extreme (Fig. 4.7). Summer sea temperatures regularly exceed 34 °C for several months, and can exceed 35.5 °C for a week or more during extreme heat waves (Riegl et al. 2011; Burt et al. 2019), while 6 months later winter sea temperatures plummet below 20 °C for several months, reaching as low as 15 °C during winter shamals (J.Burt, unpubl. data). This seasonal variation is the largest annual temperature range occurring in marine systems globally (Sheppard et al. 1992; Coles 2003) and represents an extreme physiological challenge for the UAE's marine organisms that had evolved in more thermally stable tropical environments before colonizing the Gulf (D'Agostino et al. 2020; Smith et al. 2022). Currently the shallow, enclosed Gulf is warming at more than double the global average rate (Lachkar et al. 2021), and recurrent marine heat waves are already having substantial adverse impacts on marine organisms and ecosystems across the UAE's southern Gulf waters (see Chap. 11; Burt et al. 2019).

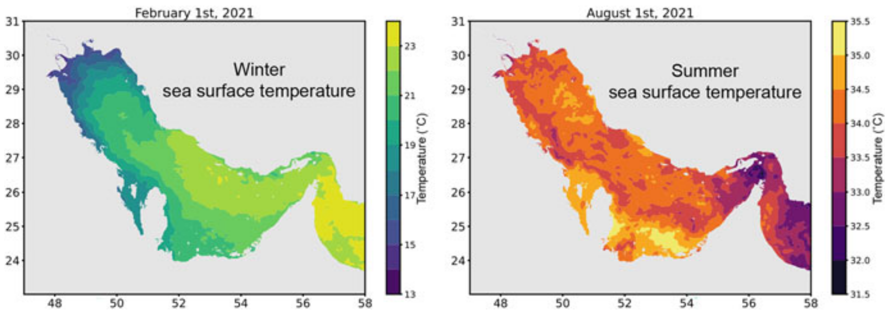


Fig. 4.7 Sea surface temperature map from February 1st, 2021 (left) and August 1st, 2021 (right) illustrating the dramatic shifts in sea temperature that occurs between winter and summer in the Arabian Gulf, while those in the Sea of Oman are less extreme. Data source: GHRSST project (JPL MUR MEaSUREs Project 2015), shared per the PO.DAAC open data policy

4.3.3 Gulf Sea Temperatures and Dissolved Oxygen

High summer water temperatures have been implicated in affecting the oxygen dynamics of the UAE's Gulf waters. Virtually all marine organisms are 'cold-blooded' ectotherms whose metabolism is directly tied to water temperature. As temperature climbs, so too does metabolic demand for oxygen by marine organisms. This is generally not an issue during the daytime as photosynthesis by microscopic phytoplankton, algae and corals can compensate for this demand by producing oxygen, but when photosynthesis ceases after sunset the metabolic demand for oxygen can exceed availability, leading to the occurrence of low oxygen conditions (hypoxia) and in rare cases near absence of oxygen (anoxia). Recent research has shown that near-shore coral reefs in Abu Dhabi regularly experience hypoxia for several hours in the pre-dawn period during summer, occasionally dipping to anoxic levels (Fig. 4.8) (de Verneil et al. 2021). Such conditions likely represent a dire—and previously unrecognized—stressor for marine organisms along the UAE's southern Gulf coast, particularly for sedentary or non-mobile organisms such as urchins and corals that are unable to relocate out of the affected area. Alarmingly, hypoxia is also increasing at the Gulf-wide scale as a result of climate change. The near-bottom hypoxic zone in the central Gulf has increased in area from 20,000 km^2 in the 1980s to over 30,000 km^2 in the 2000s (Lachkar et al. 2022), representing a major threat to the future of fisheries and marine ecosystems as it grows towards the UAE's Gulf coast.

4.3.4 Salinity-Driven Circulation in the Gulf

Evaporation in the Gulf far exceeds precipitation and river run-off. On a yearly average, the net evaporation amounts to 1105 million cubic meters per day (± 270) (Johns et al. 2003). The net evaporation has a strong seasonal cycle with an amplitude of 50% the yearly average. The timing of the cycle has a great variability

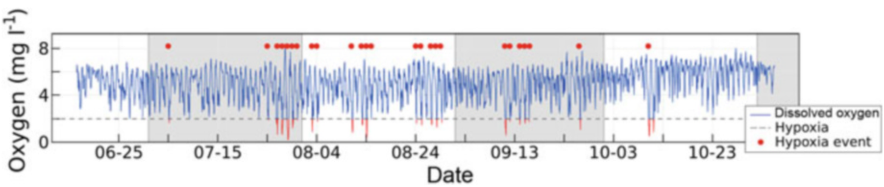


Fig. 4.8 Dissolved oxygen levels (blue line) recorded on Dhab'iya reef, Abu Dhabi, between June and October 2019 (white/gray shading denotes different months), where daily fluctuations between daytime (higher) and night (lower) are due to the balance of photosynthesis and respiration by marine organisms. The dashed line indicates the low-oxygen (hypoxia) threshold of 2 mg/L, under which most marine organisms would suffer hypoxic stress (red lines, bottom). Red dots (top) indicate when a hypoxic event has occurred; 26 events were observed between July and October 2019, many lasting several hours. Modified from Fig. 4.2 in de Verneil et al. 2021 (CC-BY-4.0)

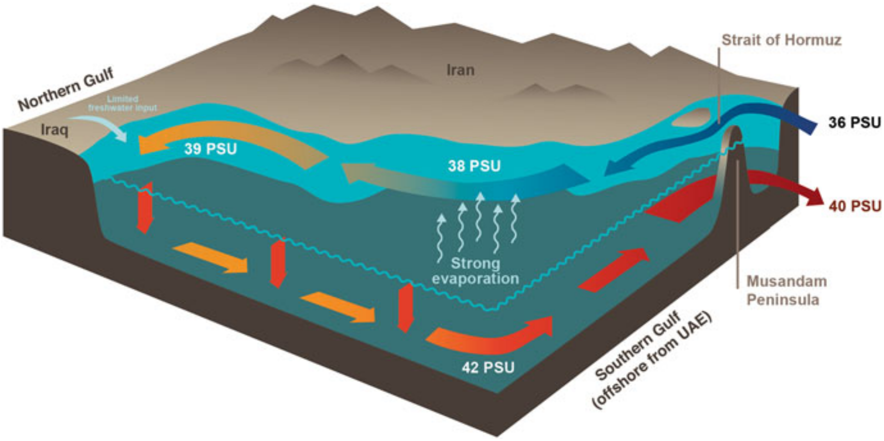


Fig. 4.9 General circulation pattern of Gulf waters, illustrating the importance of evaporation in producing salinity-driven currents. Incoming surface waters are oceanic, and become increasingly saline through evaporation as they move north along the Iranian coast. The denser, saline water then sinks and flows across the bottom (mixing with the incoming water to somewhat reduce bottom-water salinity), exiting into the Sea of Oman. This general circulation passes offshore of the UAE coast, where high salinity (≥42 PSU) occurs in the shallow evaporative basin of the southern Gulf. Modified from Fig. 2.5 in Sheppard et al. 1992 and reprinted with permission of Elsevier

between years, but generally the minimum evaporation occurs in March, and the maximum in November, when Gulf waters still warm from the summer heat are exposed to cool, strong winds (Paparella et al. 2022). Evaporation of surface waters increases their salinity and therefore their density, and they sink downward in the water column. This drives a vigorous overturning circulation in the Gulf, which is characterized by a reverse estuarine circulation through the Strait of Hormuz. Surface water enters the Gulf from the Indian Ocean at normal oceanic salinity (36 PSU) and forms the north westward-flowing Iranian Coastal Current (ICC) which travels against the prevailing winds up to Kuwait. A return, wind-driven current flows along the eastern Saudi Arabian and Qatari coast, then moves towards the Strait of Hormuz, leaving the UAE shallows mostly unaffected. The Gulf is thus dominated by a basin-wide cyclonic (counter-clockwise) circulation. Dense, salty water is formed by evaporation in the shallowest regions of the Gulf. It then sinks into the deeper part of the Gulf, where it follows a broad, gently sloping valley until it flows out into the Sea of Oman (Fig. 4.9). The Kuwait branch of this circulation has been directly observed (Swift and Bower 2003), while the branch close to the UAE shallows has only been studied by means of ocean circulation models (Al-Shehhi et al. 2021).

4.3.5 Seasonal Eddies on the UAE's Gulf Coast

In addition to Gulf-wide processes driven by salinity, smaller meso-scale (ca. 50–100 km) vortices (eddies) can develop in summer as a result of summer shamal winds. During the late spring and the summer the deepest part of the Gulf develops a thermocline, where warm surface water sits on top of cooler, deep water. This two-layer stratification is favorable to eddy-formation. Thus, every year from late spring until the end of the summer, a small number of meso-scale cyclonic (counter-clockwise) vortices appear in the central Gulf offshore from the UAE (typically four), characterized by current speeds of about 0.5 m/s (Thoppil and Hogan 2010b). These highly unsteady vortices vigorously mix the surface waters of the central Gulf, and have been suggested to be important for the long-distance transport of coral larvae from the diverse and healthy reefs of Iran to various parts of the UAE's Gulf coast,where reefs have become increasingly degraded in recent years and require supply of larvae from external sources to aid their recovery (Burt and Bauman 2019; Cavalcante et al. 2016, 2020; de Verneil et al. 2021).

4.3.6 Spatial and Seasonal Variation in Gulf Salinity

The physical and biological oceanography of UAE waters is poorly known. All of the oceanographic cruises conducted in the last 60 years have focused on the deepest part of the Arabian Gulf, and only two have ventured close to the UAE coastline (Al-Yamani and Naqvi 2019). However, the presence of a southerly gradient of increasing salinity towards the UAE coast is presumed and is supported by satellite-based measurements (Fig. 4.10), although these remain prone to error in shallow

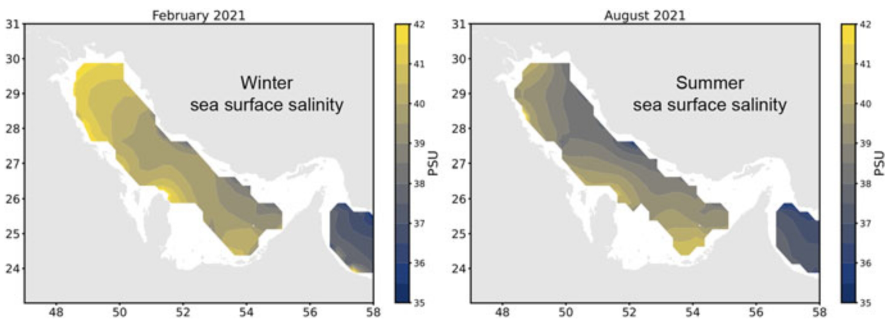


Fig. 4.10 Monthly averaged sea surface salinity in February (left) and August (right), 2021. The uncertainty far from the coastline is <1 psu but it may grow in excess of 5 psu at the land-sea edge (JPL CAP 2020). Areas with no data available represent areas where cell sizes are insufficient for modeling salinity. Paradoxically, surface salinity is higher in early winter (February), as a result of the peak in evaporation in late autumn. Data source: SMAP satellite (JPL CAP SMAP Sea Surface Salinity Products Ver 5.0 2020), shared per the PO.DAAC open data policy

waters and close to the coastline. *In situ* measurements show that water masses close to the UAE coastline may reach 44 PSU (compared with normal oceanic salinity of 36 PSU), while coastal lagoons and embayments regularly exceed 50 PSU, characterizing these areas as hyper-saline (Evans et al. 1973).

Salinity can represent a major stressor for marine fauna, and the hyper-salinity of southern Gulf seawater has been associated with dwarfism in fish and various invertebrate animals as a result of the metabolic costs of coping with osmotic stress (Price 1982; D'Agostino et al. 2021). There have been suggestions that growing desalination activities, particularly in combination with climate change, may exacerbate these salinity issues at the Gulf wide-scale (Le Quesne et al. 2021). However, recent modeling efforts show that natural evaporation is a far more important contributor to salinity at the basin-wide scale (Paparella et al. 2022), although localized impacts immediately adjacent to desalination plant outfalls in the Emirates are likely to be significant at scales of a few hundred meters or less (Lattemann and Höpner 2008).

4.4 The UAE's East Coast: A Sub-Tropical Indian Ocean Margin

The UAE's east coast is a much more ordinary and more benign marine environment than the Arabian Gulf. It constitutes a small segment of the much larger Indian Ocean margin and is influenced by currents driven by the Indian Ocean Monsoon cycle. The winter Northeast Monsoon pushes waters southward along the coast, and induces subsidence (sinking of the surface waters) along the continental shelf. The summer Southwest Monsoon reverses the direction of the coastal current and induces upwelling (uplift of deep waters) along the coast (Schott et al. 2002). Summer upwelling of deep, cold waters is particularly strong all along the southern Oman coast, along the Arabian Sea, causing a pseudo-high-latitude effect on marine systems along that coast, with conditions cooler than would be expected for its location (Sheppard et al. 1992). This results, among other things, in the anomalous association of dense kelp beds mixed with coral communities (Claereboudt 2019). The coastal Oman current does not penetrate as far north into the Sea of Oman as the UAE coastal waters, but it breaks into several highly variable meso-scale eddies, which mix the saline waters exiting from the Strait of Hormuz with the Indian Ocean surface waters (Pous et al. 2004).

While the Sea of Oman coast of the Emirates is exposed to extreme air temperatures and aridity, the presence of deep, well-mixed offshore waters adjacent to the coast results in environmental conditions that are far more congenial to most marine life than occur on its Arabian Gulf coast. Summer upwelling, and winter subsidence, although mostly occurring in southern Oman, are nevertheless capable of mitigating the amplitude of the seasonal sea surface temperatures fluctuations along the UAE coast of the Sea of Oman, albeit to a lesser extent than occurs in southern Oman. In

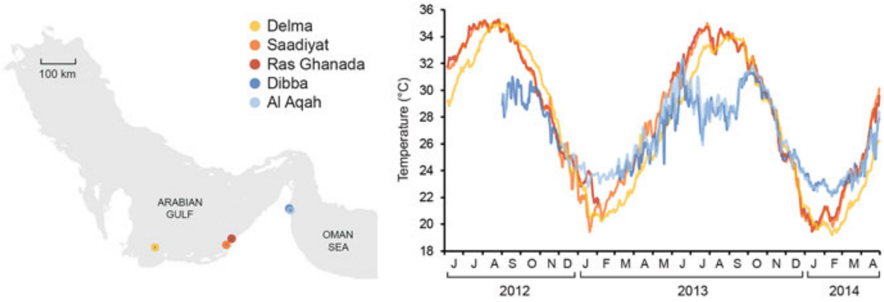


Fig. 4.11 Sea temperature profile at three sites on the UAE's Arabian Gulf coast and two on the Sea of Oman coast from 2012 to 2014. Temperature extremes (both warm and cool) and variability are higher in the Arabian Gulf due to its shallow depth and restricted circulation, while temperatures in the Sea of Oman are more moderate as a result of mixing with deeper offshore water, particularly during the summer monsoon. Modified from Fig. 4.1 in Howells et al. (2020), reprinted with permission

general, sea temperatures are approximately 3–5 °C cooler in the summer (ca. 32 °C), and similarly warmer in the winter (ca. 23 °C), on the UAE's east coast, resulting in far less extreme annual ranges in sea temperatures that are observed on the Arabian Gulf coast (Fig. 4.11) (Reynolds 1993). Similarly, tidally-driven cooling can occur on very short timescales on the east coast, with temperatures dropping by up to 6 °C in 3 h as tides push deep, cold water up onto coastal shoals, with important implications for heat-sensitive ecosystems such as coral reefs (Coles 1997).

4.5 Winds in a Regional Context

One of the principal localized wind systems of importance to the Emirates is the 'shamal' winds (Arabic for north), north-northwesterly winds which funnel down the length of the Gulf. These air masses form as high pressure systems over the Anatolian area of the eastern Mediterranean and flood over Iraq and Kuwait at ground level before crossing the Arabian Gulf as they flow towards a low pressure system developed over the Iranian plateau (Perrone 1979).

Regional physiography plays an important role in structuring these winds, with the Zagros mountain range in Iran serving as an important barrier, funneling and concentrating the strength of the shamal system over the Arabian Gulf on the western flank of the mountains. Wintertime shamal events are occasional, mainly occurring from late January to March. They last up to 5 days and may exceed gale strength, with wind speeds of over 50 km/h, and gusts of over 100 km/h (Thoppil and Hogan 2010a). The weaker summer shamal winds, although highly variable from year to year, are recurrent from May until August, with a recognizable seasonal onset and termination which gives them monsoon-like characteristics (Rao et al. 2003, Yu et al. 2016).

4.5.1 Winds and Waves on the Gulf Coast

Due to the long, unbroken length of the Arabian Gulf, shamal wind events can generate large waves and storm surge across much of the UAE's Arabian Gulf coast, although the Qatar peninsula somewhat shelters areas furthest west and the presence of the Zagros mountains and the oblique curve of the coastline relative to the wind direction also reduces their influence towards Ras Al Khaimah (Alsharhan and Kendall 2003; Vieira et al. 2020). In more exposed areas, such as around the cities of Abu Dhabi or Dubai, sustained (3–5 day) shamal events often lead to waves in excess of 2.5 m, reaching over 6 m in severe 1-in-100 year storms (Mocke and Smit 2008). When storms coincide with high tides, they can induce a storm surge that floods low-lying areas along much of the UAE's Gulf coast, including nearshore urban areas and roadways (El-Sabh and Murty 1989; Mocke and Smit 2008; Smit et al. 2008; Vieira et al. 2020; Aboobacker et al. 2021).

Storm-generated wave action is also sufficient to suspend sea-bottom sediments in near-shore areas along the UAE's Gulf coast, with suspended sediments resulting in turbid, milky-looking water that can last for several days after the cessation of winds (Fig. 4.12) (Van Parys 2006). Such suspended sediments represent a severe stressor for many marine organisms (Riegl and Branch 1995), and near-shore coral communities along the UAE Gulf coast reflect this with an unusually high abundance of sediment-tolerant species (Riegl 1999; Burt et al. 2010).

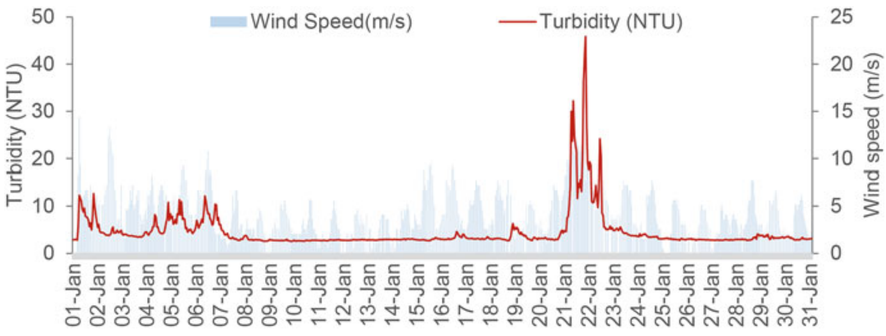


Fig. 4.12 Turbidity (red line) along the southern Gulf coast of the UAE often increases in response to 'shamal' wind events (winds in blue), when wind speed persists above 10 m/s for sustained periods; below this, 'breeze' conditions are not sufficient to cause waves to turn over the sea-bottom sediments. At the left is a period of moderate but recurrent shamal winds (01–06 January), with a sustained shamal event from 21–23 January. Data from January 2022 at Dhab'iya reef, Abu Dhabi. (J. Burt, unpubl. data)

4.5.2 The Importance of Shamal Winds for Cooling the Gulf

Shamal winds are extremely important in controlling water temperatures in the southern Gulf during the summer. Much like blowing on a coffee cools it through evaporative heat loss, summer winds can pull tremendous amounts of thermal energy out of the Gulf. A single shamal event can cool summer sea temperatures by 2–3 °C through evaporation, with these cooler temperatures persisting for several days after wind cessation (Fig. 4.13a; Paparella et al. 2019). This has important implications in the southern Arabian Gulf as most marine organisms there live very close to their upper thermal limits each summer, and any extended period of calm can lead to temperatures that push marine fauna beyond their physiological thresholds. As an example, in the summer of 2017 calm conditions persisted for over 5 weeks and allowed sea temperatures to reach as high as 37.7 °C, causing widespread coral bleaching and the loss of over two-thirds of corals across the UAE's Gulf coast reefs (Fig. 4.13b,c; Burt et al. 2019). Whether continuing climate change will produce more or fewer summer shamal wind events remains uncertain (Paparella et al. 2019), but if summer shamals become less common it is nearly certain that this will have substantial negative impacts on already stressed marine systems on the UAE's Gulf coast.

Winds can also play an important role on the UAE's Sea of Oman coast, but the mechanism and effect differs. Even on the east coast, shamal winds are a predominant feature of the wind climate for much of the year, but with the presence of the Hajar mountain range and the land serving as barrier to wind-driven wave development, these northerly winds have a limited impact on the marine environment in the Sea of Oman. Instead, the marine system is much more strongly influenced by the occurrence of the summer monsoon and associated cold-water upwelling, when

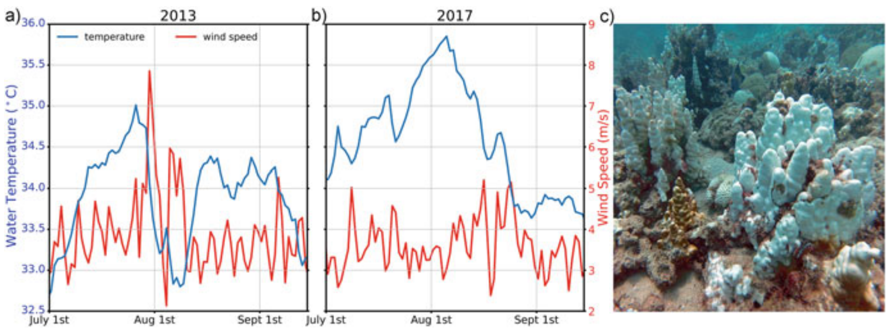


Fig. 4.13 The influence of summer winds on seawater temperatures and the impacts of calm conditions. (**a**) Sea temperatures in summer 2013 show dramatic declines after the onset of a shamal wind event, while (**b**) extended weak breeze conditions in summer 2017 resulted in temperatures rising to extreme levels due to a lack of evaporative cooling. In consequence, (**c**) coral bleaching was widespread across the Gulf coast of the UAE, leading to loss of over two-thirds of corals by October 2017. Graphs modified from Fig. 4.4 in Paparella et al. (2019) and reused under Creative Commons license (CC-BY-4.0)

winds shift from being predominantly from the northwest and instead become dominated by east-southeasterly winds that travel up the coast of Oman and across the eastern emirates of the UAE from late June through to mid-October.

4.6 Tides in the Emirates

Variations of sea-level height on time scales ranging from hours to weeks are commonly called ‘tides’. All tides have a wave-like nature, and are strongly affected by depth and coastal features such as channels, islands, and sills. The name ‘tides’, however, lumps together different phenomena, stemming from different causes: seiches, meteotsunamis and astronomical tides.

In enclosed or semi-enclosed basins, the action of winds and atmospheric pressure differences may induce large-scale oscillations of the water masses, producing waves with wavelengths comparable with the size of the basin. These are called ‘seiches’, the best known ones being those occurring in the Adriatic sea, because they cause the high waters in Venice. Seiches have been observed in the Gulf (Afshar-Kaveh et al. 2020), but have not been extensively studied.

Meteotsunamis are also due to resonances between atmospheric features (typically a fast-moving front) and long-wavelength sea waves. But, just like an ordinary tsunami, they take the form of a fast-moving wave, which, in proximity to a coastline, turns into a destructive bore. The latest of such events occurred in the Gulf on 19 March 2017, resulting in a bore up to 3 m tall that flooded about 100 km of coastline in the southeastern Bushehr province of Iran (Kazeminezhad et al. 2021). The very shallow waters of the UAE’s Gulf coast make the occurrence of severe meteotsunamis unlikely, because a large portion of the energy would be dissipated through friction with the sea-bottom offshore from the coast. The UAE’s east coast is also unlikely to experience destructive waves triggered by atmospheric forcing, but for the opposite reason, because the great depth makes a resonance between the atmospheric forcing and the ocean long waves nearly impossible to attain.

Proper tides (AKA astronomical tides) are generated by the perturbation of the Earth’s gravitational field caused by the Moon and the Sun. These perturbations may be expressed as the sum of a small number of periodic constituents, each characterized by a well-defined period. The dominant tidal constituent is due to the Moon, and it is called ‘M2’, which produces a rise and fall of the waters approximately twice a day. M2 is thus called a ‘semidiurnal’ tide. Many other constituents, each with its own well-defined period, contribute to the total astronomical tide. The relative importance of each component is determined by the latitude and by the shape of the bathymetry and of the coastline. The Gulf is one of the few places in the world where a diurnal constituent (that is, a constituents having a period close to 1 day) attains a magnitude comparable with that of M2. The two components contributing the most to the total astronomical tide in the Gulf are the Principal Lunar Semidiurnal M2, with a period of 12.421 h (Fig. 4.14), and the Lunar Diurnal K1 with a period of

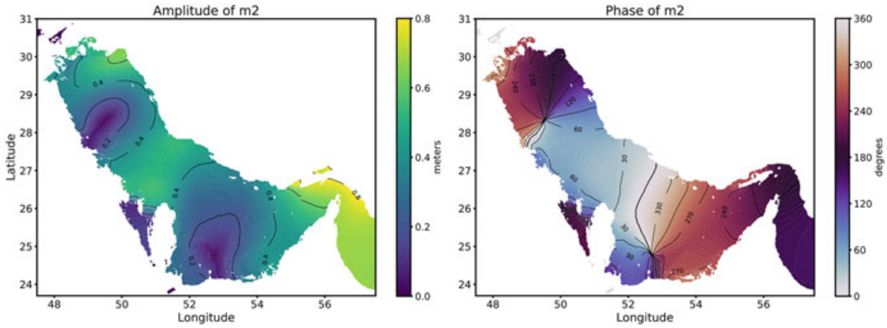


Fig. 4.14 Elevation amplitude (left: height above average sea level) and co-tidal lines (right) of the M2 semidiurnal tidal component in the Gulf. Data from the 1/60 degree Arabian Sea TPXO barotropic tide model (Egbert and Erofeeva 2002), reused under the terms of use for research

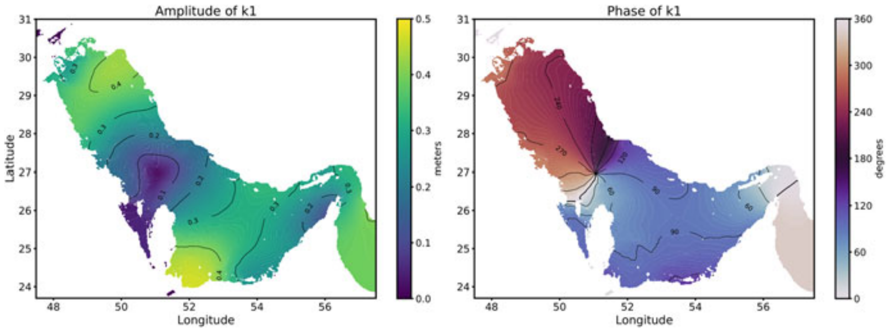


Fig. 4.15 As in Fig. 4.14, but for the K1 diurnal tidal component. The interaction of the semidiurnal and diurnal tidal forces illustrated in Figs. 4.14 and 4.15 is the primary determinant of tidal patterns in the Arabian Gulf. Data from the 1/60 degree Arabian Sea TPXO barotropic tide model (Egbert and Erofeeva 2002), reused under the terms of use for research

23.934 h (Fig. 4.15). The Principal Solar Semidiurnal S1 (12 h) and Lunar Diurnal O1 (25.819 h) also give small contributions to Gulf tides.

When all the components reach their maximum simultaneously, the height of the astronomical tide on the east coast of the UAE slightly exceeds 3 m. In addition (and somewhat singularly), tides are synchronized along the whole of the east coast, including that of northern Oman (i.e. when it is high tide in Dibba, it is also high tide in Fujairah and in Muscat).

In the Gulf (as along most coastlines), the tidal cycle does not rise and fall simultaneously at all locations. When the diurnal K1 is at its maximum, say, in Bahrain, it will be already dropping in Qatar, and will be halfway down along the UAE coastline, and at its lowest near the estuary of the Mond river (on the north-western Iranian coast near Bushehr), while rising and halfway to its maximum in Kuwait. The points where a tidal constituent has the same phase are called co-tidal lines. The co-tidal lines of K1 are shown in Fig. 4.15b, (right panel). They radiate from a single central hub, which is called an amphidromic point, like rays of a wheel. As time goes on, the K1 tidal wave rotates around this point in a counter-clockwise direction, around the Gulf. The height of the tidal wave is zero at the amphidromic point, and increases moving away from it. The semidiurnal M2 tidal constituent in the Gulf has two amphidromic points: one in the western part of the UAE shallows, and the other in the northern part of the basin, off the Saudi coast (Fig. 4.14b). The interaction of the various tidal constituents (e.g. K1 and M2), each with its own different period and co-tidal lines, produces surprisingly complicated tidal patterns that change from place to place throughout the Gulf.

The largest height (approximately 4 m) of the total astronomical tide is attained in the northernmost part of the Gulf, and in the Strait of Hormuz. In the western part of the UAE shallows along the Abu Dhabi coast, the tidal height is lowest, generally less than 2 m. This is still sufficient to generate very strong currents where the coastal features choke the free flow of the tide. For example, in the channel between the mainland and Sir Bani Yas Island, tidal currents in excess of two knots are the norm.

Even though tides are periodic in time, a water parcel starting at any given position would hardly return to that same position at the end of the tidal cycle, even neglecting the effect of all other currents. This displacement of water parcels, over a large number of tidal cycles, is known as residual tidal current. This is not very high in the central part of the Gulf, but it can reach 5 cm/s in the UAE's Gulf coast shallows, where the residual tidal current may induce a net transport from west to east. Given that the eddying, wind-driven currents that dominate the central Gulf in the spring and summer are unable to reach the shallows, tides and evaporation-driven flows are thus the main mechanism that transport the water in and out of the shallows.

4.7 Conclusion

The marine environment of the Emirates is among the most unique and interesting on earth, principally due to the unusual climatic conditions, geomorphology and hydrology that characterize the Arabian Gulf, and make it one of the most extreme and variable marine environments known. Those conditions are emphasized by comparison with the UAE's east coast, along the Sea of Oman, which is largely characterized by normal oceanic conditions for the northwest Indian Ocean margin. Those differences explain the differences in composition, diversity and ecology of the marine communities that occur on the two coasts of the Emirates, topics that will be explored in detail in subsequent chapters.

4.8 Recommended Readings

For further information on the marine environment of the UAE written towards a broad audience we recommend Sheppard et al. (1992), which covers the Arabian region broadly, and Riegl et al. (2012), which specifically focuses on the Arabian Gulf and includes a variety of data from the Emirates and is available in both print and online formats.

References

Aboobacker VM, Shanas PR, Al-Ansari EMAS, Sanil Kumar V, Vethamony P (2021) The maxima in northerly wind speeds and wave heights over the Arabian Sea, the Arabian/Persian Gulf and the Red Sea derived from 40 years of ERA5 data. Clim Dyn 56:1037–1052. https://doi.org/10.1007/s00382-020-05518-6

Afshar-Kaveh N, Nazarali M, Pattiaratchi C (2020) Relationship between the Persian Gulf Sea-level fluctuations and meteorological forcing. J Mar Sci Eng 8:285. https://doi.org/10.3390/jmse8040285

Alsharhan AS, Kendall CGSC (2003) Holocene coastal carbonates and evaporites of the southern Arabian Gulf and their ancient analogues. Ear-Sci Rev 61:191–243. https://doi.org/10.1016/S0012-8252(02)00110-1

Al-Shehhi MR, Song H, Scott J, Marshall J (2021) Water mass transformation and overturning circulation in the Arabian gulf. J Phys Ocean 51:3513–3527. https://doi.org/10.1175/jpo-d-20-0249.1

Al-Yamani F, Naqvi SWA (2019) Chemical oceanography of the Arabian Gulf. Deep Sea Res Part II Top Stud Oceanogr 161:72–80. https://doi.org/10.1016/j.dsr2.2018.10.003

Bejarano I, Orenes-Salazar V, Bento R, García-Charton JA, Mateos-Molina D (2022) Coral reefs at sir Bu Nair Island: an offshore refuge of *Acropora* in the southern Arabian Gulf. Mar Pollut Bull 178:113570. https://doi.org/10.1016/j.marpolbul.2022.113570

Boer B (1997) An introduction to the climate of The United Arab Emirates. J Arid Environ 35:3–16. https://doi.org/10.1006/jare.1996.0162

Böer B (2002) The coastal and sabkha flora of The United Arab Emirates. In: Barth H, Boer B (eds) Sabkha ecosystems Vol 1: the Arabian peninsula and adjacent countries. Kluwer Academic Publishers, Dordrecht, pp 303–309

Böer B, Saenger P (2006) The biogeography of the coastal vegetation of the Abu Dhabi gulf coast. In: Khan MA, Böer B, Kust GS, Barth H-J (eds) Sabkha ecosystems: volume II: West and Central Asia. Springer, Netherlands, Dordrecht, pp 31–36. https://doi.org/10.1007/978-1-4020-5072-5_3

Burt JA, Bauman AG (2019) Suppressed coral settlement following mass bleaching in the southern Persian/Arabian Gulf. Aquat Ecosyst Health Manag 23:166–174. https://doi.org/10.1080/14634988.2019.1676024

Burt J, Feary D, Bauman A, Usseglio P, Sale PF (2010) The influence of wave exposure on coral community development on man-made breakwater reefs, with a comparison to a natural reef. Bull Mar Sci 86:839–859

Burt J, Paparella F, Al-Mansoori N, Al-Mansoori A, Al-Jailani H (2019) Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. Coral Reefs 38:567–589. https://doi.org/10.1007/s00338-019-01767-y

Claereboudt MR (2019) Chapter 2 - Oman. In: Sheppard C (ed) World Seas: an Environmental Evaluation (Second Edition). Academic Press, pp25–47 https://doi.org/10.1016/B978-0-08-100853-9.00002-6

Cavalcante GH, Feary DA, Burt JA (2016) The influence of extreme winds on coastal oceanography and its implications for coral population connectivity in the southern Arabian Gulf. Mar Pollut Bull 105:489–497. https://doi.org/10.1016/j.marpolbul.2015.10.031

Cavalcante G, Vieira F, Mortensen J, Ben-Hamadou R, Range P, Goergen E, Campos E, Riegl B (2020) Biophysical model of coral population connectivity in the Arabian/Persian Gulf. Adv Mar Biol 87(1):193–221. https://doi.org/10.1016/bs.amb.2020.07.001

Clarke MWH, Keij AJ (1973) Organisms as producers of carbonate sediment and indicators of environment in the southern Persian Gulf. In: Purser BH (ed) The Persian Gulf: Holocene carbonate sedimentation and diagenesis in a shallow epicontinental sea. Springer, Berlin, pp 33–56

Coles S (1997) Reef coral assemblages occurring in a highly fluctuating temperature environment at Fahal Island, Gulf of Oman (Indian Ocean). Coral Reefs 16:269–272

Coles S (2003) Coral species diversity and environmental factors in the Arabian gulf and the Gulf of Oman: a comparison to the Indo-Pacific region. Atoll Res Bull 507:1–19

D'Agostino D, Burt JA, Reader T, Vaughan GO, Chapman BB, Santinelli V, Cavalcante GH, Feary DA (2020) The influence of thermal extremes on coral reef fish behaviour in the Arabian/Persian Gulf. Coral Reefs 39:733–744. https://doi.org/10.1007/s00338-019-01847-z

D'Agostino D, Burt JA, Santinelli V, Vaughan GO, Fowler AM, Reader T, Taylor BM, Hoey AS, Cavalcante GH, Bauman AG, Feary DA (2021) Growth impacts in a changing ocean: insights from two coral reef fishes in an extreme environment. Coral Reefs 40:433–446. https://doi.org/10.1007/s00338-021-02061-6

de Verneil A, Burt JA, Mitchell M, Paparella F (2021) Summer oxygen dynamics on a southern Arabian Gulf coral reef. F Mar Sci 8:1676. https://doi.org/10.3389/fmars.2021.781428

Egbert GD, Erofeeva SY (2002) Efficient inverse modeling of barotropic ocean tides. J Atmos Ocean Tech 19:183–204. https://doi.org/10.1175/1520-0426(2002)019<0183:EIMOBO>2.0.CO;2

El-Sabh MI, Murty TS (1989) Storm surges in the Arabian Gulf. Nat Haz 1:371–385. https://doi.org/10.1007/BF00134834

Embabi NS (1993) Environmental aspects of geographical distribution of mangrove in the United Arab Emirates. In: Lieth H, Al Masoom AA (eds) Towards the rational use of high salinity tolerant plants: Vol 1 deliberations about high salinity tolerant plants and ecosystems. Springer, Netherlands, Dordrecht, pp 45–58. https://doi.org/10.1007/978-94-011-1858-3_5

Erftemeijer PLA, Shuail DA (2012) Seagrass habitats in the Arabian Gulf: distribution, tolerance thresholds and threats. Aquat Ecosyst Health Manag 15:73–83. https://doi.org/10.1080/14634988.2012.668479

Evans G, Murray JW, Biggs HEJ, Bate R, Bush PR (1973) The oceanography, ecology, sedimentology and geomorphology of parts of the Trucial coast barrier Island complex, Persian Gulf. In: Purser B (ed) The Persian Gulf. Springer, Berlin, pp 233–277

Friis G, Burt JA (2020) Evolution of mangrove research in an extreme environment: historical trends and future opportunities in Arabia. Ocean Coast Manag 195:105288. https://doi.org/10.1016/j.ocecoaman.2020.105288

GEBCO Compilation Group (2021) GEBCO 2021 Grid. https://doi.org/10.5285/c6612cbe-50b3-0cff-e053-6c86abc09f8f

Goudie AS, Parker AG, Al-Farraj A (2000) Coastal change in Ras Al Khaimah (United Arab Emirates): a cartographic analysis. Geogr J 166:14–25. https://doi.org/10.1111/j.1475-4959.2000.tb00003.x

Grizzle RE, Ward KM, AlShihi RMS, Burt JA (2016) Current status of coral reefs in The United Arab Emirates: distribution, extent, and community structure with implications for management. Mar Pollut Bull 105:515–523. https://doi.org/10.1016/j.marpolbul.2015.10.005

Howells EJ, Bauman AG, Vaughan GO, Hume BCC, Voolstra CR, Burt JA (2020) Corals in the hottest reefs in the world exhibit symbiont fidelity not flexibility. Mol Ecol 29:899–911. https://doi.org/10.1111/mec.15372

Johns WE, Yao F, Olson DB, Josey SA, Grist JP, Smeed DA (2003) Observations of seasonal exchange through the straits of Hormuz and the inferred heat and freshwater budgets of the Persian Gulf. J Geophys Res 108:3391. https://doi.org/10.1029/2003jc001881

JPL CAP SMAP Sea Surface Salinity Products Ver 5.0 (2020) PO.DAAC, CA, USA. Dataset accessed 2022-06-07 at https://doi.org/10.5067/SMP50-3TMCS

JPL MUR MEaSUREs Project (2015). GHRSST level 4 MUR global foundation Sea surface temperature analysis (v4.1). Ver 4.1 PO.DAAC, CA, USA. Dataset accessed 2022-06-06 at https://doi.org/10.5067/GHGMR-4FJ04

Kazeminezhad MH, Vilibić I, Denamiel C, Ghafarian P, Negah S (2021) Weather radar and ancillary observations of the convective system causing the northern Persian Gulf meteotsunami on 19 March 2017. Nat Haz 106:1747–1769. https://doi.org/10.1007/s11069-020-04208-0

Kendall C, Skipwith P (1969) Geomorphology of a recent shallow-water carbonate province: Khor Al Bazam, Trucial Coast, Southwest Persian Gulf. GSA Bull 80:865–892. https://doi.org/10.1130/0016-7606(1969)80[865:Goarsc]2.0.Co;2

Kennett DJ, Kennett JP (2006) Early state formation in southern Mesopotamia: sea levels, shorelines, and climate change. J Island Coast Archaeol 1:67–99. https://doi.org/10.1080/15564890600586283

Kinsman DJJ (1964) The recent carbonate sediments near Halat El Bahrani, Trucial Coast, Persian Gulf. In: van Straaten LMJU (ed) Developments in sedimentology. Elsevier, Amsterdam, pp 185–192. https://doi.org/10.1016/S0070-4571(08)70485-0

Lachkar Z, Mehari M, Al Azhar M, Lévy M, Smith S (2021) Fast local warming is the main driver of recent deoxygenation in the northern Arabian Sea. Biogeosciences 18:5831–5849. https://doi.org/10.5194/bg-18-5831-2021

Lachkar Z, Mehari M, Levy M, Paparella F, Burt J (2022) Recent expansion and intensification of hypoxia in the Arabian Gulf and its drivers. Front Mar Sci 9:891378. https://doi.org/10.3389/fmars.2022.891378

Lambeck K (1996) Shoreline reconstructions for the Persian Gulf since the last glacial maximum. EPSL 142:43–57. https://doi.org/10.1016/0012-821X(96)00069-6

Lattemann S, Höpner T (2008) Impacts of seawater desalination plants on the marine environment of the Gulf. In: Abuzinada A, Barth H-J, Krupp F, Böer B, Abdessalaam T (eds) Protecting the Gulf's marine ecosystems from pollution. Birkhäuser, Basel, pp 191–205. https://doi.org/10.1007/978-3-7643-7947-6_10

Le Quesne WJF, Fernand L, Ali TS, Andres O, Antonpoulou M, Burt JA, Dougherty WW, Edson PJ, El Kharraz J, Glavan J, Mamiit RJ, Reid KD, Sajwani A, Sheahan D (2021) Is the development of desalination compatible with sustainable development of the Arabian Gulf? Mar Pollut Bull 173:112940. https://doi.org/10.1016/j.marpolbul.2021.112940

Lindauer S, Santos GM, Steinhof A, Yousif E, Phillips C, Jasim SA, Uerpmann H-P, Hinderer M (2017) The local marine reservoir effect at Kalba (UAE) between the Neolithic and bronze age: an indicator of sea level and climate changes. Quat Geochronol 42:105–116. https://doi.org/10.1016/j.quageo.2017.09.003

Lokier SW (2013) Coastal sabkha preservation in the Arabian Gulf. Geoheritage 5:11–22. https://doi.org/10.1007/s12371-012-0069-x

Mocke G, Smit F (2008) Coastal processes understanding for safeguarding the dynamic Dubai coastal zone solutions to coastal disasters. American Society of Civil Engineers, Reston, VA, pp 643–654. https://doi.org/10.1061/40968(312)58

Murray JW (1970) The foraminifera of the hypersaline Abu Dhabi lagoon, Persian Gulf. Lethaia 3:51–68. https://doi.org/10.1111/j.1502-3931.1970.tb01263.x

Paparella F, Xu C, Vaughan GO, Burt JA (2019) Coral bleaching in the Persian/Arabian Gulf is modulated by summer winds. Front Mar Sci 6:1–15. https://doi.org/10.3389/fmars.2019.00205

Paparella F, D'Agostino D, Burt J (2022) Long–term, basin–scale salinity impacts from desalination in the Arabian/Persian Gulf. Sci Rep 12(1):20549. https://doi.org/10.1038/s41598-022-25167-5

Perrone TJ (1979) Winter shamal in the Persian Gulf. Naval Environmental Prediction Research Facility, Monterey, CA
Pilcher NJ, Antonopoulou MA, Rodriguez-Zarate CJ, Mateos-Molina D, Das HS, Bugla I, Al Ghais SM (2021) Movements of green turtles from foraging areas of The United Arab Emirates: regional habitat connectivity and use of marine protected areas. Mar Biol 168:10. https://doi.org/10.1007/s00227-020-03815-6
Pous SP, Carton X, Lazure P (2004) Hydrology and circulation in the strait of Hormuz and the Gulf of Oman – results from the GOGP99 experiment: 2. Gulf of Oman. J Geophys Res 109:C12038. https://doi.org/10.1029/2003jc002146
Preen A (2004) Distribution, abundance and conservation status of dugongs and dolphins in the southern and western Arabian Gulf. Biol Conserv 118:205–218. https://doi.org/10.1016/j.biocon.2003.08.014
Price ARG (1982) Western Arabian Gulf echinoderms in high salinity waters and the occurrence of dwarfism. J Nat Hist 16:519–527
Purkis S, Renegar D, Riegl B (2011) The most temperature-adapted corals have an Achilles' heel. Mar Pollut Bull 62:246–250
Purser BH, Evans G (1973) Regional sedimentation along the Trucial Coast, SE Persian Gulf. In: Purser B (ed) The Persian Gulf. Springer, Berlin, pp 211–231. https://doi.org/10.1007/978-3-642-65545-6_13
Rao PG, Hatwar HR, Al-Sulaiti MH, Al-Mulla AH (2003) Summer shamals over the Arabian Gulf. Weather 58:471–478. https://doi.org/10.1002/wea.6080581207
Reynolds M (1993) Physical oceanography of the Gulf, strait of Hormuz, and the Gulf of Oman: results from the Mt Mitchell expedition. Mar Pollut Bull 27:35–39
Riegl B (1999) Corals in a non-reef setting in the southern Arabian Gulf (Dubai, UAE): Fauna and community structure in response to recurring mass mortality. Coral Reefs 18:63–73
Riegl B, Branch G (1995) Effects of sediment on the energy budgets of four scleractinian (Bourne 1900) and five alcyonacean (Lamouroux 1816) corals. J Exp Mar Biol Ecol 186:259–275
Riegl BM, Purkis SJ, Al-Cibahy AS, Abdel-Moati MA, Hoegh-Guldberg O (2011) Present limits to heat-adaptability in corals and population-level responses to climate extremes. PLoS One 6: e24802
Riegl B, Benzoni F, Samimi-Namin K, Sheppard C (2012) Environmental constraints for reef building in the Gulf. In: Riegl BM, Purkis SJ (eds) Coral reefs of the Gulf: adaptation to climatic extremes. Springer Science+Business Media BV, Dordrecht, pp 187–224. https://doi.org/10.1007/978-94-007-3008-3_2
Schott FA, Dengler M, Schoenefeldt R (2002) The shallow overturning circulation of the Indian Ocean. Prog Oceanogr 53:57–103. https://doi.org/10.1016/S0079-6611(02)00039-3
Sheppard C, Price A, Roberts C (1992) Marine ecology of the Arabian region: patterns and processes in extreme tropical environments. Academic Press, Toronto
Smit F, Mocke G, Giarusso C, Baranasuriya P (2008) Coastal modelling of the Dubai coastline with emphasis on morphological model validation. Conference on coastal and port engineering in developing countries VII. PIANC-COPEDEC, Dubai, UAE, Paper No. 71
Smith EG, Hazzouri KM, Choi JY, Delaney P, Al-Kharafi M, Howells EJ, Aranda M, Burt JA (2022) Signatures of selection underpinning rapid coral adaptation to the world's warmest reefs. Sci Adv 8:eabl7287. https://doi.org/10.1126/sciadv.abl7287
Swift SA, Bower AS (2003) Formation and circulation of dense water in the Persian/Arabian Gulf. J Geophys Res Oceans 108:4-1–4-21. https://doi.org/10.1029/2002jc001360
Thoppil PG, Hogan PJ (2010a) Persian Gulf response to a wintertime shamal wind event. Deep Sea Res Part I Oceanogr Res Pap 57:946–955. https://doi.org/10.1016/j.dsr.2010.03.002
Thoppil P, Hogan P (2010b) A modeling study of circulation and eddies in the Persian Gulf. J Phys Oceanogr 40:2122–2134. https://doi.org/10.1175/2010JPO4227.1
Van Parys M (2006) Environmental monitoring during the construction of the Jebel Ali new container terminal. Proceedings of the 15th international congress of the International Federation of Hydrographic Societies 55:18–22

Vieira F, Cavalcante G, Campos E (2020) Analysis of wave climate and trends in a semi-enclosed basin (Persian Gulf) using a validated SWAN model. Ocean Eng 196:106821. https://doi.org/10.1016/j.oceaneng.2019.106821

Yu Y, Notaro M, Kalashnikova OV, Garay MJ (2016) Climatology of summer Shamal wind in the Middle East. J Geophys Res Atmos 121:289–305. https://doi.org/10.1002/2015JD024063

Part II
Ecosystems of the Emirates

Chapter 5
The Vegetation of the United Arab Emirates and Ecosystem Management Issues

Gary Brown and Gary R. Feulner

5.1 Introduction

This chapter discusses the vegetation of the terrestrial ecosystems of the United Arab Emirates (UAE). Brown and Böer (2005) gave an initial overview of the vegetation of the country, partly based on the accounts of others, most notably Roshier et al. (1996). However, that account was somewhat lacking in detail with respect to the mountains. Due to their considerable interest, a separate section covering various ecological aspects of the Hajar Mountains is given in Chap. 6.

The landscape of a large part of the UAE is dominated by low-lying, sandy desert with extensive dune systems, although salt flats (sabkha) are a highly characteristic feature in coastal areas, especially in Abu Dhabi emirate. In the east, the Hajar Mountains rise sharply above the surrounding plains. For the most part, summits are 1000 m or less, but to the north, in the Musandam peninsula, a number of peaks and plateaux exceed 1500 m and one rises to an elevation of just over 2000 m. Despite a massive increase in human activity over the past decades, natural terrestrial habitat types continue to occupy, by far, the larger part of the country, albeit often severely degraded. Characteristic anthropogenic habitat types such as oases, farmland, forestry plantations and urban areas account for a relatively small proportion of the total area.

The bi-seasonal, Mediterranean-type climate with mainly low winter rainfall and summer drought is characterized by high temperatures throughout many months of the year. In summer, daytime temperatures are normally in excess of 40 °C in the desert. Total annual mean rainfall is generally less than 100 mm in the desert

G. Brown (✉)
Centre for Biodiversity Monitoring and Conservation Science, Leibniz Institute for the Analysis of Biodiversity Change, Bonn, Germany

G. R. Feulner
Dubai Natural History Group, Dubai, UAE

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_5

environment, with distinctly higher amounts received in the mountains (up to about 160–190 mm). However, long-term mean values do not reflect the substantial fluctuations in rainfall amounts from one year to another, with some years experiencing virtually no or very little effective rainfall.

Potential evaporation (i.e. that water that would evaporate if present) far exceeds precipitation in most parts of the country by a factor of about 20, indicating the high degree of stress to which organisms are exposed. The effectiveness of precipitation is substrate-dependent. In general terms, sand sheets and dunes are much better for plant growth in arid regions than finer-grained substrates due to the 'inverse-texture effect' (Noy-Meir 1973). It is no coincidence that the most impressive stands of the UAE's national tree (*Prosopis cineraria*—or *'ghaf'*) are found on deep sands and dunes. However, sand is only a favorable medium for plant growth if it is reasonably stable (Brown and Al-Mazrooei 2003).

Vegetation is one of the defining features of many natural landscapes, including in deserts such as in the UAE. As primary producers, plants are an indispensible source of food on which all organisms ultimately depend. Herbivores are directly reliant on plants; carnivores indirectly so in that they often prey on herbivores. Apart from sabkha, which typically does not support plant growth (except on its margins—Brown (2006)), the majority of major habitat types in the UAE are characterized by one or several plant communities. However, vegetation cover in terrestrial desert habitats is generally sparse and often patchy, and this is especially the case in western and southern regions that receive less rainfall than in other parts of the country. Given the extreme climatic and other environmental parameters, vegetation cover is highly sensitive to overgrazing, and this has led to a severe reduction of it in many locations. In addition, the floristic composition has become depauperate, with species intolerant of high grazing pressures disappearing.

In the following, an account is given of characteristic plant communities according to broad habitat type in which they typically occur. In desert areas, communities are usually referred to after the dominant perennial species and sometimes co-dominant species present (Brown and Mies 2012). It is important to understand that the current vegetation characteristics reflect a snapshot in time, and that even several decades ago, vegetation cover may have looked quite different in some areas. Vegetation degradation, which has led to profound changes in cover and floristic attributes, has proceeded rapidly in many parts of the country, as explained below.

Given the lack of English common names for most plant species of the Emirates, the scientific nomenclature used here follows that of Jongbloed et al. (2003) to allow non-specialist readers the opportunity to check plants in that widely-used book. In the meantime, there have been considerable nomenclatural changes, but not all of them are likely to remain 'valid' for any length of time (see also Chap. 13).

5.2 Broad Terrestrial Habitat Types and Their Vegetation

5.2.1 Coastal Zone

The coastline of mainland UAE extends for about 650 km. It comprises the Arabian Gulf coast to the west of the Hajar Mountains and the Indian Ocean (Gulf of Oman) coast to the east. The Arabian Gulf coastline is predominantly flat, with warm, shallow waters. Numerous inlets and lagoons ('*khors*') have served historically as harbours for fishing, trading and pearling.

When compared to many terrestrial habitats, the coastal vegetation of the UAE and adjacent countries with comparable climates is often species-poor. In some cases, the stands are virtually monospecific, but they can be highly productive nonetheless, and often much more so than the inland vegetation types (Deil 1998; Brown et al. 2008). Furthermore, coastal vegetation often occurs as distinct belts that run more-or-less parallel to the coast, indicating the overriding influence of the sea in affecting species composition. With increasing distance from the coastline, the influence of salinity often, but by no means always, diminishes. Within coastal vegetation belts, abrupt changes in key abiotic factors are reflected in corresponding changes in the vegetation cover. This can lead locally to the development of specialised habitats and the formation of small-scale vegetation mosaics (Deil 1998).

5.2.1.1 Mangroves

Mangroves can be regarded as a woodland formation below the high-tide mark (Walsh 1974). They are generally typical of tropical areas where summer temperatures are not too extreme. Along the Arabian Gulf coast, mangroves are found mainly east of Jebel Dhanna (Böer and Aspinall 2005; Saenger et al. 2004). They are particularly well-developed in the vicinity of Abu Dhabi Island and Umm Al-Quwain, continuing north-eastwards into Ras Al Khaimah, but are absent from the Musandam due to the steep rocky shoreline there. Mangroves are also found at Khor Kalba on the Indian Ocean coast, where the extensive and venerable stand continues into Oman (see Chap. 7).

Mangroves have been, and continue to be, planted in various locations along the coastline, and separating natural stands from artificial ones is not straightforward. It is also probably the case that some planted stands occur in sites that were once home to natural mangrove forests or woodlands, and which were cut down for economic purposes at some time in the distant past.

Mangroves occupy the transitional zone between the open sea and the often rather sparsely vegetated coastal plain. They are usually found growing on fine-grained substrates in bays and inlets where they are protected from wave action. This allows the seedlings to become rapidly established in such situations.

Probably due to the harsh summer climate throughout most of the region, only one species of mangrove, *Avicennia marina*, is able to thrive naturally, although it has been speculated that in historical times, a second species, *Rhizophora mucronata*, might have occurred in some areas (Saenger et al. 2004). In addition, due to the extreme climatic conditions and the high salinity of the Arabian Gulf waters, the *Avicennia* trees rarely exceed 3–4 m in height (Saenger et al. 2004). However, the stands are much denser than all other terrestrial vegetation types in the country.

The accompanying vegetation is almost invariably very poor in species. A regular associate in the UAE is the halophytic (i.e. associated with saline environments) dwarf shrub *Arthrocnemum macrostachyum*, which, however, occupies only the uppermost intertidal zone. Cover values of this chenopod (former member of the goosefoot family, Chenopodiaceae, now Amaranthaceae) vary from 0 to ca. 80%.

5.2.1.2 Saltmarsh Vegetation

In the following, the main saltmarsh plant assemblages are described. These are communities that are inundated by seawater for substantial periods of time, usually at high tides, and where the coastal mud is exposed at low tide. Saltmarsh vegetation is characterized floristically to a large extent by chenopods, and most species, especially the dominants, are perennial dwarf shrubs (Brown et al. 2008). Notable exceptions include the annual chenopods *Salicornia sinus-persica* (Fig. 5.1), *Bienertia cycloptera* and *Suaeda aegyptiaca*. Locally, the rush *Juncus rigidus* predominates.

Fig. 5.1 *Salicornia sinus-persica*, a local annual chenopod (now Amaranthaceae) that was formerly assumed to be *S. europaea*. Photo credit: Gary Brown

Arthrocnemum macrostachyum forms a highly characteristic, almost monospecific salt-marsh community that can cover quite large expanses of both the Arabian Gulf and Indian Ocean coasts of the UAE. In contrast to the morphologically similar *Halocnemum strobilaceum*, *Arthrocnemum* is also associated with mangroves. It would appear that the community is best developed in muddy, sheltered locations with little wave impact, as has been described for various countries in the region, including for the UAE (Brown et al. 2008). Over the past two decades, several large areas of *Arthrocnemum* coastal marshland have been lost to coastal development. For example, a large patch has been destroyed on the east coast of the UAE just north of Fujairah city where *Limonium axillare* was present in the less-frequently inundated sites.

The *Salicornia sinus-persica* community has a distinctly patchy and very localised distribution in the UAE, as indeed is the case along the entire coastline of the east of the Arabian Peninsula. Our own observations suggest that it is present mainly in large, sheltered bays where migratory seabirds accumulate in large numbers. In the UAE, it is predominantly found in the bay complexes near Umm Al Quwain and at Al Rams. Because *S. sinus-persica* is an annual species, it is only visible at certain times of the year.

The large rush *Juncus rigidus* is a species of poorly drained, saline ground in a few coastal locations in the UAE. It reportedly previously occurred in the vicinity of Abu Dhabi Island (Jongbloed et al. 2003), but now it seems to be restricted to a localized coastal area at Al Rams in Ras Al-Khaimah, which is associated with freshwater springs. Here it forms extensive stands that are gradually being lost due to urban encroachment (Fig. 5.2). The stands are therefore of very high conservation value.

5.2.1.3 Vegetation of the Coastal Plains

Low relief is a prominent feature of large sections of the Arabian Gulf coastline in the UAE. As a consequence, coastal plains of varying size occur in many areas. Coastal plains are regarded as flat expanses in close proximity to the coast where soil salinity exerts at least some influence on species composition. The substrate of these plains varies according to geographical location and the associated soil conditions, which range from rock, gravel, silt, silty sand to sand. The plant assemblages usually have the mild to moderately halophytic dwarf shrub *Zygophyllum qatarense* as a prominent constituent. Its cover can vary from nearly zero to in excess of 75% in particularly favourable locations. The species is usually absent where persistent highly saline conditions occur.

In contrast to some adjacent regions, the *Zygophyllum* community is rather species-poor in the UAE, probably due to climatic constraints. One of the more frequent associates is *Suaeda vermiculata*, which also occurs on disturbed, damp ground near the coast. In addition, *Zygophyllum* is often accompanied by ecotypes of the widespread tussocky sedge *Cyperus conglomeratus*, and in drier conditions, locally by the dwarf shrub *Echiochilon jugatum*. *Lycium shawii* is a widespread

Fig. 5.2 The stands with *Juncus rigidus* at Rams are of very high conservation value. Photo credit: Gary Brown

shrub of this community in the adjacent parts of Saudi Arabia and Qatar, but this does not appear to be the case in the UAE. Where elevated soil-salinity is prevalent, species such as *Salsola cyclophylla*, a rather non-descript dwarf shrub, and the perennial grass *Sporobolus ioclados* can occur locally.

5.2.1.4 Coastal Sand Sheets and Dunes

Vesey-Fitzgerald (1957) coined the term 'coastal white sand associations' to describe the vegetation of the predominantly calcareous sands that run parallel to much of the western and southern Arabian Gulf coastline, including that of the UAE. Coastal sands are derived almost exclusively from marine organisms and carbonate sediments, and therefore consist to a large extent of calcium carbonate ($CaCO_3$). In contrast, the inland desert sands are composed predominantly of quartz grains. As indicated by the observations of Vesey-Fitzgerald (1957), the coastal white sand vegetation is frequently set back somewhat from the immediate coastline, although this is not necessarily always the case.

A striking feature of the coastal white sands in many areas is the apparent lack of any direct influence of salt, despite the sometimes immediate proximity to the sea; in some cases within as little as 10 m. This is only possible where the land lies well above the high-tide mark, i.e. at least 2 to 3 m higher. In such cases, the vegetation is

Fig. 5.3 Coastal white sand vegetation near Jebel Ali. This vegetation type, characterized physiognomically by a sparse cover of perennial dwarf shrubs (here mainly *Sphaerocoma aucheri*) and grasses, is of outstanding conservation concern. In wet winters, carpets of annuals may appear. Photo credit: Gary Brown

characterized almost exclusively by glycophytes, i.e. non-halophytic species (Brown and Böer 2005).

In general terms, the vegetation of the coastal white sands is characterized physiognomically by a sparse cover of perennial dwarf shrubs and grasses (Fig. 5.3). Vegetation cover of the perennials rarely exceeds 3–5% in the UAE.

Mainly to the north-east of Abu Dhabi Island (but also probably in fragments further to the west) extending to the Musandam, the coastal white sand vegetation contains a number of highly characteristic perennials, including the perennial grass *Panicum turgidum*. Deil and Müller-Hohenstein (1996) gave the first more comprehensive insight into the coastal white sand vegetation in the UAE, and Brown et al. (2007) described the stands at Taweela, east of Abu Dhabi Island. The coastal white sand vegetation at Taweela has since been largely destroyed due to development. Characteristic species are the dwarf shrubs *Sphaerocoma aucheri* and *Cornulaca monacantha*. Other dwarf shrubs that are regular associates include *Helianthemum lippii* and *Heliotropium kotschyi*. The most widespread perennial grass is *Coelachyrum piercii*, which, along the Arabian Gulf coast of the UAE, appears to be restricted to the stretch between Taweela and the Musandam. It is highly characteristic of the coastal white sands, but it also grows as a ruderal by roads in Dubai and, in the north-east of the UAE, it occurs up to several kilometres inland on red sands. The tussock grass *Pennisetum divisum* is also occasionally present. The sedge *Cyperus arenarius* is usually widespread and abundant.

These and other perennials are accompanied by a profusion of annuals, particularly in wet years, including *Arnebia hispidissima, Herniaria hemistemon, Hippocrepis areolata, Launaea mucronata* and *Lotus halophilus*.

On more saline sands, species richness is much lower, and *Panicum turgidum* is generally absent, as are *Sphaerocoma* and *Coelachyrum.* Instead, the slightly to moderately salt-tolerant *Sporobolus ioclados* and *Zygophyllum qatarense* can be locally common and widespread. In addition, perennial dwarf shrubs such as *Heliotropium kotschyi* and *Salsola drummondii* appear in varying degrees of abundance.

Coastal white sands are perhaps one of the most threatened habitat types regionally, much more so than the more high-profile but more plant species-poor mangrove forests (see Brown et al. 2007). In fact they were already listed by Brown and Böer (2004/2005) as a habitat type of major conservation importance.

5.2.1.5 Vegetation of Some Islands

The UAE possesses at least 200 islands, most of which are rather small and flat, primarily occurring in the southern Gulf basin in Abu Dhabi. However, some islands can be relatively high, attaining elevations well in excess of 100 m. Such higher islands are invariably salt domes.

Zirku is a typical salt dome island that covers an area of 7.8 km^2. It is characterized by a largely flat coastline, a wide coastal plain and hills in the interior that are dissected by wadis. Perennial vegetation cover is extremely sparse on the slopes, typically well below 2%. However, in more favourable years, cover increases markedly, but probably not more than about 5%. The annual herb *Zygophyllum simplex* and the chenopod *Salsola imbricata* are the two most conspicuous species. The trailing caper *Capparis spinosa* is also fairly widely distributed on the rocky slopes. Short-lived plant species such as *Forsskaolea tenacissima* and *Mesembryanthemum nodiflorum* presumably occur where moisture is temporarily available.

The wadis undoubtedly have the highest diversity of plant species in the interior of the island, and species recorded include *Aizoon canariense*, *Cenchrus ciliaris*, *Emex spinosa*, *Lotononis platycarpa*, *Salsola imbricata* and *Zygophyllum simplex* (Brown 2008).

Locally, the beach vegetation just above the high tide mark comprises *Halopyrum mucronatum*, *Salsola imbricata* and *Sphaerocoma aucheri*.

In contrast to salt dome islands, other islands such as Marawah are flat and generally featureless. Some areas of Marawah are occupied by sabkha that is lacking in vegetation cover (see below), but where sand overlies the sabkha and also on more rocky substrates, plants can be quite conspicuous. Species present include *Anabasis setifera*, *Halopeplis perfoliata*, *Limonium axillare*, *Salsola imbricata*, *Seidlitzia rosmarinus* and *Suaeda vermiculata*. Quite extensive stands of mangroves (*A. marina*) occur predominantly on the sheltered side of Marawah, i.e. facing towards the mainland, but also locally elsewhere, including in the north-west.

5.2.1.6 Sabkha Vegetation

Sabkha refers to salt-encrusted, flat desert. It constitutes an extremely inhospitable environment due to the high temperatures, exposure to severe wind erosion, and in particular, the hypersaline substrate (see Fig. 2.20, Chap. 2). Depending on its location, but also its genesis, a broad distinction can be made between coastal and inland sabkha. Coastal sabkha is a major landscape feature in Abu Dhabi emirate, occasionally extending far inland where it can intergrade with inland sabkha. It lies close to the high intertidal, usually less than a few metres above, or even below the high-tide level in places. After heavy rainfall or severe northerly coastal storms in association with high tides, parts of the sabkha may become immersed for up to several weeks (see Fig. 2.18, Chap. 2). Even after the flooding has receded, the surface usually remains slightly moist due to several factors, most importantly the capillary action from the underlying water table and the highly hygroscopic nature of the surface salts. The surface crust can absorb moisture not only from below, but also from the air, even at low relative humidity.

Sabkha proper is typically devoid of vascular plant species (Brown et al. 2008). Plant life is mainly restricted to the margins or where there is a veneer of wind-blown sand overlying the highly saline surface. Various members of the Chenopodiaceae (now Amaranthaceae) are best represented in terms of species number, but the Zygophyllaceae also play a prominent role in the vegetation cover. Halophytes inevitably predominate, ranging from mildly halophytic species such as *Zygophyllum qatarense* to the succulent *Halopeplis perfoliata*, which, along with *Halocnemum strobilaceum*, is one of the most salt-tolerant species in the Arabian Peninsula. In fact one of the most widespread communities occurring on sabkha is dominated by *Halocnemum strobilaceum*, with the woody succulent *Halopeplis perfoliata* also occurring in small stands locally. Where the overlying sand layer is thicker on the sabkha surface, i.e. more than 30 cm above the capillary fringe, non-halophytic vegetation gradually gains a foothold.

Zygophyllum qatarense is one of the more widespread and common species on sabkha, both coastal and inland, where the salinity is not so pronounced due to the presence of an overlying sand layer. This is typically wind-blown coastal sand and may contain a significant fraction of shells and corals in some locations. *Zygophyllum* plants may appear dead, often for substantial periods of time (possibly years), only to become green and physiologically active again when the conditions are more amenable, usually after heavy rainfall.

Other chenopods associated with the margins of sabkha include *Atriplex leucoclada*, *Bienertia cycloptera*, *Salsola imbricata*, *Seidlitzia rosmarinus*, *Suaeda aegyptiaca* and *Suaeda vermiculata*. The chenopod *Anabasis setifera* is a characteristic pioneer species of reclaimed sabkha in coastal areas, for instance near Abu Dhabi Island.

Extensive inland salt flats, often referred to as 'inland sabkha', are found in various parts of Abu Dhabi emirate. Sabkha Matti, located in the far west of the emirate, is the largest of these, but impressive salt flats also occur among the high dunes in the south and east, particularly in the Al Khatam, Umm Al Zumul and Liwa areas, where they are developed on interdunal plains (see Chap. 2). These areas of sabkha are flooded after heavy rainfall, and temporary lakes may persist for several weeks (see Chap. 2).

Halophytic species found on inland sabkha include the widespread *Zygophyllum qatarense*, *Seidlitzia rosmarinus* (e.g. in the Liwa area of southern Abu Dhabi emirate), *Halopeplis perfoliata* (very local away from the coast, e.g. in the Liwa), *Suaeda aegyptiaca* (usually in more disturbed locations) and *Limonium axillare* (generally very rare inland).

5.2.1.7 Vegetation of Tertiary Mesas Associated with Sabkha

A characteristic feature of many areas of coastal sabkha are low, rocky hills of flat-lying Tertiary sedimentary rocks (mesas), which relieve the monotony of the landscape. Depending on the influence of salt-laden dust, these rock exposures are colonised by a mix of halophytic and non-halophytic species (Brown 2006). Salinity is presumably introduced by wind-blown saline dust from the surrounding sabkha. Halophytes found in such locations in the Western Region of Abu Dhabi include *Anabasis setifera*, *Seidlitzia rosmarinus* and *Salsola* spp., such as *S. drummondii*, which can be dominant locally. The mesas act as 'refugia' for glycophytes, which typically do not grow on the surrounding sabkha. These plants exploit small accumulations of soil behind rocks or in gullies on the smaller jebels. On the flat tops of larger mesas, the influence of salt appears to be diminished, and so glycophytes can cover larger areas. Among the plant species present are a number of desert annuals, such as *Arnebia hispidissima* and *Savignya parviflora*. *Dipcadi erythraeum* is a characteristic lily-like plant that can occur in large populations locally on some jebels after heavy rainfall. *Calligonum comosum*, *Cornulaca monacantha*, *Helianthemum lippii*, *Indigofera* spp., *Panicum turgidum* and *Pennisetum divisum* are some of the characteristic perennials found on the plateaux of larger jebels.

Tertiary jebels are also found locally far inland, such as in Al Khatam to the south-west of Al Ain in Abu Dhabi emirate, and inland of Ras Al Aysh and the Shuweihat peninsula in the Baynouna area of western Abu Dhabi, but these tend to be largely devoid of plants.

5.2.2 Vegetation of the Inland Deserts

The following section deals with the vegetation of the inland deserts. As a convenient, albeit often imprecise differentiation, the sand sheets and sand dunes can be separated from the plains (alluvial and interdunal, which themselves can be sandy).

Sand seas occupy a significant part of the country and consist of extensive sand dune systems and deeper sand sheets (see Figs. 2.5, 2.7, 2.8, 2.9, 2.11 and also

Fig. 5.4 Megadunes, i.e. dunes taller than 20 m, are characteristic of the far south of the UAE. Photo credit: Gary Brown

Chap. 2). Sandy habitats vary in the degree of substrate mobility, depending on location and the specific situation, even within small geographical areas. This has important repercussions for plant colonisation: stable sand sheets are generally favourable for plant establishment, whereas mobile sandy substrates are at best colonised by a few specialist species. As a consequence, it is usually the case that the dune hollows have the highest cover, also due to the more favourable water availability for shallow-rooting plants. Megadunes, i.e. dunes taller than 20 m, are characteristic of the far south of the UAE (Figs. 5.4). Particularly in western parts of the country, aeolianite, i.e. cemented dune sand, is a widespread feature (see Fig. 5.11 below).

Plains of various soil types occur throughout the UAE. They are generally regarded as more-or-less flat or rugged expanses of land away from the major sand seas and mountains. Plains in the vicinity of the mountains are typically alluvial (i.e. erosion deposits), with interdunal plains associated with the sand seas. In some cases, rocky sections or areas of exposed caliche ('*gatch*'—i.e. a relatively thin, but solid crust of soil or sediment that has been cemented together by the precipitation of calcium carbonate, gypsum or other minerals) occur on the plains.

In the following, the vegetation formations are arranged according to main growth form present, beginning with the trees, followed by shrubs, dwarf shrubs and others.

5.2.2.1 *Prosopis cineraria* Community

The tree *Prosopis cineraria* ('*ghaf*') is a characteristic species of the eastern part of the UAE. It has been named the national tree of the UAE due to its considerable cultural and ecological significance. It provides shade and shelter for native fauna and domestic livestock, and it is used as an important source of forage. It occurs in four distinct habitat types (1) on dunes, (2) very locally (in Ras Al Khaimah) on interdunal sand sheets, (3) on alluvial plains, but mainly to the east of the Hajar Mountains, and (4) in mountain wadis. However, it is only on the dunes and sand sheets that it predominates and forms a distinctive community. Although the four habitat types are markedly different, one common feature is that large amounts of water are stored in the substrate, allowing *Prosopis* to thrive.

The remaining *Prosopis* stands are most probably remnants of former, more extensive woodlands and forests that have gradually disappeared with the aridification of the climate over the past several thousand years. Anthropogenic causes may have accelerated the decline in more recent times.

Prosopis cineraria often forms small groves (i.e. clusters of trees—Fig. 5.5) or extensive parkland. 'Parkland' refers to individual or small groups of trees scattered over large areas. *Prosopis* groves are typically developed on dunes that can attain heights well in excess of 10 m. The extensive rooting system of the tree is key to its survival in such situations. Perhaps the best existing stands in the region are developed 5 to 40 km inland from the coast, extending from the eastern part of Dubai emirate through Umm Al Quwain and Sharjah into Ras Al Khaimah. However, smaller well-developed stands also occur much further inland, such as in the vicinity of Al Ain. In addition, some stands are found on high dunes (10–20 m high) in immediate proximity to the sheltered coastline to the south-west of Ras Al Khaimah city. The sand there is red rather than white, indicating a non-marine origin and the lack of influence of salinity.

Fig. 5.5 A grove of *Prosopis cineraria* with the sedge *Cyperus conglomeratus* in the foreground at Ghaf Nazwa (Dubai). Photo credit: Gary Brown

Lycium shawii is often encountered in the stands, although nearly always heavily browsed due to the high grazing pressure from camels. *Haloxylon salicornicum* is frequently present, at least locally.

The stands in the north-east of the UAE display, by far, the richest annual flora in the country with respect to the desert areas. Characteristic species include, among many others, *Asphodelus tenuifolius*, *Emex spinosa*, *Eremobium aegyptiacum*, *Gisekia pharnaceoides*, *Launaea capitata*, *Lotus halophilus*, *Plantago boissieri*, *Schismus barbatus* and *Tragus racemosus*. *Malva parviflora* is often abundant, and a sure indicator of overgrazing. The same applies to a lesser extent to *Aizoon canariense* and *Plantago ovata*.

Elsewhere in the UAE, the stands are generally poorer in annuals, although species such as *Astragalus hauarensis* sometimes occur (e.g. near Al Faqa).

5.2.2.2 *Acacia tortilis* Parkland on the Alluvial Plains Associated with the Hajar Mountains

In the UAE, *Acacia tortilis* is mainly restricted to the north-east of the country where it is often the physiognomically most conspicuous, but not necessarily dominant species. As a general rule of thumb, the species occurs east of the Dubai-Al Ain highway, although a few trees make it slightly further west, and also in the vicinity of Al Ain. In addition, there are a few scattered individuals on the Sila'a Peninsula in the far north-west of the country.

The *Acacia tortilis* stands on the alluvial plains associated with the Hajar Mountains are quite extensive (Fig. 5.6). Typical perennial associates include *Lycium shawii*, *Haloxylon salicornicum* and *Rhazya stricta*, and occasionally the shrub *Acacia ehrenbergiana*. The last species also occurs on some interdunal plains to the west of any *A. tortilis* stands (e.g. Umm Al Zumul, Al Marmoum Desert Conservation Reserve and near Sweihan).

5.2.2.3 *Haloxylon persicum* Community

In the UAE, the shrub *Haloxylon persicum* (Arabic: '*ghada*') is highly characteristic of a narrow belt extending some 75 km from Al Wathba, roughly to the south of Abu Dhabi Island, south-westwards towards, but not reaching Medinat Al-Zayed. This UAE population represents an eastern outlier of the Rub Al Khali 'islands' of the species, which are otherwise found in Saudi Arabia.

The typical environmental setting of the open shrublands comprises low dunes and deep sand sheets. The shrub forms a species-poor plant assemblage in which *Haloxylon salicornicum* can be co-dominant, at least locally (Fig. 5.7). It should be noted that although it is sometimes referred to as 'saltbush vegetation', *Haloxylon persicum* vegetation is not a halophytic type, nor is it even characteristic in Arabia of sabkha margins.

Fig. 5.6 *Acacia tortilis* parkland on the alluvial plains near Dibba (Fujairah). Photo credit: Gary Brown

Fig. 5.7 *Haloxylon persicum* stands in the Al Ghada Protected Area (Abu Dhabi). Photo credit: Gary Brown

Frequent fog in the areas of occurrence of *H. persicum* enables the growth of crustose lichens (e.g. *Arthonia* sp., *Caloplaca* sp. on the bark of the shrubs (Brown 2005). Aspinall and Hellyer (2003) refer to the stands in the UAE as a 'dew-forest', which is not strictly accurate as *H. persicum* is a shrub, rather than a tree, and forest implies at least fairly dense vegetation cover, which is not the case. Although the stands occur in an area of high humidity, this is unlikely to be a major determining environmental factor given the much drier climatic conditions in other parts of the regional range of the species.

The *Haloxylon persicum* shrublands in the UAE are of outstanding conservation value.

5.2.2.4 *Calligonum* Communities

Calligonum comosum was probably a widespread species of low desert dunes and sand sheets throughout much of the region, absent from parts of the Rub Al Khali where it is replaced by the endemic and morphologically similar *Calligonum crinitum*. However, the species has suffered substantially from massive overgrazing by domestic livestock over the past decades, which has led to a marked decline in its abundance. On the dunes in the east of the UAE, where *C. crinitum* does not occur, stands with *C. comosum* as the main woody species are developed extremely locally. This is especially the case where the species is protected from grazing by domestic livestock. For example, the species has begun making an impressive return after camels were removed from the Dubai Desert Conservation Reserve (DDCR—Fig. 5.8) and the same phenomenon was recently observed by us in the Al Houbara Protected Area in Abu Dhabi.

Calligonum crinitum is a species endemic to the Arabian Peninsula and in the UAE appears to be restricted primarily to the elevated dune areas in the southern half of the country, although also found on lower dunes closer to the coast in the west. The shrub forms a very open, species-poor community. Typical accompanying species include *Cyperus conglomeratus* and *Limeum arabicum*.

5.2.2.5 *Leptadenia pyrotechnica* Community

Leptadenia pyrotechnica is a virtually leafless shrub that has a wide natural distribution, ranging from Senegal in West Africa eastwards through Arabia into western India.

In the UAE, the species is absent or very rare in the western half of the country, but it becomes increasingly prevalent east of Abu Dhabi Island. To the west of the Hajar Mountains, it forms a distinct shrub community on low dunes, mainly in Dubai, Sharjah, Umm Al Quwain and Ras Al Khaimah. However, *Leptadenia* is absent from the plains to the east of the Hajar Mountains in the UAE.

The community is characterized by a well-developed ground layer of perennials, often woody-based, consisting mainly of *Dipterygium glaucum*, *Indigofera colutea*,

Fig. 5.8 *Calligonum comosum* is making a comeback in areas where it has been protected from grazing by domestic livestock, such as here in Dubai Desert Conservation Reserve. Photo credit: Gary Brown

I. intricata, *Limeum arabicum* and *Tribulus arabicus*, occasionally also *Calligonum comosum*. Common annuals include *Arnebia hispidissima*, *Eremobium aegyptiacum* and *Neurada procumbens*, as well as the rather delicate, short-lived perennial *Monsonia nivea*.

5.2.2.6 *Calotropis procera* Community

As a species, *Calotropis* is found throughout many parts of the Arabian Peninsula, where it is usually regarded as a sure indicator of disturbance or overgrazing because it is a toxic plant that is one of the few species remaining in heavily denuded areas. For instance, in the west of the UAE, it is often restricted to urban or agricultural environments. Extensive stands on low dunes and extensive sand sheets characterized by the dominance of *Calotropis procera* are found in the same broad geographical location as the *Leptadenia* community in the east of the UAE. In fact such *Calotropis* stands often represent a highly degraded, species-poor stage of the *Leptadenia* community. Two regular associates are the perennial prostrate vine *Citrullus colocynthis* and the sedge *Cyperus conglomeratus*.

Apart from on dunes, the typical species assemblage also dominates in some sandy wadis away from the mountains where there is occasional inundation. For instance, extensive stands occur in Wadi Faya (Sharjah emirate—Fig. 5.9) and in Wadi Lamhah, on the Umm Al Quwain-Ras Al Khaimah border.

Fig. 5.9 Extensive stand of *Calotropis procera* in Wadi Faya (Sharjah). Photo credit: Gary Brown

5.2.2.7 *Cornulaca arabica* Community

Cornulaca arabica is an endemic dwarf shrub that according to Mandaville (1990) dominates extensive tracts of the high dunes of the Rub Al Khali in Saudi Arabia. It also occurs in the far south of Abu Dhabi emirate and although it inhabits the higher dunes (Fig. 5.10), it is also found on the lower slipfaces. Typical associates include *Cyperus conglomeratus*, locally *Limeum arabicum* and, to a lesser extent, *Tribulus arabicus* agg.

5.2.2.8 *Haloxylon salicornicum* Community

Haloxylon salicornicum is a species that thrives on sand sheets and low dunes as well as on gravelly near-coastal plains in the country. In fact it could well be the case that the occurrence on plains is due to sand deflation associated with landscape degradation, at least in some locations.

In the north-east of the UAE, for instance on the mainly red sands of Sharjah emirate, the northern part of Ras Al Khaimah and locally in the east of Dubai emirate, the *Haloxylon salicornicum* stands can be quite species-rich in terms of accompanying desert annuals.

In the north-west of the country, species-poor *Haloxylon salicornicum* stands predominate locally on sand sheets and low dunes, for instance in the Al Houbara Protected Area, where grazing by domestic livestock has ceased (Fig. 5.11).

Fig. 5.10 The endemic dwarf shrub *Cornulaca arabica* on dunes in the Liwa. Photo credit: Gary Brown

Perennial associates in the Western Region of Abu Dhabi include *Dipterygium glaucum*, *Fagonia ovalifolia*, *Heliotropium kotschyi*, *Monsonia nivea*, *Polycarpaea repens* and *Zygophyllum qatarense*. On sandier substrates, species such as *Limeum arabicum* occur.

However, the stands in the UAE are generally much poorer in accompanying desert annuals when compared to the north-eastern part of the Arabian Peninsula (see Brown 2003).

The Desert Hyacinth, *Cistanche tubulosa*, is a frequent root parasite on *Haloxylon salicornicum* throughout many parts of the UAE.

Typical micro-nebkhas (mounds of wind-blown sand) are often formed at the base of the plants, which, depending on their stability, can provide an important habitat for burrowing faunal species (see Fig. 5.11). In some cases, true nebkhas, mounds of sand generally taller than 1 m, can be observed, as for instance in the Yaw Al Debsa Protected Area (Fig. 5.12).

5.2.2.9 *Zygophyllum qatarense* Community

The highly variable dwarf shrub *Zygophyllum qatarense* is a typical species of mildly to moderately saline habitats near the coast, but also in the desert interior. Inland, it forms a distinct community on low to medium dunes (Fig. 5.13). As a rough guide, the inland community is found to the south-west of the Dubai–Al Ain

Fig. 5.11 *Haloxylon salicornicum* community on slightly mobile sand sheets in Abu Dhabi emirate. Micro-nebkhas are clearly visible as lighter coloured mounds of sand at the base and in the lee of the individual dwarf shrubs. Extensive patches of aeolianite, i.e. lithified dune sand, are visible in the foreground. Photo credit: Gary Brown

Fig. 5.12 True nebkhas supporting many *Haloxylon salicornicum* individuals in the Yaw Al Debsa Protected Area (Abu Dhabi). Photo credit: Gary Brown

Fig. 5.13 Species-poor *Zygophyllum qatarense* vegetation on low dunes in the Al Marmoum Desert Conservation Reserve (Dubai). Photo credit: Gary Brown

road and extending throughout large sections of the western part of the UAE. Cover of *Zygophyllum* can be quite high—up to about 3% in places. However, the accompanying vegetation is largely restricted to *Cyperus conglomeratus*. Annuals appear to be extremely scant in this community.

Zygophyllum qatarense is also a common and widespread species on interdunal plains with slightly to moderately saline soils, where it can form extensive stands. The species is often developed best towards the margins of the plains where there is a thin veneer of sand from the adjacent dunes covering the surface, or on sand sheets that are developed towards the centre of wider plains. Typical associates include *Fagonia ovalifolia* and *Monsonia nivea* as well as desert annuals such as *Neurada procumbens*, *Savignya parviflora* and *Zygophyllum simplex*.

5.2.2.10 Vegetation Types with *Rhanterium epapposum*

Satchell (1978) reported that the composite *Rhanterium epapposum* was once found on the alluvial plains to the west of the Hajar Mountains, apparently where sand overlies mainly limestone rock. This is presumably in the vicinity of the foreland ridges such as Jebels Buhais and Faya (see below). It was also common as part of a 'wooded plain community' *with Prosopis cineraria* and *Lycium shawii* on the Jiri Plain (i.e. on alluvial plains in the north-east of the UAE, north of Idhan (= Adhan)). Currently, it appears that *Rhanterium* has now completely disappeared from the plains except in areas that are protected from grazing in some form or another, where the species remains rather sparse.

It should also be noted that the *Rhanterium* community was also once fairly widespread on sand sheets in the vicinity of Dubai as recently as 1987, especially in the transition zone between coastal white sands and inland red sands (Deil and Müller-Hohenstein 1996). These stands have now all but disappeared, largely due to urbanisation, but possibly also on account of overgrazing. A small remnant of this vegetation persists in the Al Marmoum Desert Conservation Reserve (Fig. 5.14).

Small *Rhanterium* plants can be found by roadsides in the north-east of the UAE, i.e. in sites that domestic livestock cannot reach, for example to the south-east of Dubai. Such observations give some insight into the former distribution of the species.

5.2.2.11 *Rhazya stricta*-Dominated Stands

The woody-based perennial herb *Rhazya stricta* is a common species on the alluvial plains in the east of the UAE extending into Oman. It is avoided by livestock due to its reputed toxicity and as a consequence, it can become dominant locally on silty gravel plains.

Fig. 5.14 Small patch of *Rhanterium epapposum* dwarf shrub vegetation in the Al Marmoum Desert Conservation Reserve (Dubai). Photo credit: Gary Brown

5.2.2.12 Vegetation Types with *Fagonia ovalifolia*

Apart from *Zygophyllum qatarense*, which was dealt with above, the woody-based perennial herb *Fagonia ovalifolia* can predominate on some interdunal plains, mainly in the northern half of the country, in addition to alluvial plains associated with the Hajar Mountains. As with *Zygophyllum*, this species requires heavy rainfall to develop leaves and become physiologically active, otherwise it appears distinctly 'dead'. Mixed stands of *Zygophyllum qatarense* and *Fagonia ovalifolia* are frequently observed on interdunal plains in some parts of the UAE.

5.2.2.13 *Tribulus-Dipterygium-Limeum* Community

This community is composed primarily of various dwarf shrubs and woody-based herbs, notably *Tribulus arabicus* agg., *Dipterygium glaucum* and *Limeum arabicum*. *Cyperus conglomeratus* is also a widespread associate. The community is found in various parts of the UAE. Depending on the location, it can also contain a variety of other perennials, especially *Indigofera* spp. (e.g. *Indigofera intricata* and *I. colutea*). In the climatically more extreme parts of the UAE, i.e. in the Rub Al Khali, the community is species-poor and comprises mainly *Tribulus arabicus* agg., *Cyperus conglomeratus* and *Limeum arabicum*. Towards the coast, *Dipterygium glaucum* is often more characteristic. In addition, various desert annuals become locally abundant, especially in the north-east.

5.2.2.14 *Cyperus conglomeratus* Community

Away from the mountains, *Cyperus conglomeratus* is a widespread species found throughout the region, often on deeper sands (see Fig. 13.5 and also Fig. 13.12 Chap. 13). The species may be the only perennial present in large sections of the sand seas. It is particularly well adapted to such environments, as highlighted in Chap. 13. Vegetation cover is often extremely low.

5.2.2.15 *Panicum turgidum* Community

Extensive inland sand sheets with perennial grass vegetation dominated by *Panicum turgidum* are found in the north of the Al Marmoum Desert Conservation Reserve (Dubai emirate). Accompanying perennial grasses include *Pennisetum divisum*, *Stipagrostis plumosa* and *S. uniplumis*. The last species is distinctly rare and localized in the UAE. It is interesting to note that *Cyperus conglomeratus* is uncommon in this community, and yet there is a rather abrupt transition to *Cyperus*-dominated vegetation in Al Marmoum, largely without the aforementioned perennial grasses, that remains unexplained.

Perennial vegetation cover can be remarkably high—in excess of 15% in some cases. This habitat type is of exceptional conservation value, as it appears to be largely restricted to Dubai in the country, where it has probably been disappearing at an alarming rate over the past decades. Our observations have shown it to be a key habitat for the remarkable Persian Wonder Gecko (*Teratoscincus keyserlingii*).

5.2.3 Vegetation of the Hajar Mountains

The Hajar Mountains in the UAE comprise three ecologically distinct sections: the main Hajar range, the Ru′us Al Jibal (Musandam) and the Foreland Ridges. Only a small part of the Ru′us Al Jibal lies within the UAE, the largest portion belonging to Oman.

Elevation, geology and substrate interacting in response to the local environmental conditions contribute to a surprisingly varied vegetation cover in the mountains. Describing the variety of plant assemblages and making relevant generalisations is not an easy task due to the lack of exhaustive field studies undertaken to date, the relatively sparse vegetation cover and the absence of clear plant indicators. Furthermore, associating plant communities with specific elevational belts is problematic because in some cases, changes in vegetation cover vary quite markedly in different areas of the mountains depending on geographic location, underlying bedrock, substrate type, aspect and other environmental factors. A prominent feature of the Hajar Mountains is the intricate network of wadi systems, and a few characteristic species are given in a separate section below. Most gullies and wadis do not carry flowing water, but nonetheless, vegetation is often concentrated in them as they represent distinct 'sinks' for moisture. In the following, a summary is given of the key vegetation characteristics according to elevational range or ecological zone. Some aspects are also touched upon up in Chap. 6.

5.2.3.1 Main Hajar Mountain Range

5.2.3.1.1 *Submontane zone (0–) 50–500 (−600) m*

The submontane zone of the widespread harzburgite slopes and other rock types (i.e. up to about 500 m) is characterized primarily by *Acacia tortilis* and *Euphorbia larica*. This general assemblage was referred to more specifically (in phytogeographical terms) as the 'Pseudogaillonio hymenostephanae-Euphorbietum laricae' by Deil and Müller-Hohenstein (1996). The stands appear to correspond with the *Euphorbia larica*-*Gaillonia aucheri* association described in brief from southern Iran by Zohary (1973), especially as *Gaillonia* (= *Plocama*) *aucheri* is a regular and conspicuous associate in the Hajar Mountains (Fig. 5.15).

Fig. 5.15 Lower mountain slope in the Hatta Mountain Conservation Area (Dubai emirate) with *Euphorbia larica*, *Leucas inflata*, *Gaillonia aucheri* and *Pulicaria glutinosa*. Photo credit: Gary Brown

5.2.3.1.2 *Medium-elevation montane zone (400–) 500–1000 (–1300) m*

***Caralluma arabica-Euphorbia larica* slopes**

On the harzburgite slopes above ca. (400–) 500 m and up to about 1000 m (–1300 m), a somewhat different community type becomes more prevalent. *Euphorbia larica* is often the physiognomically dominant species. *Acacia tortilis* remains a conspicuous element in the vegetation cover up to about 800–900 m, but it is generally scattered. These are accompanied by a number of other species that vary somewhat according to location. The most notable include *Dodonaea viscosa*, *Ficus johannis*, *Moringa peregrina*, *Caralluma (= Desmidorchis) arabica*, *Ochradenus arabicus*, *Pulicaria edmondsonii* and *Stipagrostis hirtigluma*.

***Olea europaea* stands of Fujairah**

A small and remarkable population of *Olea europaea* occurs in a high-elevation area of gabbro south-west of Fujairah City. The fragmentary *Olea* stands were referred to as the 'Olive Highlands' in a detailed study published by Feulner (2014), and they represent an ecologically unique island of biodiversity. As such, they are of outstanding conservation concern.

5.2.3.2 Ru′us Al Jibal (Musandam)

5.2.3.2.1 *Vegetation zones*

In his detailed monograph, Feulner (2011) divided the vegetation of the Ru′us Al Jibal into three broad zones, characterized by habitat and elevation.

5.2.3.2.2 *Zone 1: Mountain wadi zone*

This zone includes wadi beds, wadi banks as well as associated gravel fans and terraces. In the Ru′us Al Jibal, this environment is common at elevations from ca. 100–600 m. At higher elevations, wadis tend to be narrower and rockier, and the distinction between wadi vegetation and slope vegetation (Zone 2) is less evident.

The characteristic trees are *Acacia tortilis*, *Ficus salicifolia* and *Ziziphus spina-christi*. Locally common small shrubs and dwarf shrubs include *Gaillonia* (= *Plocama*) *aucheri*, *Pulicaria edmondsonii* and *Ochradenus aucheri*. *Tephrosia apollinea*, a sure indicator of overgrazing, is omnipresent.

5.2.3.2.3 *Zone 2: Low and medium-elevation montane zone*

This zone encompasses all terrain at elevations from ca. (5–) 100–1100 m, other than the mountain wadi zone (Zone 1), and therefore includes slopes, cliffs, plateaux and basins, upper wadis and gullies as well as terraced fields.

The predominant species of Zone 2 are *Acacia tortilis*, *Euphorbia larica* and *Cymbopogon* spp. In some locations, extensive stands of *E. larica* are developed very close to sea-level. *Prunus arabica* (Arabian Almond) first appears and effectively replaces the morphologically similar (but ecologically distinct) *Moringa peregrina* above ca. 600 m.

5.2.3.2.4 *Zone 3: High-elevation zone*

This zone encompasses all terrain from ca. 1100 m to the summit plateaux and peaks at 1500–2000 m. In the UAE, areas above 1550 m are restricted to the broad summit region of Jebel Jais.

Any one of the following shrubs or dwarf shrubs can predominate in the typical plant assemblages of this zone, namely *Convolvulus acanthocladus*, *Artemisia sieberi, Dodonaea viscosa*, with the others and/or *Ephedra pachyclada* as associates. Collectively, these assemblages have been referred to as the '*Artemisia* steppe' (Mandaville 1985), following the terminology of Zohary (1973), who found associations of the same species and/or genera to be characteristic of the plateaux of central Iran.

5.2.3.3 Foreland Ridges

The Foreland Ridges comprise a series of narrow, north-south trending, anticlinal ridges to the west of the main mountain front, such as Jebels Buhais, Faya, Hafeet and Nazwa. At the surface, latest Cretaceous and Paleogene marine carbonate sediments are exposed, and so the ridges are geologically distinct from the Hajar range proper. Jebel Hafeet (Fig. 5.16) has been the subject of a fairly detailed treatment of its natural history (Aspinall and Hellyer 2004), including its flora and vegetation (Brown and Sakkir 2004). In ecological terms, these isolated mountains represent distinctive 'inselberg' environments and are of considerable biodiversity interest. They have a similar vegetation structure to the main Hajar Mountains, but support a number of distinctive plant species, including, amongst many others, *Acridocarpus orientalis* (unique from a UAE perspective, but more common further to the east in Oman), *Anvillea garcinii*, *Koelpinia linearis*, *Nannorrhops ritchieana* (all Jebel Hafeet), *Dipcadi biflorum* and *Heliotropium* (= *Euploca*) *rariflorum* (Jebel Hafeet, Jebel Nazwa). The rocky slopes of some of these ridges appear to represent distinct refuges for several formerly more widespread species, where they can be locally common, including *Lasiurus scindicus*, *Rhanterium epapposum* and *Rhynchosia schimperi* (Fig. 5.17).

Fig. 5.16 Wadi Tarabat with Jebel Hafeet in the background (right). Most of the vegetation in the mountains and their associated gravel plains is found in wadis and shallow drainage channels. The main species visible is the small tree *Acacia tortilis*. Photo credit: Gary Brown

Fig. 5.17 Rocky slope of Jebel Nazwa with *Haloxylon salicornicum*, *Rhanterium epapposum* and *Rhynchosia schimperi*. Photo credit: Gary Brown

5.2.4 Freshwater Habitats

Natural freshwater habitats are generally rare in the UAE, being largely confined to the mountains where there are small numbers of permanent pools and springs as well as a larger number of temporary ones, connected by ephemeral streams (see Chap. 6).

Characteristic species of the moist to wet wadis include the rush *Juncus socotranus*, *Nerium oleander* (Oleander) and the tall perennial grass *Saccharum griffithii* (Fig. 5.18). In localized springs and seepages, the only native orchid species in the UAE can sometimes be found, namely *Epipactis veratrifolia*. This is often accompanied by the fern *Adiantum capillus-veneris* and occasionally the rare annual *Centaurium pulchellum*.

A number of artificial aquatic habitats have been created over the years, such as Al Wathba near Abu Dhabi, the lakes in Al Marmoum Desert Conservation Reserve (Dubai) and Lake Zakher (Al Ain). *Phragmites australis* (Common Reed) forms dense stands around some of these lakes whereas in some mountain reservoirs (e.g. at Hatta), the morphologically similar *Arundo donax* predominates.

Fig. 5.18 Wadi with temporary water flow and pools in Ras Al Khaimah. Two characteristic species, *Nerium oleander* and *Saccharum griffithii*, predominate here. Photo credit: Gary Brown

5.2.5 Oases, Intensive Agricultural Farms and Plantations

Freshwater oases occur throughout various parts of the country. The plains on either side of the Hajar Mountains support a relatively large number of oases, as do several desert locations in Abu Dhabi emirate. The most famous and largest desert oasis is found in the Liwa Crescent. With a ready supply of subterranean water, the Liwa supports a long chain of many individual oases that extend over a distance of more than 100 km.

Many species found in such environments are introduced annuals, often pantropical weeds, that do not become invasive. Other species are recruited from the local flora that can take advantage of the abundant resources and are not sensitive to occasional disturbance. Typical plant species of such agricultural areas include *Anagallis arvensis*, *Bacopa monnieri*, *Capsella bursa-pastoris*, *Cardaria draba* (local in the east), *Chenopodium murale*, *Eruca sativa*, *Euphorbia peplus*, *Phyla nodiflora*, *Sisymbrium erysimoides*, *S. irio* and *Sporobolus spicatus*.

Farms have sprung up in desert areas where there is a sufficient water supply, and fields of *Chloris gayana* (Rhode's grass) are dotted around the country. These tend to be poorer in species than the traditional date palm groves.

Over the past few decades, numerous forestry plantations have been created in various parts of Abu Dhabi emirate. Some of the trees used to establish the plantations are native species, but others such as *Conocarpus* sp., are not. Huge amounts of irrigation water are needed to sustain the trees, which can lead to soil salinisation. In some parts of the region, the plantations have been abandoned.

5.2.6 Urban Environments

Urban areas have expanded massively in recent years. This means that large areas of what was until recently fairly intact, albeit overgrazed desert have been lost to development. For instance, it was only 20 years ago that the site where the Burj Khalifa now stands (in urban Dubai) was open desert with scattered populations of *Prosopis cineraria* on low, near-coastal sand sheets. As a consequence of this urban development, there has been a marked shift in the flora. A number of different plant species have been able to exploit these new habitats, which include, parks, lawns and gardens. Some of these plant species are indigenous to the UAE and are able to tolerate well-irrigated, anthropogenic habitats. Such species include the perennial grasses *Aeluropus lagopoides* and *Sporobolus spicatus*. Others species have been unintentionally introduced from various parts of the world, for example *Coronopus didymus*, *Fimbristylis* sp., *Poa annua* and *Sonchus oleraceus*. The status of some species, for instance *Cressa cretica* (typically found in garden beds and some plantations), is unclear as in the case of *Cressa*, it is known from saline habitats in adjacent countries where it is locally common. It may also occur naturally in the UAE in such situations. The orchid *Zeuxine strateumatica*, reported by Aspinall (2006), is a good example of a species that suddenly appeared in the country, in this case in a newly-laid golf course in Al Ain. In the context of urban ecology and biophilia as well as from a scientific perspective, urban habitats represent a treasure trove for studying such unintentionally introduced species and how they come to terms with their specific environmental conditions. To date, this aspect has hardly been explored.

Open spaces in urban settings that have not been built upon sometimes support typical desert species. For instance, in a minute patch of land near the Sheikh Zayed Road in Dubai just a few square metres in size, the dwarf shrub *Indigofera intricata* and *Coelachyrum piercii* were found growing in abundance, and *Heliotropium kotschyi* can be found in various locations growing on 'wasteland' in Dubai (Fig. 5.19).

5.3 Threats to the Flora and Vegetation of the UAE

The main issues affecting the flora and vegetation of the UAE are largely the same as in other arid parts of the world. They were recently highlighted by Brown et al. (2016) in the State of the Environment report prepared for the Executive Council in Dubai. A major challenge in desert areas remains overgrazing, even in some protected areas, which leads to a massive reduction of vegetative cover or substantial

Fig. 5.19 Urban 'wasteland' can constitute an interesting refuge for biodiversity, both flora and fauna: here with *Calotropis procera* (an indicator of disturbance), *Heliotropium kotschyi* and *Zygophyllum qatarense* near the Sheikh Zayed road in Dubai. Photo credit: Gary Brown

shifts in dominant plant species, including a severe decline of most palatable species (Fig. 5.20). This also results in the impoverishment of the fauna. Apart from numerous scientific publications from the country (e.g. Böer 1999; Aspinall 2001; Brown et al. 2006; Gallacher and Hill 2006, 2007; Gallacher 2007; Tourenq and Launay 2007; Brown 2008; El-Keblawy et al. 2009; Alzahlawi et al. 2019), overgrazing is also highlighted as a major contributory factor to land degradation and desertification in the UAE's federal *State of the Environment Report* (MOEW 2015). The term 'desertification' is somewhat controversial, but is used in accordance with Dregne (1986), referring particularly to a reduction in plant productivity, a decline in species diversity and the loss of soil resources (see Fig. 5.24 below). Desertification was a topic that was 'en-vogue' several decades ago, but the seriousness of this menace is beginning to be recognised again in recent years.

Native or subnative species that expand rapidly in response to ecosystem degradation are termed 'expansive' species or 'increasers' ('subnative' refers to species native to adjacent areas or ecosystems). In more extreme cases, they are highly detrimental to ecosystem functioning. The shrub *Calotropis procera* (Sodom's Apple), which is particularly common in parts of the north-east of the country, is a good example of an expansive plant species that has had a major transforming role to the detriment of biodiversity in desert settings in the UAE. In the mountains and adjacent plains, common expansive species are the woody-based perennial herb *Tephrosia apollinea and* the toxic dwarf shrub *Rhazya stricta*. Most species of

Fig. 5.20 Heavily overgrazed *Prosopis cineraria* area. Some of the trees have been severely lopped to provide forage for domestic livestock. The stumps in the ground layer are dead remnants of *Haloxylon salicornicum*, which were not able to tolerate the massive grazing pressure. Note the virtual absence of a ground layer, despite the favourable spring when the image was taken. Photo credit: Gary Brown

Fagonia where they occur in large amounts can be regarded as indicators of overgrazing and ecosystem degradation.

Heavily-stunted individuals of *Lycium shawii*, a shrub that is browsed by camels, are a common sight in north-eastern parts of the country where the species naturally occurs. Other effects of massive land degradation will only become more obvious in future decades. For instance, it appears that all of the *Acacia* woodland of the alluvial plains is now extremely degraded (Fig. 5.21), and recruitment of young trees is severely impeded in most locations. If there are no trees to replace the older ones, which will eventually die off, the woodland will disappear completely in the medium term. This process has already been described in detail for parts of the Arabian Peninsula by Chaudhary (2010).

Relatively few desert annuals appear able to withstand heavy grazing pressures, but some of the more obvious examples include, in the north-east at least, *Malva parviflora* and *Emex spinosa*.

Construction activities are underway in many locations nowadays, but it is the coastal habitats that have suffered most massively from development to date. This is particularly the case along the entire coastline east of Abu Dhabi island. There has also been substantial development on the Indian Ocean coast over the past two decades. Indirectly, other issues have led to the demise of coastal areas. For example, it is often the case that coastal vegetation in the region is equated solely to

Fig. 5.21 Highly degraded *Acacia tortilis* parkland. The demise of this vegetation type typically proceeds slowly and easily goes unnoticed due to the relative longevity of the trees. It is a typical example of the shifting baseline syndrome. Photo credit: Gary Brown

mangroves. In fact mangroves account for only a very small percentage of the total coastal vegetation, meaning that other vegetation types are largely or completely ignored. Such narrow perspectives coupled with the focus on specific vegetation types deemed worthy of protection have severe conservation repercussions, as has happened to the ‘coastal white sand vegetation’ (see above).

In the mountains, two factors are having a particularly negative effect on the flora and vegetation, namely quarrying and road-building (see Chap. 6). Both leave large scars on the landscape, often visible from considerable distances, that will persist for decades at least, and the latter is opening up areas to the wider public, initiating a chain of events that ultimately leads to the simplification of the vegetation.

Habitat fragmentation is an issue that not only affects the fauna, but also the flora. The increasing degradation and fragmentation of habitats with intact and species-rich vegetation, which often remain as islands in an otherwise degraded landscape, could be expected to have implications for gene flow mediated through pollination processes. This would be especially the case for rare species that remain in island-like remnants, potentially leading to genetic erosion including inbreeding depression (Aguilar et al. 2019). This topic has not been addressed so far in the UAE or the wider region.

Off-road driving is a major issue that causes soil compaction and the direct destruction of vegetation, as well as disturbance to the fauna (Brown and Schoknecht 2001).

It is unclear to what extent groundwater abstraction has had an impact on the vegetation. Deil and Müller-Hohenstein (1996) suspected that the dramatic lowering of the groundwater table may have seriously affected formerly dense *Prosopis cineraria* woodlands in parts of the desert.

The invasion of ecosystems by non-native species is a global phenomenon, which can have major ecological and economic consequences. The impact of such introduced species can be very serious if so-called 'transformers' are involved, species with the potential to alter entire ecosystems (Richardson et al. 2000). A distinction can be made between these invasive alien species and expansive native or subnative species, but the overall effects on the ecosystem can be equally devastating.

At present, the UAE has been affected by relatively few invasive alien plant species, likely as a result of the extreme local climate relative to natal sites of many introduced species. The most serious is undoubtedly *Prosopis juliflora* (mesquite), which has wreaked havoc in other parts of mainland Arabia. In the UAE, it has its stronghold in some near-coastal areas of the Northern Emirates (Fig. 5.22), where it forms open woodlands and outcompetes the native *Prosopis cineraria* (ghaf), but scattered trees occur in many areas elsewhere.

Climate change is an issue that requires special attention. It is clear that the global climate is undergoing rapid changes, without doubt driven primarily by human activities (see Chap. 3). At present, it is very difficult to assess how the climate is changing in particular regions—partly because of the inherent problems of differentiating between short-term fluctuations of weather patterns over several years and

Fig. 5.22 *Prosopis juliflora* invading a stand of *Prosopis cineraria* (ghaf) in a near-coastal area of the Northern Emirates. The ground layer consists to a large extent of the annuals *Emex spinosa* and *Malva parviflora*, both tolerant of heavy grazing. Photo credit: Gary Brown

actual long-term changes. Although it is generally accepted that the climate is currently warming at an unprecedented rate, the outcomes may not be as expected over the longer term. From a biodiversity perspective, the responses to climate change are extremely complex due to the myriad of factors and interdependencies that affect the ecological performance of individual species under specific climatic conditions. It is also important to realise that rapid shifts in climatic conditions will produce clear 'winners' apart from 'losers'. Although it is perhaps reasonably straightforward to monitor, for example, how the ranges of certain species may be changing in response to changes in climate, overall ecosystem responses are far from clear. Whereas fauna and flora have had to come to terms with changes in the climate in the past, the current situation is far more worrying because of the speed of apparent changes that allows organisms no time (in evolutionary terms) to adapt.

However, it is important to emphasise that although climate change is a key issue, some of the others listed above are, currently at least, much more threatening from a biodiversity perspective in terrestrial ecosystems, but they have not received the same degree of general attention. This applies in particular to the massive overgrazing issue, as was clearly underlined by Le Houérou (1996) and Brown and Mies (2012) for Socotra. In fact in a very recent study, Caro et al. (2022) confirm this view and conclude that although climate change is highly relevant issue, it detracts focus and effort from the primary threats to biodiversity, namely habitat destruction and overexploitation. This is apparent throughout the Arabian Peninsula when comparing areas that have long been protected from overgrazing from those that have not (e.g. Brown 2001; Brown and Al-Mazrooei 2003; Al-Rowaily et al. 2015), including for the UAE (Figs. 5.23 and 5.24).

Finally, a major problem exists in that many people in the region are unaware of what desert ecosystems previously looked like, even in the not too distant past. This is in part due to the lack of reliable records from the region. In this context, and due to the widespread nature of this problem, the 'shifting baseline syndrome' should be mentioned, which has received much attention globally. The concept was first described by Pauly (1995), examining the problems of massively depleted and declining fish stocks. He pointed out that fisheries scientists at the beginning of their careers perceive then current stock sizes and species composition as the norm (baseline) against which subsequent changes are assessed. With generally declining stock sizes, the following generation has a lower perception as to what constitutes the norm. In more general terms therefore, the shifting baseline syndrome (SBS) describes the incremental lowering of standards that results in each new generation lacking knowledge and experience of the historical, and presumably more natural condition of the environment. The shifting baseline syndrome can be applied unreservedly to the situation of the terrestrial ecosystems of the UAE. The strong implication of SBS is that with the continuing deterioration of the natural environment, baseline standards for environmental health will continue to decline, which represents an enormous challenge for the conservation, restoration and management of terrestrial ecosystems in the country. The gradual demise of the *Acacia tortilis* parkland throughout much of its occurrence in the Arabian Peninsula is a typical example of SBS, as indicated above.

Fig. 5.23 Undulating sand sheets with the dwarf shrub *Haloxylon salicornicum* were once widespread in the north-west of the UAE, but are now restricted to areas that are protected from grazing such as here in the Yaw Al Debsa Protected Area (Abu Dhabi emirate). The *Haloxylon* dwarf shrubs play a key role in stabilising the sand sheets and protecting them from wind erosion. Photo credit: Gary Brown

Fig. 5.24 Seriously degraded landscape immediately outside of the Yaw Al Debsa Protected Area where overgrazing and other detrimental activities such as off-road driving are prevalent. Note the loss of the undulating sand sheets to reveal the underlying compact surface, which is generally less favourable for plant establishment. Photo credit: Gary Brown

With regard to how to tackle some of these key issues, Aspinall (1996) recognised many of the key biodiversity challenges facing the country and proposed a network of protected areas comprising 41 distinct sites. Although ornithological criteria played an important role in the selection of these sites, many of them were of high conservation value for other groups of organisms, too. In the meantime, the various emirates have designated a number of protected areas, some of which correspond to those suggested by Aspinall. Now, effective management plans will need to be developed and implemented to help protect their biodiversity.

Brown and Böer (2004/2005) compiled the first detailed habitat classification scheme for Abu Dhabi emirate, closely aligned with the general approach of the '*Interpretation Manual of European Union Habitats*', which provides the legislative foundation for all conservation planning in the EU, and was last updated in 2013 (European Commission DG Environment 2013). The Abu Dhabi scheme, still in use today, provides a list of 'priority habitat types', i.e. ones of major conservation concern, which remain highly relevant. In the meantime, it has been updated to cover the whole of the UAE (Brown in prep.). This means that at a fundamental level, sufficient information is available to facilitate the decision-making process for a rigorous biodiversity policy. Mapping of habitats has been conducted in some areas based primarily on a remote-sensing approach. However, as personal experience has shown throughout the Arabian Peninsula, this in itself is often not effective in discriminating and delimiting habitats and vegetation units for conservation purposes. That can only be achieved if supported by rigorous field-based studies, preferably conducted by experienced persons. Field-based studies are also the only meaningful way to collect exhaustive 'raw' biodiversity data.

On a welcome note, Abu Dhabi emirate has recently introduced a grazing law (Abu Dhabi Law No. 11, 2020), which, once fully implemented by the Environment Agency—Abu Dhabi (EAD), should help alleviate the substantial pressure on the rangelands that has led to the denudation or simplification of the vegetation cover over substantial tracts of the desert. To improve ecosystem functioning, however, wide-ranging restoration measures are required given the extent of degradation.

5.4 Recommended Readings

For a general overview of terrestrial habitats of the UAE, see Brown and Böer (2005). For details on the coastal vegetation of the western and southern Gulf, see Brown et al. (2008) and for the Arabian region as a whole see Ghazanfar and Fisher (1998).

References

Aguilar R, Cristóbal-Pérez EJ, Balvino-Olvera FJ, de Jesus Aguilar-Aguilar M, Aguirre-Acosta N, Ashworth L, Lobo JA, Martén-Rodríguez S, Fuchs EJ, Sanchez-Montoya G, Bernardello G, Quesada M (2019) Habitat fragmentation reduces plant progeny quality: a global synthesis. Ecol Lett 22:1163–1173

Al-Rowaily SL, El-Bana MI, Al-Bakre DA, Assaeed AM, Hegazy AK, Ali MB (2015) Effects of open grazing and livestock exclusion on floristic composition and diversity in natural ecosystem of Western Saudi Arabia. Saudi J Biol Sci 22:430–437

Alzahlawi N, Binkulaib R, Al Kharusi Y, Javed S (2019) The contribution of oral history interviews in ecological conservation – a case study in grazing practices and perspectives from Abu Dhabi, United Arab Emirates. Tribulus 27:11–19

Aspinall S (1996) Time for a protected area network in the UAE. Tribulus 6(1):5–8

Aspinall S (2001) Environmental development and protection in the UAE. In: Al-Abed I, Hellyer P (eds) United Arab Emirates: a new perspective. Trident Press, London

Aspinall S (2006) Soldier's orchid *Zeuxine strateumatica* marches on. Tribulus 16:19

Aspinall S, Hellyer P (2003) Abu Dhabi's dew forest. Tribulus 13:8–10

Aspinall S, Hellyer P (eds) (2004) Jebel Hafit, a natural history. Emirates Natural History Group, Abu Dhabi

Böer B (1999) Ecosystems, anthropogenic impacts and habitat management techniques in Abu Dhabi. Paderborner Geographische Studien 12:13–104

Böer B, Aspinall S (2005) Life in the mangroves. In: Hellyer P, Aspinall S (eds) The Emirates, a natural history. Trident, London

Brown G (2001) Vegetation ecology and biodiversity of degraded desert areas in North-Eastern Arabia. Habilitation thesis. University of Rostock

Brown G (2003) Factors maintaining plant diversity in degraded areas of northern Kuwait. J Arid Environ 54:183–194

Brown G (2005) Lichens. In: Hellyer P, Aspinall S (eds) The emirates, a natural history. Trident Press, UK

Brown G (2006) The sabkha vegetation of The United Arab Emirates. In: Khan MA, Böer B, Kust GS, Barth H-J (eds) Sabkha ecosystems. Volume II. Springer, Berlin

Brown G (2008) Flora and vegetation. In: Perry RJ (ed) Desert ecology of Abu Dhabi. EAD, Abu Dhabi

Brown G. (in prep) Interpretation manual of the major natural and semi-natural terrestrial and freshwater habitat types of The United Arab Emirates. Prepared for the Ministry of Climate Change and Environment, Dubai, UAE

Brown G, Al-Mazrooei S (2003) Rapid vegetation regeneration in a seriously degraded *Rhanterium epapposum* community in northern Kuwait after four years of protection. J Environ Manag 68: 387–395

Brown G, Böer B (2004/2005) Interpretation manual of major terrestrial and semi-natural habitat types of Abu Dhabi emirate. Research report, environmental research and wildlife development agency, Abu Dhabi. 2nd edn. February 2005

Brown G, Böer B (2005) Major terrestrial habitat types, flora and vegetation of the UAE. In: Hellyer P, Aspinall S (eds) The Emirates: a natural history. Trident Press, London

Brown G, Mies BA (2012) Vegetation ecology of Socotra. Springer, Dordrecht

Brown G, Sakkir S (2004) Flora and vegetation of Jebel Hafit. In: Aspinall S, Hellyer P (eds) Jebel Hafit, a natural history. Emirates Natural History Group, Abu Dhabi

Brown G, Schoknecht N (2001) Off-road vehicles and vegetation patterning in a degraded desert ecosystem in Kuwait. J Arid Environ 49:413–427

Brown G, Peacock J, Loughland R, Alhadrami GA (2006) Coastal and terrestrial ecosystem management requirements in the Arabian Peninsula. In: Amer KM, Böer B, Brook MC, Adeel Z, Clüsener-Godt M, Saleh W (eds) Policy perspectives for ecosystem and water management in the Arabian Peninsula. United Nations University, Ontario

Brown G, Aspinall S, Sakkir S (2007) The vegetation of the coastal white sands at Taweela (Abu Dhabi Emirate). Tribulus 17:5–15

Brown G, Böer B, Sakkir S (2008) The coastal vegetation of the western and southern Gulf – characterisation and conservation aspects. In: Abuzinada AH, Barth H-J, Krupp F, Böer B,

Abdessalaam TZ (eds) Protecting the Gulf's marine ecosystems from pollution. Birkhäuser Verlag, Switzerland
Brown G, Smithson J, Carminati S (2016) Biodiversity. In: TEC/DP: Dubai environment outlook 2015–2021. The Executive Council, Dubai, UAE
Caro T, Rowe Z, Berger J, Wholey P, Dobson A (2022) An inconvenient misconception: climate change is not the principal driver of biodiversity loss. Conserv Lett 15. https://doi.org/10.1111/conl.12868
Chaudhary SA (2010) Destructions of *Acacia* woodlands and *Juniper* forests in Asia and Eastern Africa. Pak J Bot 42:259–266
Deil U (1998) Coastal and sabkha vegetation. In: Ghazanfar SA, Fisher M (eds) Vegetation of the Arabian Peninsula. Springer, Dordrecht
Deil U, Müller-Hohenstein K (1996) An outline of the vegetation of Dubai (UAE). Verh Ges Ökologie 35:77–95
Dregne HE (1986) Desertification of arid lands. In: El-Baz F, Hassam MHA (eds) Physics of desertification. Martinus Nijhoff Publishers, Dordrecht
El-Keblawy A, Ksiksi T, El Aqamy H (2009) Camel grazing affects species diversity and community structure in the deserts of the UAE. J Arid Environ 73:347–354
European Commission DG Environment (2013) Interpretation manual of European Union habitats. EUR28
Feulner GR (2011) The flora of the Ru'us al-Jibal – the mountains of the Musandam Peninsula: an annotated checklist and selected observations. Tribulus 19:4–153
Feulner GR (2014) The olive highlands: a unique "Island" of biodiversity within the Hajar Mountains of The United Arab Emirates. Tribulus 22:9–34
Gallacher DJ (2007) Overgrazing their welcome. Zawaya 2007:30–33
Gallacher DJ, Hill JP (2006) Effects of camel grazing on the ecology of small perennial plants in the Dubai (UAE) inland desert. J Arid Environ 66:738–750
Gallacher DJ, Hill JP (2007) Effects of camel grazing on density and species diversity of seedling emergence in the Dubai (UAE) inland desert. J Arid Environ 72:853–860
Ghazanfar SA, Fisher M (eds) (1998) Vegetation of the Arabian Peninsula. Springer, Dordrecht
Jongbloed MVD, Feulner GR, Böer B, Western AR (2003) The comprehensive guide to the wild flowers of The United Arab Emirates. ERWDA, Abu Dhabi
Le Houérou HN (1996) Climate change, drought and desertification. J Arid Environ 34:133–185
Mandaville JP (1990) Flora of Eastern Saudi Arabia. Kegan Paul International, London
Mandaville JP Jr (1985) A botanical reconnaissance of the Musandam region of Oman. J Oman Stud 7:9–28
MOEW (2015) State of environment report United Arab Emirates 2015. Ministry of Environment and Water, Dubai
Noy-Meir I (1973) Desert ecosystems: environment and producers. Annu Rev Ecol Syst 4:25–51
Pauly D (1995) Anecdotes and the shifting base-line syndrome of fisheries. Trends Ecol Evol 10: 430
Richardson DM, Pysek P, Rejmanek M, Barbour MG, Panetta FD, West CJ (2000) Naturalization and invasion of alien plants: concepts and definitions. Divers Distrib 6:93–107
Roshier DA, Böer B, Osborne PE (1996) Vegetation of Abu Dhabi and a preliminary classification of its plant associations. In: Osborne, PE (ed) Desert ecology of Abu Dhabi Pisces publications
Saenger P, Blasco F, Auda Y, Aizpuru M, Youssef AM, Loughland RA (2004) Mangroves of The United Arab Emirates. In: Loughland RA, Al Muhairi FS, Fadel SS, Almehdi AM, Hellyer P (eds) Marine atlas of Abu Dhabi. Emirates Heritage Club, Abu Dhabi
Satchell JE (1978) Ecology and environment in The United Arab Emirates. J Arid Environ 1:201–226

Tourenq C, Launay F (2007) Challenges facing biodiversity in The United Arab Emirates. Manag Environ Qual 45:779–798

Vesey-Fitzgerald DF (1957) The vegetation of central and eastern Arabia. J Ecol 45:779–798

Walsh GE (1974) Mangroves: a review. In: Reimold RJ, Queen WH (eds) Ecology of halophytes. Academic Press, New York

Zohary M (1973) Geobotanical foundations of the Middle East. Gustav Fischer Verlag, Stuttgart

Chapter 6
The Mountain Regions of the United Arab Emirates: An Ecosystem Perspective

Gary R. Feulner

6.1 The Mountain Regions as an Ecosystem

6.1.1 Physical and Structural Parameters: A Mountain "Reef" in a "Sea" of Sand

The mountain regions of the United Arab Emirates (UAE) are introduced in Chap. 2 (Fig. 6.1). They are part of the chain of mountains stretching for more than 600 km along the Gulf of Oman coast of Arabia, from the Musandam peninsula almost to Ras Al Hadd at the easternmost tip. Peaks and ridges in most of the UAE are generally 900 m or less in height, but in the Ru′us Al Jibal (the mountains of the Musandam) a few UAE summits exceed 1500 m and UAE territory in the broad summit area of Jebel Jais (pronounced *Yais*) reaches almost 1900 m.

The UAE's mountain regions receive mean annual rainfall of ca. 160–190 mm (UAE University 1993; Feulner 2011) and are therefore routinely classified as arid overall, although not hyper-arid (see also Chap. 3). The amount of annual precipitation, however, is only a crude measure of the nature of the environment. From an ecosystem point of view, the mountain regions of the UAE can more usefully be understood by analogy to a coral reef in the ocean environment, but in this case the mountainous "reef" is bounded by a "sea" of sand.

Like a coral reef, the extreme physical and structural diversity of the mountain landscape creates a wealth of habitats and microhabitats, differentiated by substrate, elevation, geochemistry, humidity, wind, aspect, exposure, shelter, vegetation cover, the timing of precipitation in relation to vegetative stages, the ability of the substrate to retain moisture, and more. These individualized parameters can ameliorate the effects of overall aridity, and exploitation of the many alternative habitats by different organisms results in substantial floral and faunal diversity (Fig. 6.2).

G. R. Feulner (✉)
Dubai Natural History Group, Dubai, UAE

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_6

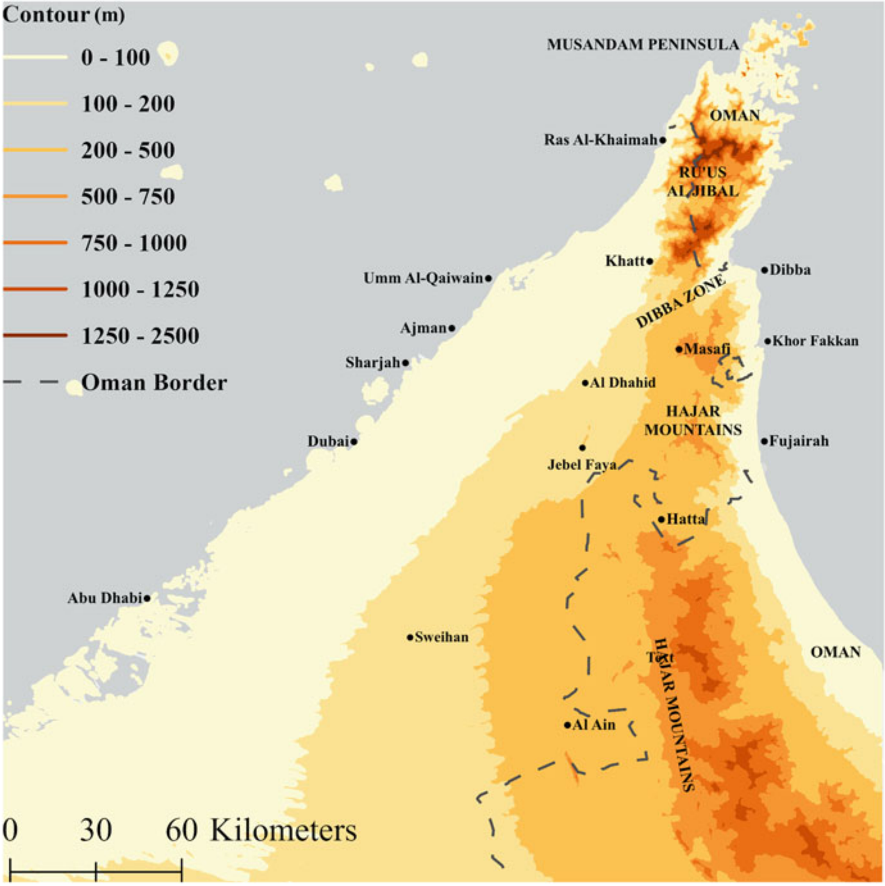


Fig. 6.1 A simplified geological map of the mountain areas of the UAE and northernmost Oman

Although the UAE's mountain regions occupy less than 5% of its surface area, it has routinely been estimated that they are home to more than 50% of its native plants and a comparable number of its animals, many of which are found only in the mountains. The final report of the September 2019 UAE Plant Red List workshop, conducted under the joint auspices of the UAE Ministry of Climate Change and Environment (MoCCE) and the International Union for the Conservation of Nature (IUCN), recognizes a total of 598 native plant species (Allen et al. 2021). Mountain plants are not separately identified in the final report, but somewhat more than 350 of the total (> 60%) are species found primarily or exclusively in mountain habitats.

The taxonomic nomenclature used for UAE flora in this chapter follows the lead of Chaps. 5 and 13 by adhering to the nomenclature used in Jongbloed et al. (2003), in order to allow non-specialist readers the opportunity to check plants in that widely-used book, available online. Exceptions are expressly noted in the text. In fact, although there have been considerable nomenclatural changes to the UAE flora as a whole over the intervening years, very few of the species mentioned in the text have been affected. Reference is made, however, to a small number of species not

Fig. 6.2 Wadi Mayy, Fujairah, after a "wet" winter season. Mountain areas of the UAE are home to some 60% of its native plants and probably a similar proportion of its animals. The number of plants and animals one can expect to see in a day is much greater in the mountain regions than in the sand deserts. Photo credit: Gary Feulner

included in Jongbloed et al. (2003) but only in subsequent works, particularly Feulner (2011).

6.1.2 Contributors to Biodiversity: Biogeographical Position, Endemism, Climate History

The UAE's privileged position at the junction of the three main Old World biogeographical regions (the Afrotropical, Palearctic and Oriental), and within the Eremic Zone (Larsen 1984) that today overlies that junction, makes an independent contribution to the biodiversity of the country (Fig. 6.3). The presence of Palearctic and Oriental floral and faunal elements is greatest in the mountain areas (Feulner et al. 2021). In terms more familiar to botanists, the mountain areas of the UAE are a meeting point for floral elements from the Saharo-Arabian, Nubo-Sindhian, Irano-Turanian and Mediterranean regions (Feulner 2011).

At the same time, the mountains of Eastern Arabia are sufficiently isolated from the mountains of Western Arabia, Dhofar and the Zagros that they have become an independent center of endemism. This has been recognized botanically (Ghazanfar 1999) but is best demonstrated by the reptile fauna. The UAE and Oman were long recognized to host two endemic lizard species (*Omanosaura cyanura* and *O. jayakari*), but early in the new millenium, a viper (Babocsay 2004), an agamid

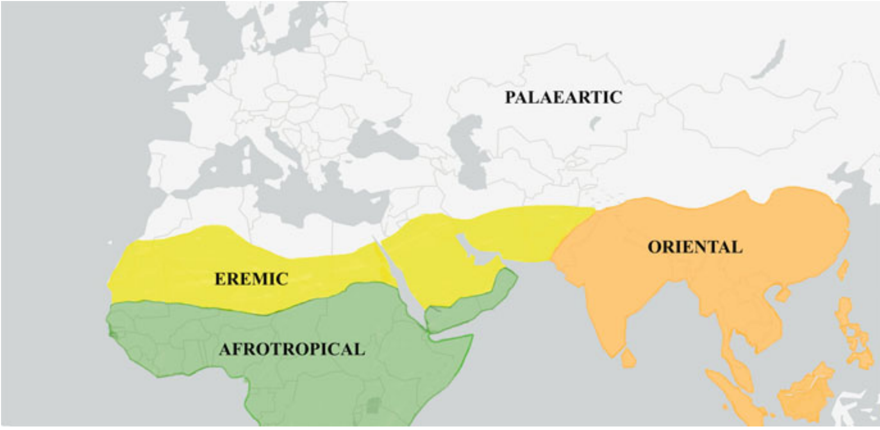


Fig. 6.3 The principal biogeographical regions of the Old World. Modified from Feulner et al. (2021) and reused with permission

(Melnikov et al. 2013) and a gecko (Nazarov et al. 2013) from the UAE/Oman mountains were segregated taxonomically from congeners (sister species) in Western Arabia and the Levant with whom they had previously been identified. More recently, "new" nocturnal geckos have been distinguished from cryptic counterparts within the UAE and Oman (Carranza et al. 2016; Simó-Riudalbas et al. 2017; Carranza et al. 2021). These newly defined species include two geckos limited to the mountains of the Musandam peninsula and a very restricted range gecko that has thereby become the UAE's only endemic vertebrate. The broader result is that 19 of the 28 reptile species that live in the mountains of the UAE and northern Oman are now considered endemic (Burriel-Carranza et al. 2022). Segregation of additional cryptic species among the UAE's diurnal geckos is anticipated from current work (Garcia-Porta et al. 2017, Burriel-Carranza et al. 2022). All this is discussed in more detail in Chap. 16.

The UAE is also home to at least one land snail endemic to the highest elevations in the UAE/Oman mountains (Feulner and Green 2003), a damselfly endemic to the dry wadis of the mountain interior (Feulner et al. 2007), and at least six of the larger but still somewhat speculative number of plant species endemic to the UAE/Oman mountains (Feulner 2016) (Fig. 6.4).

The mammalian fauna of the mountains is now dominated by feral goats. The native mammalian fauna is limited but includes a number of characteristic species such as Blanford's Fox *Vulpes cana*, Caracal *Caracal caracal schmitzi*, Brandt's Hedgehog *Paraechinus hypomelas*, Wagner's Gerbil *Gerbillus dasyurus*, Arabian Spiny Mouse *Acomys dimidiatus*, all relatively common, as well as the endemic Arabian Tahr *Arabitragus jayakari*, now threatened, and the Arabian Leopard *Panthera pardus nimr*, considered extinct in the UAE and northern Oman since early in the current millennium. See also Chap. 14.

Resident bird species include Chukar Partridge *Alectoris chukar* (effectively limited to the Ru′us Al Jibal), Sand Partridge *Ammoperdix heyi*, Rock Dove

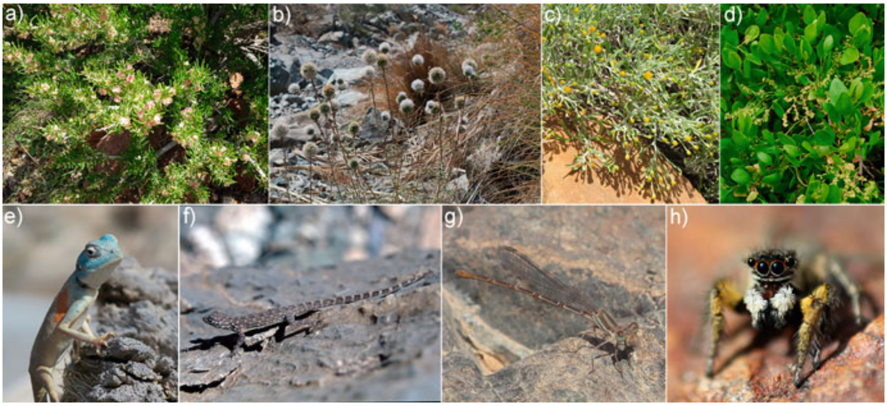


Fig. 6.4 Some UAE plants and animals endemic to the mountains of the UAE and northern Oman: (**a**) *Pteropyrum scoparium* (Polygonaceae), a woody shrub most common in harzburgite terrane; (**b**) *Echinops erinaceus* (Asteraceae), particularly common among scree accumulations; (**c**) *Pulicaria edmondsonii* (Asteraceae), common at medium elevations in both the Hajar Mountains and the Ru′us Al Jibal; (**d**) *Rumex limoniastrum* (Polygonaceae), very rare in both the UAE and Oman; (**e**) Hajar Rock Agama *Pseudotrapelus jensvindumi*, common, but only recently segregated from congeners in Dhofar and Western Arabia; (**f**) Bar-Tailed Semaphore Gecko *Pristurus celerrimus*. A primitive member of its genus, its tail signaling is less well developed than that of the *Pristurus rupestris* group (Feulner 2004); (**g**) Hajar Wadi Damselfly *Arabineura khalidi* (a female is shown here), widespread but easily overlooked; and (**h**) *Rafalus arabicus*, a common jumping spider, active on rocks even during the heat of the day (a male is shown here). Photo credits: Gary Feulner (a–g); Binish Roobas (h)

Columba livia, Laughing Dove (Palm Dove) *Spilopelia senegalensis*, White-Spectacled Bulbul *Pycnonotus xanthopygos*, Pale Crag Martin *Ptyonoprogne* (*fuligula*) *obsoleta*, Desert Lark *Ammomanes deserti*, Hume's Wheatear *Oenanthe albonigra*, Purple Sunbird *Cinnyris asiaticus*, Scrub Warbler *Scotocerca inquieta*, Long-Billed Pipit *Anthus similis*, Striolated Bunting *Emberiza striolata*, and several owl species. See also Chap. 15.

The temporal or historical dimension is another essential element for an understanding of the biodiversity and biogeography of the UAE. Together, the UAE's biogeographical position, its geographical position astride the Tropic of Cancer, mountain endemism, and the climatic oscillations of at least the past 500,000 years (Glennie 1991, 1996, 2001; Sanlaville 1992, 1998; Goodall 1994; Parton et al. 2015) and continuing into the Holocene (Parker 2009; Parker et al. 2004, 2016), have created a complex pattern of residual or relict populations, which survive in Arabia in refugia in the mountain regions. These include Palearctic species like the Wild Olive (*Olea europaea*), a native of Asia Minor and the Eastern Mediterranean; the White Edged Rock Brown (*Hipparchia parisatis*) and Loew's Blue (*Agrodiaetus loewi*) butterflies, native to Eurasian mountains (Larsen 1983, 1984; Feulner et al. 2021); and the Arabian Grizzled Skipper butterfly (*Spialia mangana*), whose recently discovered UAE and Oman populations are isolated outliers of a species today centered on Somalia (Feulner 2007; Feulner and Roobas 2014; Feulner et al. 2021) (Fig. 6.5).

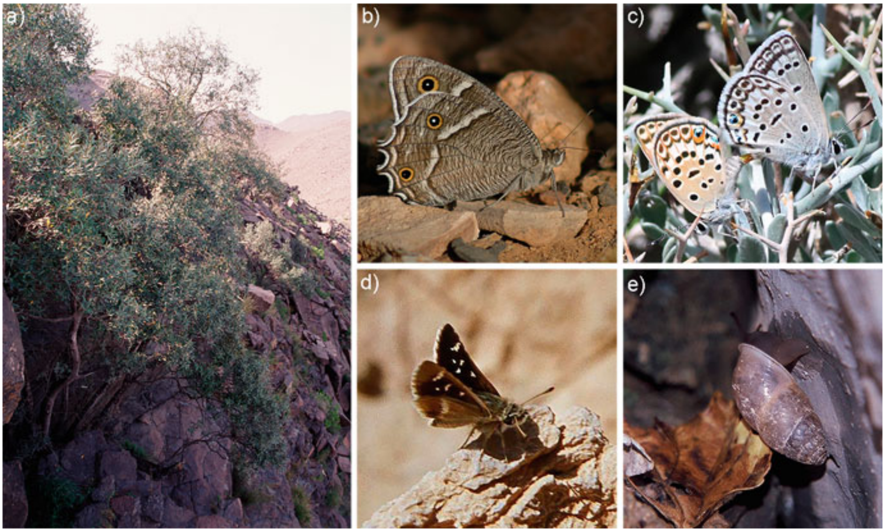


Fig. 6.5 Some UAE mountain plants and animals that are relict species, i.e., they were once more widespread at a time of more favorable climate, but have withdrawn to discrete pockets of congenial habitat in mountain areas: (**a**) Wild Olive *Olea europea*, shown here in the Olive Highlands southwest of Fujairah city. Wild Olives also occupy uninviting habitats in upper ravines along the spine of the Western Hajar from the Hatta area to the Jebel Akhdar, places where few botanists have ventured; (**b**) White Edged Rock Brown butterfly *Hipparchia parisatis*, a large Palearctic mountain species that still keeps its Palearctic schedule, even in the UAE (see text); (**c**) Loew's Blue butterfly *Agrodiaetus loewi*, a Palearctic species that is restricted in the UAE and Oman to intermediate elevations in the Ru′us Al Jibal, where its exclusive larval foodplant occurs, *Astragalus fasciculifolius* (Fabaceae); (**d**) Arabian Grizzled Skipper *Spialia mangana*. An isolated population of this sedentary butterfly was discovered in the Olive Highlands in 2013, in association with its presumed larval foodplant, *Melhania muricata* (Sterculiaceae) (see Fig. 6.19c); (**e**) *Mordania omanensis*, a 2 cm land snail endemic to the UAE and Oman mountains but found today only among bedrock cliffs at high elevation in the Ru′us Al Jibal and the Jebel Akhdar of Oman (Neubert 1998; Feulner and Green 2003). Photo credits: Gary Feulner (a,d,e); Oscar Campbell (b); Binish Roobas (c)

6.1.3 Constraints Common to all UAE Mountain Ecosystems: Unpredictable Rainfall, Poor Soil and Overgrazing

A number of distinctive sub-units of the UAE's mountain ecosystem are identified and briefly discussed below, but at the outset it is worth highlighting three limiting phenomena that are common to all of the mountain areas of the UAE, set against the general background of aridity.

The first is the unpredictability of rainfall. Most rain falls in the mountains between December and April and very little falls during summer and early autumn (Feulner 2006), although mountain front areas may experience scattered summer thunderstorms, especially southwards towards Al Ain. But while UAE rainfall patterns can be characterized statistically, that is not the same as seasonality. So it is important to emphasize that the UAE's statistical rainfall patterns are *not* highly reliable in terms of timing, and even less so in terms of amount. Rainfall in wet years can be more than five times the total in dry years (Feulner 2011) and much of the total annual precipitation can sometimes fall in one or a few rainfall events. And, despite occasional very "wet" years, e.g. the mid-1990s (1995–1998), long-term mean annual rainfall in mountain areas has been as described in Sect. 6.1.1 above (ca. 160–190 mm), so the "wet" years have ultimately been balanced by drought years, e.g. mid-1999 to mid-2003 (Feulner 2006). Rainfall variation for the UAE as a whole has been recognized to be periodic (Jongbloed et al. 2003; Feulner 2006) and appears to be related to the multi-year El Niño phenomenon (Emirates Wildlife Society-WWF 2006; Tourenq et al. 2011). The significance from an ecosystem perspective is that the terrestrial flora and fauna must be prepared to accommodate themselves to these relatively demanding conditions, and to survive the lean years.

The combination of extreme summer temperatures, low annual rainfall, and the unpredictability of rainfall pose challenges for the native flora and fauna of the UAE. Those same factors may, however, help to explain why, although developed and agricultural areas of the modern UAE are today home to countless species of exotic plants and animals, both invited and uninvited, very few of those introduced species have made significant inroads or had significant impacts in natural areas of the mainland UAE.

A second limitation is that soil is seldom developed to any significant extent, except in isolated pockets, or where specifically engineered for agriculture (Fig. 6.6), or (in recent decades) where floodwaters have deposited silt behind dams, in environments exposed to intermittent catastrophic events (see Sect. 6.3.2 Temporal Gradients, below).

Third, essentially all mountain areas of the UAE are heavily impacted by overgrazing, which has increased with growing affluence and has not been effectively controlled by legislation or cultural practices. The principal effects of overgrazing are the reduction of vegetative cover overall, the elimination of palatable herbs and shrubs, and the prevention of regeneration by large trees species. Thus the mix of species that we see in the UAE's mountains today may not closely resemble what was present even just two or three generations ago. The main culprits are feral and domestic goats, which can negotiate all but the most difficult terrain (Fig. 6.7). Camels are increasingly present in mountain wadis that are accessible by vehicle. Feral donkeys are also present in the mountains, but their numbers are small and they are generally limited to family groups of two to four animals, except on the fringes of human settlement. In wild areas they favor wadis, terraces and plains but they can also be found on slopes, except the treacherous middle and upper slopes of harzburgite areas. In popular discourse, donkeys seem to receive a disproportionate share of the blame for overgrazing, perhaps because they no longer have a human constituency with a vested economic interest in defending them. It can be argued that the population of feral grazers is at or near carrying capacity, since die-offs can be seen in times of severe drought, e.g., the turn-of-the-century drought from mid-1999 to mid-2003 (see Feulner 2006).

Fig. 6.6 A locally rare, edible fern *Ophioglossum polyphyllum* (**a**), usually associated with traditional agriculture, was discovered not far above the Wadi Wurayah waterfall, in (**b**) silty soil on a terrace that still shows the remains of a series of small cultivated plots along it. The downstream direction is towards the observer. Photo credits: Gary Feulner

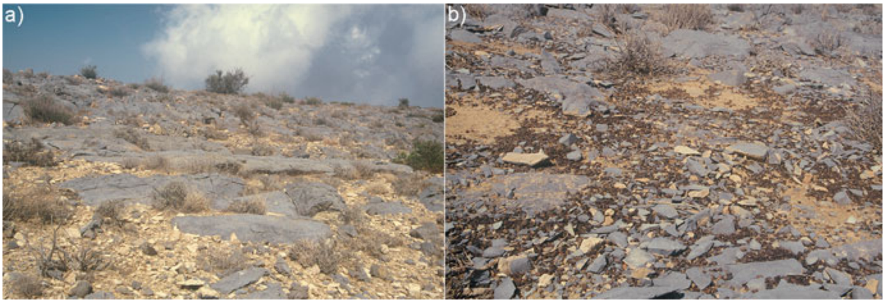


Fig. 6.7 Overgrazing in the mountain environment: (**a**) The barren summit of Ras Mintera (1800+ m), the third highest in the Ru′us Al Jibal, just a few kilometers north of Jebel Harim and far from any settlement. (**b**) A close-up reveals thousands of goat droppings that help to explain the state of the vegetation. Photo credits: Gary Feulner

6.2 The Principal UAE Mountain Ecosystems

Chapter 2 introduced the main geographical divisions of the UAE Mountains:

(a) the Hajar Mountains, comprising almost all of the mountain areas of the UAE to the south of the Musandam peninsula.
(b) the Ru′us Al Jibal in the north, occupying the Musandam peninsula.
(c) the Dibba Zone, which separates the Ru′us Al Jibal and the Hajar Mountains.
(d) the Foreland Ridges, a broken line of rocky hills and ridges west of the main mountain front, e.g., Jebel Hafeet near Al Ain and Jebel Faya and others, south of Dhaid.
(e) the Alluvial Plains which flank the mountains to the east and west, representing the product of erosion of the mountains over time.

These geographical units and a number of their specialized geological and ecological sub-units are discussed below from an ecosystem perspective.

6.2.1 The Hajar Mountains

The Hajar Mountains account for about 85% of the mountain areas of the UAE. They consist mostly of the brown-weathering igneous rocks of the UAE/Oman ophiolite, originally a thick slab of oceanic crust and uppermost mantle. Their topography is generally rugged and steep, but low foothills along the west flank can be deeply weathered. Exposed bedrock slopes are typically barren, with vegetation concentrated in wadis, wadi banks, terraces, slope rubble, lower slopes and gullies, especially of higher order tributaries. Main channels often appear to be swept clean of vegetation by occasional floods, but smaller tributaries can be relatively rich in life.

6.2.1.1 Hajar Mountain Wadis: Some General Considerations

Although vegetation cover is often conspicuously low in major wadi beds, they are nevertheless host to a large number of species overall (Brown and Sakkir 2004). The typical substrate of lower mountain wadis includes a substantial size range of coarse rocks and pebbles, with gravels and sands also locally present. The combination of different types of substrate, pronounced spatial heterogeneity in microtopography and microclimate, light availability, and regular access to water creates a patchwork of favorable microhabitats, making these environments floristically extremely rich overall.

Wadi beds are also highly dynamic habitats, not only in terms of their physical characteristics, but in terms of their floristic composition as well. This is primarily due to occasional rainfall events causing temporary inundation and rarer 'catastrophic' events causing severe flooding (Fig. 6.8). Many species can be decimated during torrents, but at the same time, new seeds are transported with the water and deposited in favourable microhabitats (Brown and Sakkir 2004).

It is certainly true that the same wadi can present very different appearances, both physically and floristically, depending on the recent history of rainfall and flooding, and on the season when the wadi is visited. Even some of the most abundant, colourful and conspicuous annual species, such as the mountain dock *Rumex vesicarius* (Polygonaceae) (Fig. 6.9h), may be all but undetectable during much of the year. In dry years many annuals may be absent altogether and many perennial species may be largely dormant.

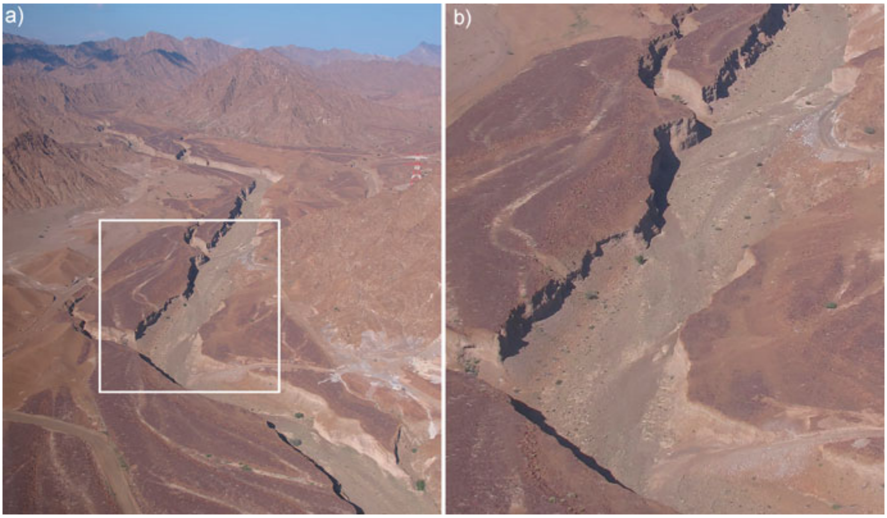


Fig. 6.8 In its lower reaches, the main northerly tributary of Wadi Wurayah (**a**) is broad and straight with a bed of coarse boulders, but closer inspection (**b**, inset) shows that small trees and shrubs nevertheless colonize the sloping wadi banks. Note that the present day wadi is carved into the center of a much broader historical valley filled with 10 m or more of coarse gravel, evidencing one or more earlier eras of more intense erosion. Photo credits: Gary Feulner

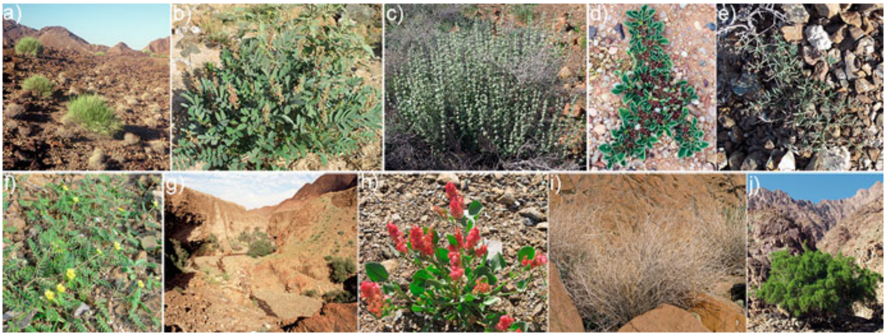


Fig. 6.9 Some common and widespread plant species of the Hajar Mountains of the UAE: (**a**) Mountain Spurge *Euphorbia larica* (Euphorbiaceae), one of the first shrubs to be refreshed after rain. (**b**) *Tephrosia apollinea* (Fabaceae), untouched by quadrupeds. (**c**) *Leucas inflata* (Lamiaceae), recognizable by its regular geometry. (**d**) *Aizoon canariense* (Aizoaceae), widespread throughout the Eremic zone, but uncommon in the Ru′us Al Jibal. (**e**) Prostrate, spiny *Fagonia bruguieri* (Zygophyllaceae). (**f**) *Tribulus terrestris* (Zygophyllaceae), a widespread Afro-Asian species. (**g**) Wadi Fig *Ficus salicifolia* (Moraceae). (**h**) Mountain Dock *Rumex vesicarius* (Polygonaceae). (**i**) *Ochradenus aucheri* (Resedaeae), with leafless, whip-like stems. (**j**) Sidr tree *Ziziphus spina-christi* (Rhamnaceae), a magnificent specimen along the middle reaches of Wadi Wurayah. Photo credits: Gary Feulner

6.2.1.2 Floral Elements Common to Hajar Mountain Habitats Generally

A number of plant species are common throughout the Hajar Mountains (and the mountains of the UAE generally) and occur in all or most of the ecological sub-units discussed here. These include Mountain Spurge *Euphorbia larica* (Euphorbiaceae), Umbrella Thorn *Acacia tortilis* (Fabaceae) and the geometric mint *Leucas inflata* (Lamiaceae) on slopes; the unpalatable legume *Tephrosia apollinea* (Fabaceae), which often predominates on wadi banks and in gullies at low and medium elevations; the prostrates *Aizoon canariense* (Aizoaceae), *Fagonia bruguieri* (Zygophyllaceae) and *Tribulus terrestris* (Zygophyllaceae) on terraces; and the Wadi Fig *Ficus salicifolia* (Moraceae), Mountain Dock *Rumex vesicarius* (Polygonaceae), the whip-like *Ochradenus aucheri* (Resedaceae) and the Sidr tree *Ziziphus spina-christi* (Rhamnaceae) along wadis (Fig. 6.9).

The foundational introductory account by Western (1989) accurately characterized the flora of the UAE mountains as a whole, except at the highest elevations, as a *Euphorbia larica—Tephrosia apollinea* association.

Most of the foregoing species are also regionally widespread. Nevertheless, even these common and widespread species are not uniformly distributed. Field work in the mountains of the UAE is arduous and quantitative comparison studies are non-existent, but wide-ranging qualitative investigations over many years confirm the expected result, that the mix of plant species present varies significantly among the different ecological units discussed here, most of which are based on geology (see, e.g., Feulner 1997, 1999b, 2011, 2014, 2016; Jongbloed et al. 2003; El-Keblawy 2011; El-Keblawy et al. 2016).

The following sections briefly introduce the most important ecological sub-units of the Hajar Mountains.

6.2.1.3 Harzburgite Terrane

“Terrane” is a geological term that denotes an extensive and more or less contiguous body or area of rock(s) of similar kind, origin and/or history. The term is used to contrast such a body with differing rocks to which it is juxtaposed or by which it may be surrounded in whole or in part. The boundaries of a terrane are normally tectonic, i.e., faulted. In the present discussion “terrane” is used principally to characterize, collectively, the many areas of (1) ultrabasic harzburgite and (2) gabbro, both belonging to the ophiolite suite of rocks, and (3) the carbonate sedimentary rocks of the Ru′us Al Jibal.

Within the boundaries of the UAE, harzburgite (ultrabasic) bedrock is found primarily (i) in the Shimayliyah range of the East Coast; (ii) along the west flank of the mountains from Al Ghayl southwards, and especially from Wadi Shawkah south to Wadi Baraq (where the Oman border intervenes); and (iii) in the Hatta enclave of Dubai Emirate, including Jebel Hatta (see Chap. 2).

Fig. 6.10 This view in upper Wadi Zikt is typical of the harzburgite terrane of Shimayliyah: deeply incised wadis, thick gravel terraces and steep, rocky, rubble-covered slopes. Photo credit: Gary Feulner

6.2.1.3.1 The Shimayliyah Range

The rugged mountains of the Shimayliyah range, situated between the Gulf of Oman coast and the Dibba-Masafi-Fujairah roads, are composed almost entirely of harzburgite, representing a slice of the earth's uppermost mantle. This area includes all of Wadi Wurayah National Park (Wadi Wurayah and Wadi Zikt) and the relatively low, hilly region immediately south and west of Dibba Fujairah, as well as most of Wadi Madha and Wadi Shis, Wadi Shi, Wadi Safad, Wadi Deftah, uppermost Wadi Siji and uppermost Wadi Abadilah. The topography is typically very steep and rugged, generally culminating in narrow, rocky ridgetops (Fig. 6.10). Harzburgite weathers readily at the earth's surface and slopes are often littered with small, weathered chips, making ascents treacherous. Open slopes are poorly vegetated but along main wadis in harzburgite, gravel terraces ca. 10 m high are often well developed. Gullies on the rocky slopes and the boundary zone between lower slopes and gravel terraces are favored sites for plant growth (Fig. 6.11).

6.2.1.3.2 Ultrabasic Rocks and Botanical Diversity and Endemism

The extensive areas of harzburgite bedrock within the Hajar mountains present a challenging environment for most plants. Harzburgite has an unusual chemistry for

Fig. 6.11 Some characteristic plant species of harzburgite wadis, terraces and slopes: (**a**) *Convolvulus virgatus* (Convolvulaceae), a very common species in ultrabasic terrane. (**b**) Drumstick tree *Moringa peregrina* (Moringaceae). (**c**) *Gypsophila bellidifolia* (Caryophyllaceae), a diminutive wadi bed annual believed to favor ultrabasic terrane. (**d**) *Salvia macilenta* (Lamiaceae), a woody, perennial mint also believed to favor ultrabasic terrane. Photo credits: Gary Feulner

surface rocks, being very low in silica (SiO_2), calcium and aluminum, and very high in magnesium, iron and the heavy metals nickel, chromium and cobalt (Moores 2011; Kay et al. 2011). Geologists call this suite of chemical characteristics "ultrabasic" (or "ultramafic"). Soils in ultrabasic rocks are usually poorly developed, standard nutrients are scarce, the high magnesium levels interfere with uptake of calcium, and the heavy metals are toxic to many plants (Harrison and Kruckeberg 2008).

Groundwater percolating slowly in harzburgite bedrock reacts with the rock to become, over time, hyperalkaline (Moores 2011), with a long-term equilibrium pH in excess of 11 (Emirates Wildlife Society – WWF 2006). In places where such groundwater is reintroduced to surface water, it reacts immediately with atmospheric carbon dioxide (CO_2) to precipitate a surface film of calcium carbonate ($CaCO_3$). This creates the distinctive "white pools" sometimes seen in harzburgite areas, although that phenomenon is more common in the mountains to the south of the Madam-Hatta road, an area no longer readily accessible from the UAE.

Large ultrabasic terranes elsewhere in the world (e.g. in California, Cuba and New Caledonia) are well known for their low botanical diversity but also high endemism (Harrison and Kruckeberg 2008; Anacker 2011). Generally accepted information for six of the larger such areas globally puts their total number of "serpentine endemics" at from tens to many hundreds of species (Anacker 2011). This potential relationship between ultrabasic geochemistry, biodiversity and endemism has been all but totally ignored by botanists working in the mountains of the UAE and Oman, although it has sometimes been tacitly accepted as a generalization by local naturalists that the ophiolite terrane exhibits reduced plant diversity compared to other mountain environments (e.g., Munton 1985; Insall 1999). However, even those seemingly direct comparisons of ophiolite or ultrabasic terrane with, e.g., the Ru′us Al-Jibal or the (much better studied) Jebel Akhdar must be assessed critically, as they may often warrant adjustment for factors such as elevation, rainfall amount and timing, and human influence (Munton 1985).

The one UAE study that expressly considered the possible role of ultrabasic geochemistry on plant distribution (Feulner 2016) did not find reduced plant diversity in a large ultrabasic (harzburgite) area (Wadi Wurayah National Park, where more than 200 species were recorded) in comparison with a nearby large basic (gabbro) drainage area (Wadi Hiluw) (based on El-Keblawy (2011) as supplemented by the author's records). In comparison with the carbonate sedimentary rocks of the Ru′us Al Jibal range at comparable elevations, floral diversity in WWNP was reduced, but not greatly reduced.

To date, no UAE or Oman plant species have been confirmed to be restricted to the extensive ultrabasic terrane of the UAE/Oman mountains, best represented in the Western Hajar (the UAE and northernmost Oman). Some candidate species exist (see Sect. 6.2.1.3.3) but they are few in number and the burden of convincingly proving a negative by overland field work is formidable. In light of the oft-repeated findings of high plant endemism in large ultrabasic terranes (and especially serpentine/serpentinite) elsewhere, it is reasonable to ask why the UAE's ultrabasic rocks, being part of the world's largest such exposure, do *not* seem to exhibit similar botanical anomalies.

A possible explanation may lie in the fact that the ultrabasic terrane studied in the UAE, i.e., Wadi Wurayah, Wadi Zikt and surrounding areas in the Shimayliyah range (Feulner 2016), consists of relatively fresh, unaltered harzburgite, whereas the ultrabasic terranes studied elsewhere (see Anacker 2011) were more thoroughly altered to serpentine, often becoming effectively serpentinite, therefore more like the ophiolite exposures along the west flank of the Hajar Mountains in the UAE (see Sect. 6.2.1.3.4 below). However, this explanation remains speculative, as does the chemistry and plant physiology that might support it. Other explanations might lie in biogeographical history, including factors such as insularity.

An alternative possibility is that ultrabasic endemics are present within the Hajar Mountain flora but are sufficiently cryptic that they have not yet been distinguished by field work from their non-endemic congeners. The author has considered the possibility that bedrock geology, and ultrabasic endemism specifically, might account for the distribution of the three very similar *Geranium* species found in the UAE and Oman (*G. biuncinatum*, *G. mascatense*, and *G. trilophum*) but preliminary field work does not support that hypothesis.

A practical problem in this regard is that very few botanical investigators have worked in the mountain areas of the UAE or northern Oman, except in the carbonate rocks of the Jebel Akhdar, and almost none have indicated any sensitivity to the geological distinctions within the ophiolite rocks. The Western Hajar extends for more than 250 km to the northwest of the Jebel Akhdar, to the UAE border at Kalba and beyond, encompassing many very large wadis draining the mountains. Along the Batinah coast, these include, *inter alia*, Wadi Hawasina, Wadi Bani Umar, Wadi Shafan, Wadi Sarami, Wadi ‘Ahin, Wadi Hilti, Wadi Jizzi and its upper tributaries, Wadi Bani Umar Al Gharbi, Wadi Fizh, Wadi Dab’ayn, Wadi Ragmi and Wadi Fayd. The majority of this vast area consists of ultrabasic terrane, yet the whole area has been all but completely ignored by Muscat-based naturalists, botanists and zoologists alike.

In the segment of the Western Hajar to the north of Al Khabourah and Wadi Hawasina, Oman, and continuing into the UAE, the less complicated geology makes it relatively easy to estimate the area of exposure of ultrabasic rocks by reference to the seminal geological map by Glennie et al. (1974). In that truncated segment, which amounts to a little more than half the ultrabasic terrane of the UAE/Oman mountains as a whole, a conservative minimum estimate of the area of the harzburgite bedrock is 4500 km^2—sufficient to offer ample scope for discovery.

6.2.1.3.3 Some Candidate Species for Ultrabasic Sensitivity

Notwithstanding the foregoing generalizations, field work over many years permits the conclusion that at least a small number of UAE mountain plants “avoid” the ultrabasic harzburgite, presumably because they cannot deal with its extreme geochemistry (Feulner 2016). These include the Hanging Caper *Capparis cartilaginea* (a very conspicuous species which avoids the ophiolite rocks altogether, including both harzburgite and gabbro) (Fig. 6.12a); the Desert Thorn *Lycium shawii* (Solanaceae) (Fig. 6.12b); and the small, bristly borage *Echiochilon persicum* (Boraginaceae). The prevalence of several other UAE plant species appears to differ significantly between harzburgite substrate and gabbro and/or carbonate substrate (Feulner 2016). Feulner (2011) highlighted a dozen common Hajar Mountain species that were absent or rare in the Ru′us Al Jibal. On the other hand, and perhaps not surprisingly, at least a few UAE species seem to “prefer” the harzburgite, among them the UAE/Oman endemic shrub *Pteropyrum scoparium* (Polygonaceae) (see Fig. 6.4a), the woody mint *Salvia macilenta* (Lamiaceae) (Fig. 6.11d), and the diminutive wadi bed annual *Gypsophila bellidifolia* (Caryophyllaceae) (Fig. 6.11c) (Feulner 2016).

Another UAE endemic, *Lindenbergia arabica* (Fig. 6.12c), appears to favor harzburgite terrane, but perhaps for edaphic (i.e., soil or substrate-related) reasons as much as geochemical ones. It is typically found perched near the bottom of the vertical walls of the thick gravel terraces that line many wadis in the harzburgite, and is presumably specialized to exploit groundwater flowing slowly downward through the ultrabasic terrace gravels.

Fig. 6.12 A number of UAE plant species appear sensitive to the unusual chemistry of the extensive ophiolite rocks of the Hajar Mountains: (**a**) The Hanging Caper *Capparis cartilagenia* is absent from areas of ophiolite rocks. (**b**) The Desert Thorn *Lycium shawii* (center foreground) avoids areas of the ultrabasic rock harzburgite, but thrives on gabbro terrane. However, because it is highly palatable to livestock, most larger plants have grown up in the shelter of other trees, usually *Acacia* or *Ziziphus*, as here. The roots of the specimen shown have also been parasitized by a broomrape, *Orobanche cernua*. (**c**) The UAE/Oman endemic *Lindenbergia arabica* (Scrophulariaceae) is found almost exclusively on the vertical walls of the thick gravel terraces that form in areas of harzburgite bedrock. Photo credits: Gary Feulner

6.2.1.3.4 The Western Foothills

Harzburgite bedrock is also present along much of the westernmost edge of the Hajar Mountains in the UAE from Al Ghayl southwards, where it forms low hills and ridges among broad wadis debouching onto the plains. There the harzburgite is often pervasively altered by hydration to a platy mineral called serpentine, and/or heavily veined with white and green veins of serpentine, chlorite and other minerals, and fractured on a fine scale, so that the rock can sometimes be picked apart by hand (Fig. 6.13). This deeply weathered harzburgite (or serpentinite, as the pervasively altered rock is called) is a very poor substrate for plant growth, although plants may grow in the wadis and in the outwash gravels that inter-finger with the bedrock ridges and constitute an extension of the Alluvial Plains ecosystem.

The western foothills, including the western margins of the gabbro interior, have been enormously disrupted by quarrying of both rock and gravel; by road building, dams, pipelines and power lines; by overgrazing and the expansion of farms; and by groundwater extraction. In places the former land surface has been lowered by 2 m or more. Thus it is difficult to know exactly what the vegetation of these areas may have looked like before the modern era.

Nevertheless, there remain present in these foothill regions, but not in the UAE mountains generally, distinctive species such as Leptien's Spiny-Tailed Lizard (Arabic: *dhub*) *Uromastyx aegyptia leptieni* and Bosc's Fringe-Toed Lizard *Acanthodactylus boskianus*, found here near the southeasternmost extent of its global range (Fig. 6.14); and the Dwarf Palm *Nannorrhops ritchieana*, here at the northwesternmost extent of its global range (Fig. 6.15). The prostrate *Schweinfurthia imbricata*, a UAE/Oman endemic, is also found in this area.

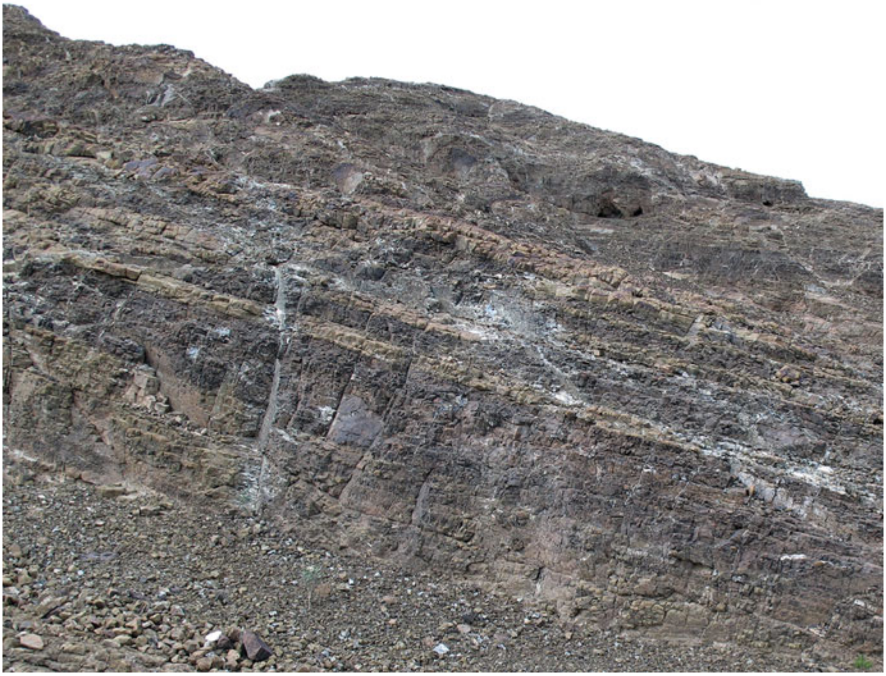


Fig. 6.13 Harzburgite bedrock exposed in the foothills along the west flank of the Hajar Mountains, near the base of the ophiolite slab, is often pervasively veined, foliated, fractured and altered to serpentine. It is sometimes mapped only as serpentinite. Photo credit: Gary Feulner

6.2.1.4 Gabbro Terranes

Gabbro rocks, part of the ophiolite suite of rocks and mostly representing former oceanic crust (Fig. 6.16), occupy much of the center and southeast of the Hajar Mountains in the UAE, south of the Dhaid-Masafi-Fujairah road (see Chap. 2). This includes, for example, all of Wadi Hiluw, upper Wadi Ashwani, upper Wadi Asfani (Wadi Baqarah), Wadi Sfai, Wadi Mayy, and lower Wadi Safad.

Topography in the gabbro terrane is rugged, as for the harzburgite, but weathering is less pervasive and fracturing is more blocky, resulting in somewhat more navigable, less precipitous terrain (Fig. 6.17). Gabbro chemistry is also more typical of surface rocks, equivalent to that of basalt produced by many oceanic and other volcanoes. As a result, gabbro areas are home to almost the full range of Hajar Mountain plant species (Fig. 6.18), including most of the species identified above that demonstrably avoid ultrabasic bedrock, as well as a number of species not yet recorded in the ultrabasic rock but which are too uncommon and/or too much restricted to higher elevations to allow us to insist that they are ultrabasic avoiders; examples of the latter include *Fagonia schimperi* (Zygophyllaceae) and the Mountain Mallow *Abutilon fruticosum* (Malvaceae).

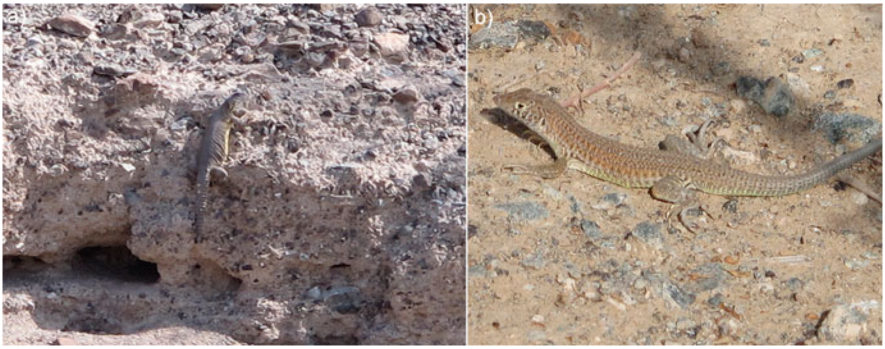


Fig. 6.14 The foothills in the southwest of the UAE mountain areas, including both harzburgite and gabbro bedrock, are home to two rare reptiles threatened by habitat destruction and overgrazing: (**a**) Small foothills populations of Leptien's Spiny-Tailed Lizard (or Dhub) *Uromastyx aegyptia leptieni* between Siji and Asfani are surrounded by an increasing number of livestock farms which decimate the local vegetation on which the dhubs depend, and they have lost habitat to routes for two major highways and a pipeline. Not surprisingly, their numbers appear to have declined. (**b**) Bosc's Fringe-Toed Lizard *Acanthodactylus boskianus* (female shown here) has not been recorded in recent years from sites on the alluvial plains, but has been discovered in two wadi environments that have been largely sidelined by development, where they seem to be able to tolerate a limited level of picnicking and agricultural activity in their immediate vicinity (Roobas and Feulner 2013; Roobas et al. 2014). Photo credits: Gary Feulner

In particular, an area of 1000 m gabbro ridges southwest of Fujairah City, that has been called the Olive Highlands, is home to a number of noteworthy plant and animal species not recorded in the harzburgite (Feulner 2014). They include, among others (see Fig. 6.19), *Ehretia obtusifolia* (Boraginaceae) and *Grewia tenax* (Tiliaceae), both edible large shrubs/small trees found most often where they are protected from grazing by terrain or by other vegetation; *Melhania muricata* (Malvaceae, formerly Sterculiaceae), the presumptive larval foodplant of a butterfly that lives in the highlands (the Arabian Grizzled Skipper *Spialia mangana*) and is a relict species itself; and most notably the wild olive tree *Olea europaea* (Oleaceae), which survives there in part because the northeast-facing cliffs of the Olive Highlands trap moist air from the Indian Ocean and promote enhanced fog and precipitation (Fig. 6.20). It was also in the Olive Highlands that the Persian Horned Viper *Pseudocerastes persicus* (Fig. 6.19d) was first recorded from the Hajar Mountains of the UAE, although its discovery spurred further investigation and it has since been found more widely (see Chap. 16).

6.2.1.5 Metamorphic Terranes

Within the ophiolite rocks north of the Dhaid-Masafi-Fujairah road, two geological "windows" expose pale colored metamorphic rocks that lie structurally beneath the ophiolite. One window is centered on the Asimah-Tayyibah area (Fig. 6.21), the

Fig. 6.15 The Dwarf Palm *Nanorrhops ritchieana* can be found in all of the wadis in the southwest of the UAE's mountain areas, but these mark the northern limit of its Arabian range. Photo credit: Gary Feulner

other on Wadi Shis, in the upper reaches of the large Wadi Madha drainage. The rocks exposed in the windows were originally sedimentary rocks deposited on the edge of Eastern Arabia, but they were later metamorphosed by heat and pressure when subduction carried them under the advancing ophiolite. The metamorphic rocks are not only paler than the ophiolite and recrystallized from their original condition; they also typically show signs of internal contortion (Fig. 6.22).

More importantly from an ecological perspective, the metamorphic rocks are geochemically very different from the ophiolite rocks: they are much richer in silica (SiO_2), calcium and aluminum and more like "average" continental rocks globally. It should not be surprising, therefore, that the metamorphic windows have been found to be home to at least a few plant species that are either unknown or rare elsewhere in the UAE. These include the delicate but ornate *Commicarpus stenocarpus* (Nyctaginaceae), which is so far known only from the metamorphic rocks; *Chaenorrhinum rubrifolium* (Scrophulariaceae), whose range extends south to Masafi; *Hyoscyamus muticus* (Solanaceae), a large-leafed henbane that is rare outside the Asimah-Tayyibah window; and *Lactuca orientalis* (Asteraceae), a brittle, spiky dwarf shrub with rectilinear architecture and peeling green stems (Fig. 6.23).

Dianthus crinitus (Caryophyllaceae), one of the UAE's showier native flowers, is found at relatively low elevation in the metamorphic rocks around Tayyibah,

Fig. 6.16 Gabbro bedrock in Wadi Sfai. The gabbro that formed part of the oceanic crust is typically layered, with alternating bands of light (plagioclase) and dark (olivine) minerals. Gabbro often weathers in a blocky fashion. Photo credit: Gary Feulner

Fig. 6.17 Summit ridges in gabbro are somewhat less forbidding than those in harzburgite, and the slopes are more hospitable to vegetation. Shown here is Jebel Qitab in the Olive Highlands. The lower slopes are shown in Fig. 6.2, above. Photo credit: Gary Feulner

whereas it is otherwise known primarily from higher elevations in the Ru′us Al Jibal. Within the ophiolite terrane (harzburgite and gabbro), *D. crinitus* is known only from a pair of plants recorded in the harzburgite of Wadi Wurayah, but the specific

Fig. 6.18 Some distinctive plant species of Hajar Mountain wadis, terraces and lower slopes. All except *Fagonia indica* are more or less equally common in harzburgite and gabbro terrane: (**a**) *Pulicaria glutinosa* (Asteraceae), very common on wadi banks and gravel terraces among the foothills. The dried bracts typically persist on the plant after the flowers have bloomed. (**b**) *Fagonia indica* (Zygophyllaceae), an erect shrub, yellow-green and usually bushy. All UAE *Fagonia* have four radiating spines at nodes along the stems. (**c**) *Physorrhynchus chamaerapistrum* (Brassicaceae), seen here growing profusely in silt behind a dam in Wadi Mayy. (**d**) *Cleome noeana* (Capparaceae), distinctively aromatic, often found as isolated specimens iin barren wadi gravel. (**e**) *Boerhavia elegans* (Nyctaginaceae) graces the landscape mostly in 'wet' years. (**f**) *Heliotropium calcareum* (Boraginaeae), the Octopus Heliotrope, most common on gravel terraces. (**g**) *Haplophyllum tuberculatum* (Rutaceae), another strongly aromatic species, the larval foodplant for the Common Swallowtail butterfly. Photo credits: Gary Feulner

site was within the weathered debris of one of a swarm of conspicuous white, granitic dikes that intrude the mountains overlooking the East Coast, so it may well be that *D. crinitus*, too, is sensitive to the bedrock geology of the substrate.

It is reasonable to suppose more generally that the less extreme geochemistry of the metamorphic rocks contributes to the success of the flourishing traditional agriculture within both of the geological windows. Unfortunately the native flora of most of the metamorphic areas has today been degraded or destroyed by the combination of extensive cultivation and overgrazing by domestic goats, except perhaps on the very steepest slopes above Wadi Shis.

6.2.1.6 Freshwater Bodies: Ponds, Pools, Streams and Seeps

6.2.1.6.1 Wadi Hydrology

Most of the rain that falls in the Hajar Mountains and is not carried off as floodwater is quickly concentrated in the coarse gravel wadi beds, where it flows within the interstitial pore space. At intervals along the wadi, where the gravel fill has been scoured or the bedrock has created an obstacle, small ponds or pools may form, sometimes connected by shallow streams that flow for tens or hundreds of meters

Fig. 6.19 Two distinctive residents of the Olive Highlands have been illustrated above, the Wild Olive *Olea europaea*, and the Arabian Grizzled Skipper butterfly *Spialia mangana* (see Fig. 6.5 a and d, respectively). Some other plant and animal species that distinguish the Olive Highlands include: (**a**) *Ehretia obtusifolia*, a large but often drooping shrub, is typically found in the shelter of Wild Olive trees or ledges; it is not found elsewhere in the UAE. (**b**) *Grewia tenax*, a rare and palatable large shrub / small tree that favors relatively mesic conditions and cliffs or ledges where it is protected from browsing quadrupeds. See also Fig. 6.38. (**c**) *Melhania muricata*, the probable larval foodplant of the relict Arabian Grizzled Skipper butterfly. (**d**) The Persian Horned Viper *Pseudocerastes persicus*, once thought to be very rare in the Hajar Mountains. This snake uses the tip of its tail as a lure to attract prey. Photo credit: Gary Feulner (a–c); Binish Roobas (d)

(Fig. 6.24; see Chap. 2). Some ponds, pools and stream reaches may be permanent but more often they are temporary.

These surface waters create a unique habitat within the context of arid Eastern Arabia: a home for aquatic organisms—a category that includes not only strictly aquatic organisms like fish, freshwater snails, flatworms and freshwater leeches, but also amphibious invertebrates such as diving beetles, water scorpions and the aquatic larvae of those and many other flying insects that breed in freshwater bodies, like dragonflies and damselflies, mosquitoes, caddisflies, craneflies and midges, as well as algae and higher plants (Fig. 6.25).

Fig. 6.20 The northeast-facing cliffs of the Olive Highlands trap moist air from the Indian Ocean and create increased fog and precipitation that support a high elevation "island" of biodiversity. Photo credit: Gary Feulner

Fig. 6.21 A panoramic view of the pale metamorphic rocks in the Asimah-Tayyibah area. Photo credit: Gary Feulner

Fig. 6.22 The metamorphic rocks exposed in the geological window at Wadi Shis often show internal contortion. They were deformed and recrystallized at depth when they were subducted under the advancing ophiolite. Photo credit: Gary Feulner

Fig. 6.23 Two of the otherwise rare plant species that are relatively common within the metamorphic terrane of the Asimah-Tayyibah area: (**a**) *Commicarpus stenocarpus*, so far recorded in the UAE only from this area, where it is locally common on slopes. (**b**) *Lactuca orientalis*, otherwise recorded only rarely at mid to high elevations in the Ru′us Al Jibal. Photo credits: Gary Feulner

Fig. 6.24 Some natural freshwater habitats in the Hajar Mountains: (**a**) A shallow gorge in Wadi Asfani, where permanent surface water (and the wadi fish *Garra barreimiae*) could still be found in recent years despite abstraction and the disruption of upstream areas by a major pipeline. (**b**) An exposed but well-vegetated permanent pool at the base of a small waterfall in a remote tributary of Wadi Asimah. The vegetation has since been cleared to facilitate use of the pool for a small farmstead on an adjacent terrace. (**c**) Extended temporary pools along the wadi track to the Wadi Wurayah waterfall, seen here during the "wet" years of the mid-1990s. (**d**) A sheltered temporary pool scoured at the base of a small waterfall in a tributary of Wadi Wurayah. Calm, shaded pools like this attract diverse diurnal flying insects, especially in hot weather. (**e**) A permanent pool near Hatta, home of the last known UAE population of the Hajar Lotak *Cyprinion mascatense*, a wadi fish now extinct in the Emirates. The site was destroyed by ill-considered construction of a recreational road. (**f**) Intermittent surface rivulets above the Wadi Wurayah waterfall, following major flooding that decimated the reeds that had previously clogged the wadi bed. (**g**) A small "slot" pool in upper Wadi Wurayah. These modest oases provide not only water but also critical habitat to wadi residents such as the endemic damselfly *Arabineura khalidi* (see Fig. 6.4g). (**h**) Sometimes the water table in a "dry" wadi may be very close to the surface. Humans have learned to exploit this phenomenon by making shallow scrapes to obtain clean fresh water. Evidence suggests that feral donkeys may also have acquired this skill. Photo credits: Gary Feulner

Fig. 6.25 Freshwater animal life in Hajar Mountain wadis: (**a**) Striped Predaceous Diving Beetle *Hydaticus* (*Prodaticus*) *histrio* (Coleoptera: Dytiscidae). (**b**) Polka Dot Predaceous Diving Beetle *Hydaticus* (*Prodaticus*) *pictus* (Coleoptera: Dytiscidae). (**c**) Aquatic larva of a predacous diving beetle (Coleoptera: Dytiscidae); the larvae are considered fierce predators. (**d**) Water Scorpion *Laccotrephes fabricii* (Hemiptera: Nepidae). This shallow water bottom dweller hunts with its pincers, usually by ambush. The long 'stinger' is not a weapon but a paired breathing tube. (**e**) Backswimmer *Notonecta* sp. (Notonectidae). This insect floats up to 30 cm below the water surface, belly up, and attacks unsuspecting surface prey. (**f**) Caddisfly larvae (Order Trichoptera). The species shown here is rather large and makes its protective "shell" by cementing sand grains. Photo credits: Gary Feulner (a,d–f); Tamsin Carlisle (b,c)

6.2.1.6.2 Mobile Cosmopolitan Species

Many, perhaps most, of the flying insects and most of the water plants and algae that inhabit these freshwater bodies are mobile cosmopolitan species that are able to colonize favorable habitats over broad geographic ranges (van Harten 2008, 2009, 2010, 2011, 2014, 2017; D.M. John, pers. comm.). UAE freshwater snails achieve the same result by relying on other organisms such as birds and perhaps even large flying insects to disperse their eggs or young. That assistance is critical because none of the UAE's native snails can survive extended desiccation at any stage of their life cycles. The most common UAE freshwater snail is the long, conical *Melanoides tuberculata* (Thiaridae) which produces live young by parthenogenesis; it is found in all the countries bordering the Indian Ocean and has become invasive globally (Feulner and Green 1999), but its pedigree in Eastern Arabia goes back to at least the pluvial lakes of the Pleistocene (McClure 1984). The largest and most typical vascular plants associated with water—e.g. Oleander *Nerium oleander*

Fig. 6.26 Freshwater plants in Hajar Mountain wadis: (**a**) Oleander *Nerium oleander*. An extensive grove in a "wet" tributary of Wadi Fay, Fujairah. The tributary is distinctive by being situated in an outlier of tectonized harzburgite and having remarkably limited floral diversity. (**b**) Giant Reed *Arundo donax*. Although native to the Middle East, this reed has a global reputation as an invasive species. (**c**) Common Wadi Grass *Saccharum griffithii*. A distinctive and characteristic species of Hajar Mountain wadi beds, this species requires a certain amount of subterranean wadi flow. (**d**) Southern Cattail *Typha domingensis*. Widespread globally in the tropics and subtropics, it is rare in the UAE because it requires more or less permanent, still surface water. (**e**) Filamentous pond algae, probably *Spirogyra* sp., growing in a temporary pond formed where an earthen road crossing dammed a shallow wadi. The algae grows first as thin, slimy green filaments, but if growth is profuse, it forms cloud-like mats at the surface and can deplete the water of nutrients available to other organisms (D.M. John, pers. comm.). Photo credits: Gary Feulner

(Apocynaceae), the Giant Reed *Arundo donax*, the common Wadi Grass *Saccharum griffithii*, and the Southern Cattail *Typha domingensis* (all Poaceae) (Fig. 6.26)—appear to rely most heavily on wind dispersal of their seeds (see also Chap. 13).

6.2.1.6.3 Isolation and Speciation of Freshwater Fishes

For fully aquatic or non-migratory animal species, both vertebrate and invertebrate, the dispersed and only intermittently connected freshwater bodies of the Hajar Mountains are like islands, each having its own population, which, over time, can diverge and result in the creation of new subspecies or even new species. This has not been demonstrated within the UAE proper, but within the UAE/Oman mountains as a whole, it has recently been shown by genetic studies that the scattered populations of the most common and widespread wadi fish, heretofore treated as several subspecies of *Garra barreimiae*, actually represent five unique species of *Garra*, each occupying geographically distinct major watersheds draining the high mountain areas of Northern Oman (Pichler et al. 2018; Freyhof et al. 2020; Kirchner et al. 2020).

As one result, only the *Garra* populations of the Western Hajar, to the northwest of the Jebel Akhdar, retain the scientific name *G. barreimiae*; this includes the fish populations on both flanks of the mountains in the UAE and northernmost Oman. Mixing of the *G. barreimiae* populations on both the interior and Gulf of Oman flanks was probably facilitated by drainage patterns like that of Wadi Jizzi, which begins in the interior near Al Ain and Buraimi and breaches the mountains to reach the Gulf of Oman north of Sohar; and of the Wadi Hatta corridor, where Wadi Hadf, the uppermost major tributary of Wadi Hatta, once fed outwash channels that flowed to both the Arabian Gulf and the Gulf of Oman (Feulner 1999a).

6.2.1.6.4 Freshwater Bodies as a Community Resource

Wadi pools and streams are important as a resource even for non-aquatic wadi life, both vertebrate and invertebrate. Birds, lizards, snakes, bees and other flying insects can all be seen coming to drink from time to time. In most cases the presence of surface water enlarges the size of the populations that an area can support, which in turn has ecological effects of its own. For example, the Wadi Racer *Platyceps rhodorachis*, probably the most commonly encountered mountain snake, often hunts submerged in shallow wadi pools to ambush *Garra*. Similarly, the Hajar Saw-Scaled Viper *Echis omanensis*, which often lies in wait beside mountain pools and streams, has come to treat the abundant wadi toads, the Arabian Toad *Sclerophrys arabica*, as a principal food resource, despite the fact that toads are normally disfavored by vipers as prey due to the noxious chemicals produced by their skin glands. *E. omanensis* can also turn the arid Hajar Mountain environment to its advantage by preying on fish trapped in drying puddles.

Among invertebrate predators, Grass Spiders or Water Orb-Weavers (Tetragnathidae) hunt from webs suspended horizontally over pools and streams (Feulner and Roobas 2015); a tiger beetle (*Lophyridia fischeri elongatosignata*) and a common UAE wolf spider (a still-to-be-described species of *Wadicosa*; T. Kronestedt, pers. comm.) are specialized hunters on damp ground beside wadi pools and streams (Fig. 6.27). The majority of UAE dragonflies and damselflies are hawkers or darters at freshwater habitats of one sort or another in the mountain environment (Feulner et al. 2007; Reimer et al. 2009).

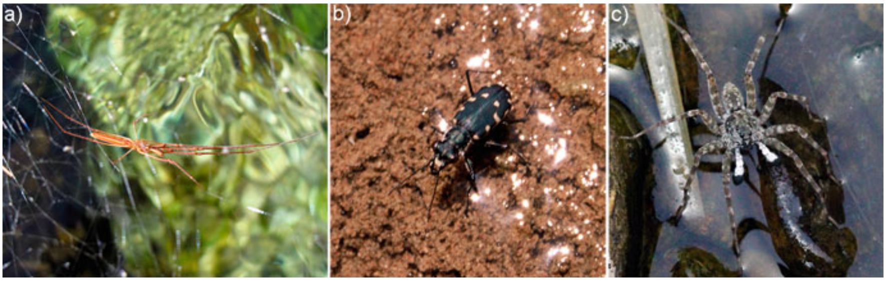


Fig. 6.27 Some invertebrate predators found at mountain pools: (**a**) The large local Grass Spider *Tetragnatha* sp. (Tetragnathidae) hunts from a web constructed horizontally over flowing water. If the spider happens to fall in the water, it can swim out quickly, but very inelegantly. (**b**) The tiger beetle *Lophyridia fischeri elongatosignata* hunts on damp ground beside pools. It is very skittish and takes flight at the first sign of approach. Normally bronze-brown in color, a rare blue-green specimen is shown here. (**c**) The wadi wolf spider male shown here is very common on gravel beside pools and streams; the female is often seen carrying her egg sac by her spinnerets. They can escape predators by running on water. Tentatively identified by Feulner and Roobas (2015) as a *Pardosa* sp., this spider is now understood to be a new species of *Wadicosa*, awaiting description (see text). Photo credits: Gary Feulner (a,b); Binish Roobas (c)

6.2.1.6.5 Physical Parameters of Wadi Water

Few published studies are known to exist of the physical parameters of surface water in the Hajar Mountains of the UAE, including possible geographical, geological, seasonal or episodic variability. An ad hoc survey of ca. two dozen sites in Wadi Wurayah from January to March 2006, including both “pools” and “riffles” of various descriptions, provides some indicative data reported by Emirates Wildlife Society—WWF (2006) and Tourenq et al. (2011). Water temperature was found to vary between ca. 22 to 28 °C. pH was slightly alkaline, said to average 8.3 with a range of ca. 8.2 to 9.1. Average dissolved oxygen varied between 5.2 and 11.22 mg/liter. Nitrate concentrations ranged from 4.6 to 7.8 mg/liter, averaging 5.76 mg/liter.

6.2.1.6.6 Freshwater Seeps

Freshwater seeps are found occasionally along Hajar Mountain wadi walls, almost always in harzburgite terranes, where gravel outwash sediments overlie bedrock or where poorly cemented sediments overlie a more thoroughly cemented layer (Fig. 6.28). They are also found today in anthropogenic settings, e.g. below a leak or frequent overflow from a falaj irrigation system. These seeps, where groundwater dripping from the overlying source dampens the rock face below with a thin film of water, are the typical habitat of the Maiden’s Hair Fern *Adiantum capillus-veneris*.

Seeps that are larger or more reliable may also host, among the more numerous ferns, small numbers of *Epipactis veratrifolia* (Orchidaceae), a helleborine orchid found in marshy environments from Turkey and Somalia in the west to south China

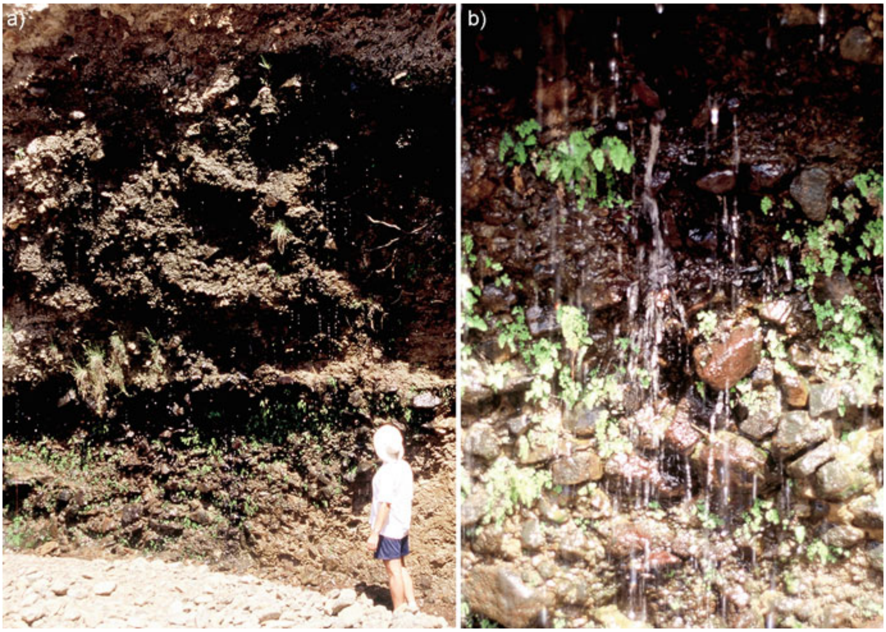


Fig. 6.28 (**a**) A "weeping wall" in ophiolite terrane near Hatta. The groundwater is exiting the wadi wall along a horizon where the upper gravels are underlain by a better-cemented unit. (**b**) The Maiden's Hair Fern *Adiantum capillus-veneris* is seen here in its typical UAE habitat. Toads can sometimes be found on walls like this. Photo credits: Gary Feulner

in the east. Because it is the UAE's only orchid, *E. veratrifolia* has understandably attracted special attention and concern for its welfare, to an extent that other rare or potentially threatened species can only dream of achieving. But in fact, the orchid's natural sites are under threat primarily from the possibility that global climate change will reduce rainfall in UAE mountain areas, which is by no means certain. In any case, anthropogenic activities have, on balance, probably created as many or more potential habitats as they have destroyed, although this might not continue if greater attention is paid to efficient water use and repair of leaky irrigation infrastructure.

6.2.1.6.7 Flooding in the Wadis

Flooding in mountain wadis (Fig. 6.29) is infrequent but consequential. It is necessary to the health of the ecosystem but, like fire in a savannah, it is also disruptive. When rain begins, it quickly accumulates in rivulets on slopes and depressions on terraces. In small tributary wadis the flow is shallow but turbulent, the waters opaque with sediment. These often take a final, steep plunge into the main wadis, where, at first, little seems to happen. The brown waters spread out in a small fan over the

Fig. 6.29 Some examples of UAE mountain wadis in spate: (**a**) Wadi Asfani, filling slowly after a thunderstorm in October 1997. Within half an hour the entire wadi bed shown here was flooded. (**b**) Wadi Sfai, flooded after modest rain in December 1998. In this instance, the waters receded enough for cars to pass comfortably after about 2 h. (**c**) Flooding at the Wadi Wurayah waterfall in December 2012. Moderate rain had fallen for an hour without affecting the main wadi, but about 45 min later the waterfall wadi and adjacent tributaries draining from the north and west began to spout brown, foaming water. (**d**) Whitewater in Wadi Ayim gorge, near Al Ghayl, in February 1993. There is no permanent surface water in this area. Photo credits: Gary Feulner (a,b,d); Jacky Judas (c)

gravel wadi bed, and sink in, filling the often substantial pore space in the surface gravels.

But then, if the rainfall continues, a threshold is crossed. The pore space in the wadi gravel is filled, after which every additional drop that reaches the wadi becomes part of the surface flow, which quickly builds and accelerates. Where wadis are relatively broad, floodwater depth in the modern era is estimated generally to be no more than about a meter to a meter and a half, based on flotsam and visual observation. In gorge areas, however, the choked waters can rise to many meters, sometimes overtopping the dramatic channels incised in cemented gravels.

The creatures resident in the wadis seem to be adapted to these flood events, as they must be, but occasionally one finds dead snakes or small mammals in their wake, and the floodwaters invariably transport and aggregate the abandoned shells of local land snails, sometimes surprisingly abundant. Naturalist observers who have overnighted in heavy rain in the mountains have reported another hazard, that of falling rocks and stones dislodged by the rain and consequent erosion.

If rainfall does not continue, most floodwaters recede within hours to days, but pools and streams in the gravel wadi beds may be refreshed for weeks or months.

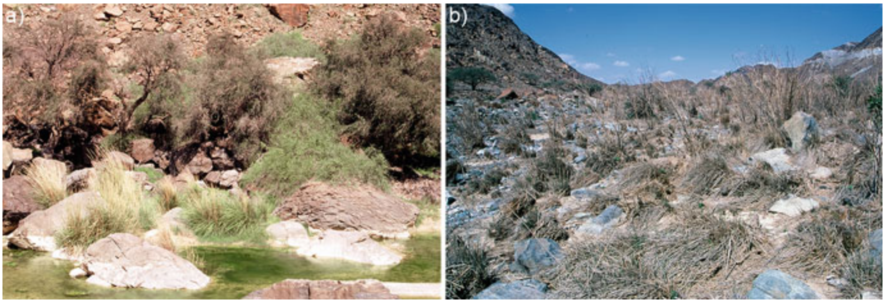


Fig. 6.30 How permanent is “permanent”? To understand Hajar Mountain ecosystems, a certain amount of patience may be required. (**a**) This photo shows a site along lower Wadi Hiluw with unusually large, old trees. It was taken in March 1996, during the very “wet” years of the mid-1990s (see Feulner 2006), when flooding destroyed power pylons and for several years the lower wadi featured intermittent surface pools and small streams year-round, with localized populations of the Arabian Killifish *Aphanius stoliczkanus*, a euryhaline species common in coastal lagoons. The wadi ecosystem was anomalous, however, in that the principal native wadi fish of the Hajar Mountains, *Garra barreimiae*, was absent (Feulner 1998). This was an indication that things were not what they seemed. Subsequent monitoring since 1999 has confirmed that Wadi Hiluw does not normally support year-round surface water. The killifish had been introduced for mosquito control—a practice which continues in mountain areas, both officially and unofficially. (**b**) The same phenomenon, including the introduction of Arabian Killifish, was confirmed for Wadi Baraq on the west flank of the mountains, where extensive stands of hygrophilic vegetation that prospered during 1995 to 1998 (Oleander, Common Wadi Grass, Mountain Bulrush and even Southern Cattail) were left to wither and die over the ensuing years, as seen here. Photo credits: Gary Feulner

The heavy rains of the mid-1990s (Feulner 2006) were sufficient to create conditions of extensive year-round surface water in several wadis that, it is now known, do not otherwise sustain it in the modern era. It may or may not be a coincidence that each of those wadis was in gabbro terrane (Fig. 6.30); in at least one case abstraction for agriculture is likely to have played a significant role in depleting the surface flow. The foregoing nothwithstanding, the map of wadi fish distribution in Feulner (1998, Fig. 6.1 at page 22), although not fully comprehensive, has often been used as a surrogate for a census of the UAE and northernmost Oman wadis that have permanent surface water. It is nevertheless difficult to identify the precise conditions that differentiate wadis with permanent surface water from those without. A striking example is the contrast between Wadi Wurayah, known for its year-round waterfall and upstream “wet” gorges, and its similarly-sized northern neighbor, Wadi Zikt (both within Wadi Wurayah National Park), where no permanent surface water has yet been discovered.

6.2.2 The Ru′us Al Jibal (the Mountains of the Musandam)

The Ru′us Al-Jibal comprises a thick (3000 m) sequence of pale grey to pale tan carbonate sedimentary rocks (limestone $CaCO_3$ and dolomite $CaMg(CO_3)_2$) that

Fig. 6.31 An exhilarating panorama of the high Ru′us Al Jibal, overlooking Wadi Naqab from Silhi in the south-central Ru′us Al Jibal, photographed in the mid-1990s. Just visible on the horizon to the north are Jebel Rahabah and Jebel Jais. Photo credit: Gary Feulner

were vertically elevated in geologically recent times. The physiognomy of the Ru′us Al Jibal is characterized by "square" or blocky profiles, with steep cliffs and flat, plateau-like summits (Fig. 6.31). The carbonate rocks are karstic, so, among other things, they are full of subterranean solution channels and there is little surface or near surface water. Consequently plants that depend on interstitial flow in wadi gravels, like Oleander *Nerium oleander* or Wadi Grass *Saccharum griffithii*, are all but absent from the Ru′us Al Jibal, although both are common in the Hajar Mountains (Feulner 2011).

As an exception to the rule, a few wadis in the Ru′us Al Jibal feature "pothole" pools scoured in bedrock. These may be relatively deep and, where they are shaded, they can retain water for substantial periods of time and so become magnets for birds and flying insects, as well as freshwater snails carried in adventitiously as sticky egg masses or clinging neonates. Their steep, smooth sides make many such pools difficult, even treacherous, for quadrupeds to access, but it is probably not a coincidence that the narrow defile of Wadi Zibat, which contains a chain of bedrock pools, accounted for many of the last reported sightings and traces of the Arabian Leopard in the Musandam region (Fig. 6.32).

Vegetation in the Ru′us Al Jibal is generally concentrated on wadi banks as well as in and along ravines and gullies on rocky slopes and plateaux (Fig. 6.33). Even on intermediate slopes, the Ru′us Al Jibal flora includes elements not generally seen in the Hajar Mountains, for example, the colorful but spiny *Astragalus fasciculifolius*

Fig. 6.32 Pothole pools in the formidable gorge of Wadi Zibat, thought to be a last refuge of the Arabian leopard in the Ru′us Al Jibal because water could be found there. Photo credit: Gary Feulner

(Fabaceae), *Fagonia schimperi* (Zygophyllaceae), *Farsetia aegyptia* (Brassicaceae) and the plume grass *Stipagrostis paradisea* (Poaceae) (Fig. 6.34). The high elevation flora of the Ru′us Al Jibal, above ca. 1100 m, is characterized by Irano-Turanian species that are absent or very rare elsewhere in the UAE—almond trees *Prunus arabica* (Rosaceae) [listed in Jongbloed et al. (2003) as *Amygdalus arabica*] and *Artemisia* steppe, dominated by dwarf shrubs and grasses, particularly the wormwood *Artemisia sieberi* (Asteraceae) [listed in Jongbloed et al. (2003) as *Seriphidium herba-alba*], the spiny *Convolvulus acanthocladus* (Convolvulaceae), the lemon grass *Cymbopogon jwarancusa* (Poaceae), the gymnosperm *Ephedra pachyclada* (Ephedraceae) and the spiky-budded *Centaurea wendelboi* (Asteraceae) (Figs. 6.35 and 6.36). Notably absent at high elevations is *Euphorbia larica*, one of the most common and characteristic shrubs of slopes and plateaux at low and medium elevations; unfortunately this significant fact has sometimes been misrepresented in print (e.g. Llewellyn-Smith 2002).

Fig. 6.33 Abundant vegetation in a bedrock gulley not far from Jebel Yibir. Photo credit: Gary Feulner

As to fauna, the Ru′us Al Jibal has recently been shown to have a number of its own endemic geckoes (*Ptyodactylus* and *Asaccus* spp.; Burriel-Carranza et al. 2022). Only Dhofar Toads *Duttaphrynus dhufarensis* are found in the interior of the Ru′us Al Jibal, not the more gregarious and water-loving Arabian Toad *Sclerophrys arabica* (Cunningham and Feulner 2001). Above about 700 m, the high Ru′us Al Jibal is home to two tiny land snails otherwise known only from more northerly regions: *Gibbulinopsis signata* (which ranges from Turkey to Central Asia) and *Granaria persica* (also found in the southern Zagros Mountains in Iran) (Feulner and Green 2003). Both snails are considered to be relicts of a more mesic climate in the UAE. The same is true of the two-centimeter land snail *Mordania omanensis*, found today only at high elevation in the Ru′us Al-Jibal and the Jebel Akhdar (see Fig. 6.5e).

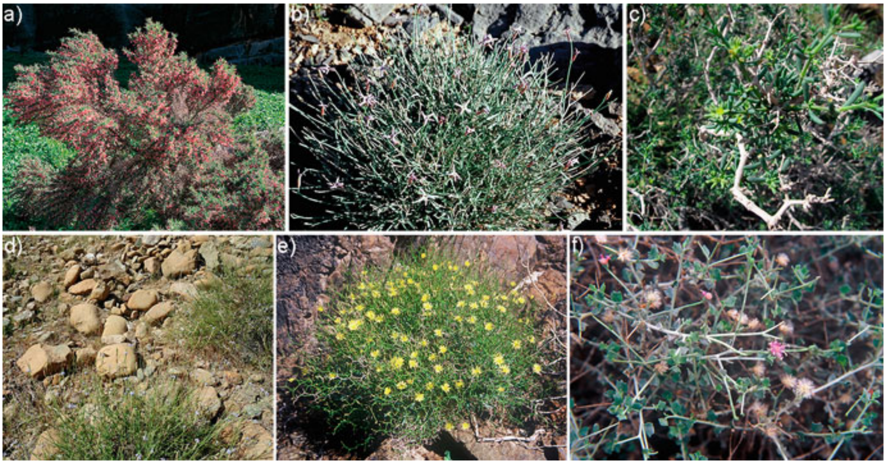


Fig. 6.34 Some typical plant species of Ru′us Al Jibal slopes at intermediate elevation: (**a**) *Astragalus fasciculifolius* (Fabaceae). (**b**) *Farsetia aegyptia* (Brassicaeae). (**c**) *Gymnocarpus decandrum* (Caryophyllaceae). (**d**) *Lavandula subnuda* (Lamiaceae). (**e**) *Launaea bornmuelleri* (Asteraceae). (**f**) *Vernonia arabica* (Asteraceae). Photo credits: Gary Feulner

6.2.2.1 Cliff Environments

Mountain areas provide opportunities for cliff-dwelling plants or chasmophytes. Cliffs, defined operationally as rock surfaces over 2 m in height and sloping at an angle of more than 60°, are widespread in the UAE/Oman Mountains, and especially so in the Ru′us Al Jibal. Globally, they represent one of the least disturbed habitat types and therefore often contain extensive areas of natural vegetation. Studies of cliff vegetation are difficult for a number of practical and theoretical reasons, but it has been shown from other parts of the world that cliffs harbor some of the most floristically diverse communities, and cliff habitats therefore often contribute substantially to biodiversity, more than their actual surface extent would suggest (Larson et al. 2000).

In the UAE, cliff-dwelling species include prominently two large hanging shrubs: (i) *Capparis cartilaginea* (Capparaceae) (see Fig. 6.12a) is common on cliffs at low elevations in the Ru′us al Jibal and is a dominant species on Jebel Hafeet, but is conspicuously absent from the ophiolite rocks in between; (ii) *Cocculus pendulus* (Menispermaceae) (Fig. 6.37) is also common in the Ru′us Al Jibal and present, but rarer, in the Hajar Mountains (Jongbloed et al. 2003, Feulner 2011). The smaller Common Caper *Capparis spinosa* is found most often as a cliff-dwelling shrub at low and medium elevations in both the Hajar Mountains and the Ru′us Al Jibal (Jongbloed et al. 2003, Feulner 2011, 2016). The diminutive *Rosularia adenotricha* (Scrophulariaceae) is found only in sheltered limestone hollows high in the Ru′us Al Jibal (Feulner 2011). The Wadi Fig *Ficus salicifolia* (Moraceae)and the wispy

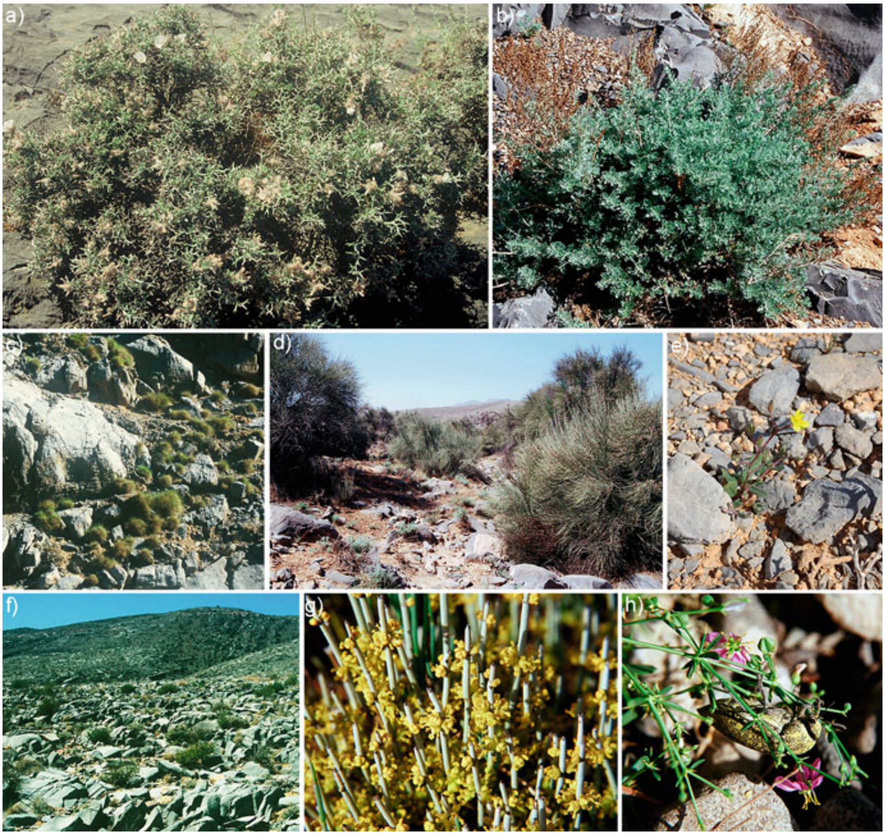


Fig. 6.35 Some typical plant species of Ru′us Al Jibal plateaux at high elevation, mostly Irano-Turanian species: (**a**) *Convolvulus acanthocladus* (Convolvulaceae), dominant in many exposed areas. (**b**) *Artemisia sieberi* (Asteraceae) (formerly *Seriphidium herba-alba*), new leaves (green) flourishing among older dry growth (brown). (**c**) *Cymbopogon jwarancusa* (Poaceae), cushions on a hillside at ca. 1200 m. (**d**) Arabian Almond *Prunus arabica* (Rosaceae) (formerly *Amygdalus arabica*) along a gentle wadi at ca. 1500 m. (**e**) *Helianthemum salicifolium* (Cistaceae), a diminutive high elevation annual. (**f**) *Dodonaea viscosa* (Sapindaceae), stunted shrubs among limestone pavement at 1600+ m. (**g**) *Ephedra pachyclada* (Ephedraeae), one of the UAE's only two gymnosperms, on a gravel plain at ca. 1600 m. (**h**) *Fagonia schimperi* (Zygopyllaceae), a poorly known high elevation *Fagonia* species, shown here with a Sulfurous Jewel Beetle. Photo credits: Gary Feulner

Drumstick Tree *Moringa peregrina* (Sapindaceae) can also occur as cliff-dwellers, but they are limited to low or medium elevations.

Several other UAE mountain plants are found primarily in cliff environments, not because that is their primary habitat, but because it is the only place where they can survive the often-substantial local browsing pressure. For those plants, cliffs serve as refugia. Species in this category include the rare UAE/Oman endemic *Rumex limoniastrum* (Polygonaceae); the large shrubs/small trees *Cordia quercifolia* (Boraginaceae) [listed in Jongbloed et al. (2003) as *C. sinensis*], *Ehretia obtusifolia*

Fig. 6.36 Winter in the Ru′us Al Jibal: The author and colleagues at ca. 1800 m, near the summit of Jebel Jais, in January 2019. At right is stunted *Prunus arabica*, at left is *Ephedra pachylada*. The dominant vegetation cover is the dwarf shrub *Artemisia sieberi*, here dry and brown. Photo credit: Gary Brown

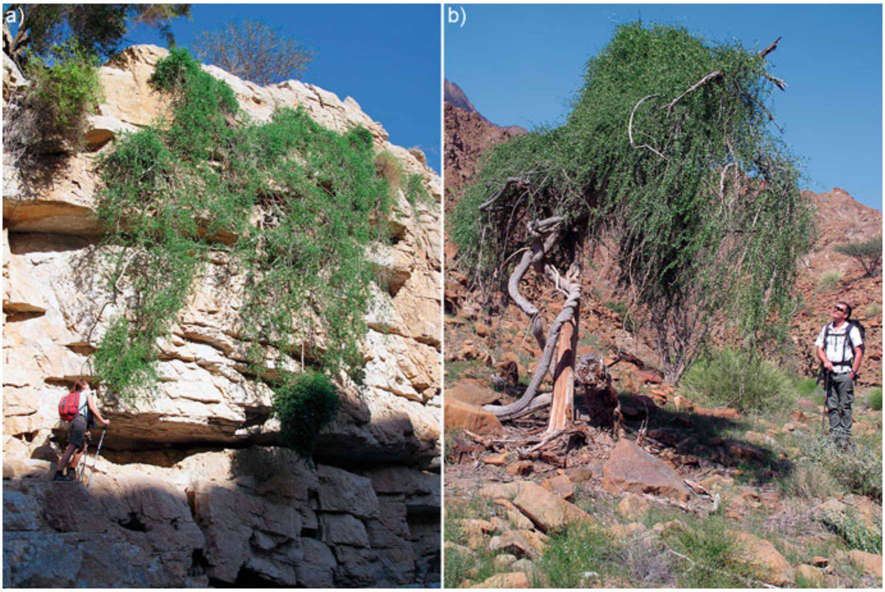


Fig. 6.37 *Cocculus pendulus* (Menispermaceae) can grow to be a very large hanging or climbing plant. (**a**) In the Ru′us Al Jibal it is locally common and is typically found on cliffs, as here in Wadi Naqab. (**b**) In the Hajar Mountains it is less common and is mostly a climber on Samr and Sidr trees, as here in a tributary of Wadi Wurayah. Photo credits: Gary Feulner

(Boraginaceae) (see Fig. 6.19a), *Grewia tenax* (Tiliaceae) (Fig. 6.38); and the dwarf shrub *Phagnalon schweinfurthii* (Asteraceae).

Cliff environments also create small sheltered nooks where limited amounts of soil can accumulate and moisture can be retained. These permit the establishment of more delicate, less dry-adapted species like two of the UAE's few ferns, *Cheilanthes pterioides* and *Cheilanthes vellea* (Adiantaceae), both diminutive, and tiny herbs like *Asterolinon linum-stellatum* (Primulaceae) and *Galium setaceum* (Rubiaceae); the latter also prospers under the skirts of larger shrubs.

One animal that depends on shaded microenvironments is the White-Edged Rock Brown butterfly *Hipparchia parisatis*, a large Palearctic mountain species that still keeps its Palearctic schedule, even in the UAE (Larsen 1983; Feulner et al. 2021) (see Fig. 6.5b). It emerges from the pupal state in mid to late March, but throughout the summer months it spends most of its daytime hours resting in the shade of cliffs, ledges and wadi banks, before breeding and dying in mid-autumn.

Fig. 6.38 In the UAE and adjacent northern Oman, *Grewia tenax*, normally a large shrub or small tree, is one of a number of mountain plants that is most often seen as a cliff dweller, because that is the most effective way to escape the often substantial local browsing pressure. See also Fig. 6.19b. At the top of the cliff is an Arabian almond *Prunus arabicus*. Photo credit: Gary Feulner

The rocky mountain environments of cliffs, ledges and boulders are also home to many of the diverse array of endemic reptiles summarized in the introduction to this chapter, particularly *Asaccus* spp., *Omanosaurus* spp., and *Ptyodactylus* spp. (see also Chap. 16).

6.2.3 The Dibba Zone

The Dibba Zone is a low and geologically diverse corridor that separates the ophiolite of the Hajar Mountains from the carbonate sediments of the Ru′us al-Jibal. The Dibba Zone rocks are a structurally discontinuous mix of deep and shallow water marine sediments and volcanics (Fig. 6.39) that were pushed ahead of the ophiolite as it was forced over the edge of the Arabian continent. The native flora has been heavily degraded by extensive cultivation and overgrazing by domestic livestock. The Dibba Zone is not considered to be distinctive from a botanical point of view, but one plant species, *Chesneya parviflora* (Fabaceae) (Fig. 6.40), is known in the UAE only from a handful of specimens recorded in the eastern half of the Dibba Zone (Feulner 2011, A. Gardner unpublished data). *C. parviflora* is otherwise known from the Makran, the hilly regions of southern Iran and Pakistan.

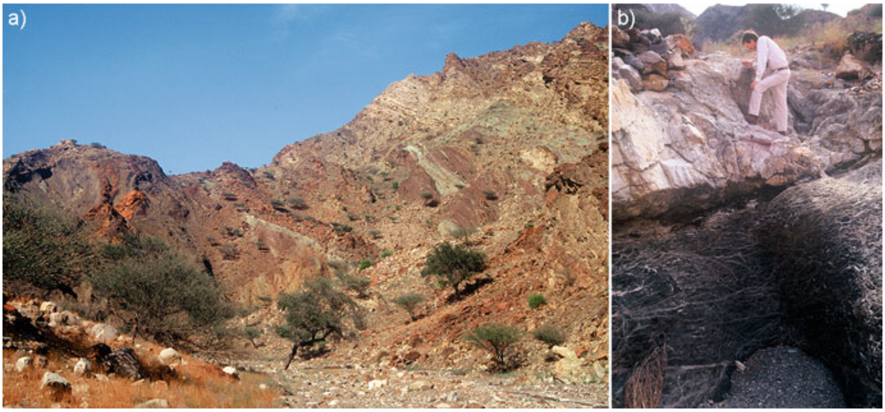


Fig. 6.39 (**a**). The multi-colored rocks of the Dibba Zone divide the carbonate sediments of Ru′us Al Jibal from the ophiolite rocks of the Hajar Mountains. They consist of a mix of tectonically jumbled rock units pushed ahead of the ophiolite while it was emplaced. (**b**) Most of the rocks found in the Dibba Zone are deep water sediments, but carbonate breccias and pillow lavas (seen here) are also present, probably representing former coral atolls. Photo credits: Gary Feulner

Fig. 6.40 *Chesneya parviflora* is known from the Makran region of Iran and Pakistan, and has also been found in the UAE, but so far only in the Dibba Zone. Photo credit: Drew Gardner

6.2.4 The Foreland Ridges (Jebel Hafeet et al.)

The Foreland Ridges are a discontinuous linear alignment of narrow, north-south trending, anticlinal ridges set about 20 to 25 km west of the main mountain front, and parallel to it (Figs. 6.41 and 6.42). At the surface, they expose latest Cretaceous and Paleogene shallow marine carbonate sediments deposited after the original emplacement of the Hajar Mountain ophiolite, but the forces that folded these later sediments are the same plate tectonic movements that caused the ophiolite emplacement in the first place: the continuing slow but inexorable convergence of the Arabian plate with the Eurasian plate.

Jebel Hafeet is unique among the foreland ridges by virtue of to its great height (ca. 1200+ m) and overall size (15–20 km long), but it is also, by far, the southernmost of the mountain areas that are physically within the UAE. For that reason, Jebel Hafeet also partakes of the broader biogeographical changes that are related to latitude, discussed in more detail at Sect. 6.3.1 below.

The foreland ridges have long been noted for their relatively depauperate flora, but also for the presence of plant species that are rare or absent elsewhere in the UAE, e.g. *Capparis cartilaginea* (Capparaceae) (see Fig. 6.12a), *Dipcadi biflorum* (Liliaceae), *Heliotropium rariflorum* (Lamiaceae), and *Salsola rubescens* (formerly Chenopodiaceae, now Amaranthaceae) (Fig. 6.43). The first and last listed species are among the known ophiolite "avoiders".

A small number of the UAE's native plants and animals are found only, or primarily, on Jebel Hafeet or in its immediate vicinity; many of these, however,

Fig. 6.41 Jebel Hafeet, by far the largest of the UAE's foreland ridges, rises some 800 m from the plains south of Al Ain, to reach a height of more than 1200 m. Photo credit: Gary Feulner

Fig. 6.42 The foreland ridges of Jebel Faya and its neighbors (Jebel Buhais, Jebel Mleiha et al.) are located in Sharjah, but they are geologically analogous to Jebel Hafeet, and originated in the same way. They are seen here from the west, across Wadi Faya. Photo credit: Gary Feulner

Fig. 6.43 (**a**) *Dipcadi biflorum* (Liliaceae) and (**b**) *Heliotropium rariflorum* (Boraginaceae) are associated with the smaller, northerly foreland ridges in Dubai and Sharjah, while (**c**) *Salsola rubescens* (Chenopodiaceae) is found primarily on Jebel Hafeet, but there are also more northerly records. Photo credits: Gary Feulner

are more common southwards, in northern Oman. Plants in this category include *Acridocarpus orientalis* (Malpighiaceae) (Arabic: qafas) (Fig. 6.44); the chenopod (now Amaranthaceae) *Halothamnus bottae*; and the diminutive, prostrate *Herniaria maskatense* (Caryophyllaceae).

Animals in the same category include four butterflies found in the UAE primarily at or in the vicinity of Jebel Hafeet: the Desert Orange Tip *Colotes liagore* (Pieridae); the Yellow Pansy *Junonia cebrene* (Nymphalidae: Nymphalinae); the Giant Skipper *Pyrrhiades anchises* (Hesperiidae: Coeliadinae) and the Baluchi Ringlet *Ypthima bolanica* (Hesperiidae: Hesperiinae). Jebel Hafeet is also the only UAE location known to have continuously maintained a wild population of Arabian tahr *Arabitragus jayakari*.

6.2.5 The Alluvial Plains

The ecology of the gravel outwash plains is ultimately based on the supply of sediment and water from rainfall over the adjacent mountain areas, which reaches the plains via wadis and then traverses them, when flow is sufficient, via braided streams and sheet flooding. Much of this water supply will sink into the more-or-less porous gravels en route. Some will continue its passage towards the coastal regions via established underground channels; some will take up longer term residence as near surface ground water. During intervals of greater rainfall, these processes have been sufficient to maintain scattered lakes on the plains, or in the sands to the west, over periods of thousands of years, creating a sedimentary record of former climate and vegetation in the form of isotope geochemistry, pollen and phytoliths (Parker et al. 2004).

At times the alluvial plains have probably resembled savannah environments like those seen today in East Africa. Hints of such former conditions are best preserved on the plains adjacent to the Ru′us Al Jibal, inland of Ras Al Khaimah city, where stands of the Umbrella Thorn *Acacia tortilis* still create occasional visually

Fig. 6.44 (**a**) The Qafas plant *Acridocarpus orientalis* (Malpighiaceae) is found in the UAE exclusively at the north end of Jebel Hafeet, in upper Wadi Tarabat. It is much more common immediately to the south, in the mountains of northern Oman (shown here). (**b**) The distribution of the Giant Skipper butterfly *Pyrrhiades anchises* (Hesperiidae: Coeliadinae) is tied to that of *A. orientalis*, its exclusive larval foodplant. Photo credits: Gary Feulner (a); Binish Roobas (b)

impressive landscapes of widely but regularly spaced trees (Fig. 6.45). But the resemblance ends there. Today, the understory of diverse shrubs and grasses has been lost, perhaps in part due to increased aridity, but certainly due to rampant overgrazing (see Chap. 5). Regeneration of the native trees is negligible; substantial areas have been converted to farms and others increasingly replaced by major roads, residential development and other infrastructure; peripheral areas subject to human disturbance have been aggressively colonized by the invasive mesquite tree *Prosopis juliflora*. Air pollution from massive limestone quarrying to the north and south of Ras Al Khaimah city has undoubtedly also impacted the natural environment.

Further south, on the west flank of the Hajar Mountains from Al Ghayl south to Madam, tree cover on the gravel plains (dominated by *A. tortilis* but with occasional Ghaf *Prosopis cineraria* and Sidr *Ziziphus spina-cristi*) has been less dense throughout the modern era, but all the same influences set out above have combined to create a severely degraded environment, impoverished in both abundance and diversity of vegetation. Inspection along roadside fencing in plains areas, e.g. along E102 east of Mleiha, reveals that even the modest ground cover of annual seedlings that sprouts after light rain is often missing on the grazed side of the fence.

In that same area, however, the gravel plains are occasionally home to healthy stands of *Rhazya stricta* (Apocynaceae), a dwarf shrub toxic to quadrupeds that is a sure indicator of overgrazing (Fig. 6.46). *R. stricta* is, however, a favored source of nectar for the Painted Lady butterfly *Vanessa cardui*, and it flowers early in the year, paradoxically making some areas of the otherwise degraded plains a magnet for many thousands of these butterflies on their annual migration northward to cooler climates (Feulner et al. 2021). The bristly *Heliotropium kotschyi* (Boraginaceae) is another unpalatable plant popular with multiple butterflies because it is a particularly

Fig. 6.45 *Acacia tortilis* dominates the alluvial plains on the northwest flank of the mountains, to the east and south of Ras Al Khaimah city, but today there is little or no understory and no regeneration of the trees themselves, due to overgrazing. Scientists at New York University—Abu Dhabi have determined that the average orientation of the trees on plains like these in the UAE is not vertical. Instead they are oriented 187°, nearly due south, and tilted at a 25° angle, approximating the overhead position of the midday sun at this latitude, averaged for the year (Ross and Burt 2015). South is roughly to the left in this photo, which appears to support that conclusion. Photo credit: Gary Feulner

rich source of bio-active chemicals (Feulner et al. 2021); it often colonizes waste ground around farms or other human installations on the gravel plains.

Several UAE reptiles have their principal habitats on the gravel plains. Despite the depredations described above, the diurnal lizard *Mesalina adramitana* and the nocturnal gecko *Bunopus tuberculatus* remain reasonably common, but populations of two Fringe-Toed Lizards (*Acanthodactylus* spp.) appear likely to have suffered. The only recently recorded populations of *A. boskianus* (see Fig. 6.14b, above) are from wadi environments within the western mountain front, and most of the known UAE range of *A. opheodurus*, being on the plains north of Jebel Hafeet, has been given over to residential development.

On the East Coast, where the alluvial plain is equivalent to the coastal plain, the situation is similar, except that invasion by *Prosopis juliflora* has been more pervasive and, the available land area being smaller, the extent of its sacrifice to development has been proportionately greater.

Fig. 6.46 The unpalatable shrub *Rhazya stricta* dominates many areas of the alluvial plains west of the mountains, especially in the south, between Dhaid and Madam—a sure indication of overgrazing. Photo credit: Gary Feulner

6.3 Axes of Transition: Ecosystem Gradients in Space and Time

6.3.1 Spatial Gradients: Latitude, Climate, Behavior, Biogeography

The UAE/Oman Mountains straddle the Tropic of Cancer, spanning the conceptual and practical gradient from tropical climate in the south to subtropical or temperate in the north. The mountains also span the northerly extent of the Indian Ocean Southwest Monsoon (IOSM), which brings relatively abundant summer rainfall to the south, particularly in the Jebel Akhdar range. The Hajar Mountains of the UAE are the lowest area of the UAE/Oman mountain chain, so the orographic rainfall effect of the mountains themselves is reduced there. These geographical and climatic gradients result in significant physical and biotic changes as one moves northward from northern Oman into the UAE, and the changes manifest a directional character beyond any variation that might be expected from 'mere' speciation in a relatively rich and variegated environment.

A number of common plant and animal species disappear northwards from northern Oman into the UAE. It is often difficult to identify or disentangle the precise variables that control the distribution of a species, and not all species

Fig. 6.47 *Tamarix aphylla* trees (Tamaricaceae) can grow to large size. They grace the lower and middle reaches of many wadis on the interior flank of the mountains in northern Oman, as seen here in Wadi Ajran. But north of Wadi Jizzi, only a few scattered trees are known. Photo credit: Gary Feulner

disappear at exactly the same latitude, but a rough boundary can usefully be designated at 24° 15’ North (Feulner 2011, 2016), approximating the latitudes of Wadi Jizzi, Al Ain and Buraimi. Examples of some of the more common and prominent mountain plants that disappear at or near this horizon are several large shrubs/small trees: *Acridocarpus orientalis* (Malpighiaceae), the larval foodplant of the Giant Skipper butterfly *Pyrrhiades anchises* (see Fig. 6.44); *Maerua crassifolia* (Capparaceae), a favorite of several Pierid butterflies; and *Tamarix aphylla* (Tamaricaceae), often a very large and abundant species of gravel wadi beds to the south (Fig. 6.47). Other plant species begin to disappear northward at about the same horizon, but more gradually, e.g., *Schweinfurthia papilionacea* (Scrophulariaceae) and *Cleome scaposa* (Capparaceae).

Animals that disappear north of the Al Ain/Buraimi area include *Pristuris carteri*, a semaphore gecko found primarily in Dhofar but which extends into northern Oman, especially along the mountains and foothills on the interior (southwest) flank, as well as three butterfly species: the Desert Orange Tip *Colotes liagore*, the Yellow Pansy *Junonia cebrene* and the Giant Skipper *Pyrrhiades anchises* (Feulner et al. 2021). The butterflies, however, may be responding primarily to the disappearance of their respective host plants rather than to climatic factors directly; that is certainly true for *C. liagore* and *P. anchises*. The Fig Blue butterfly *Myrina silenus*, an Afrotropical species, also tapers out gradually from northern Oman through the mountains of the UAE to the Dibba Zone (Feulner et al. 2021; Kh. Rafeek, unpublished data) although its larval host plant, the Wadi Fig *Ficus salicifolia* (Moraceae), remains common throughout the Ru'us Al Jibal to the north.

The UAE also projects into the Palearctic region. Moving north, Palearctic species of plants and animals are encountered more frequently, especially at higher elevations. The role of the high Ru′us Al Jibal in particular, as a distinct biome hosting many Irano-Turanian plant species and relict Palearctic fauna, has been discussed above. The proximity of the Palearctic boundary is also evidenced by floral and faunal records from Abu Dhabi's offshore islands. Although they are not very far north of the mainland, those islands account for most of the UAE records of Palearctic species such as *Mesymbryanthemum nodiflorum* (Aizoaceae) (Jongbloed et al. 2003), common on the coasts of Qatar, and *Pieris rapae* (Pieridae), a very common butterfly of temperate Europe and West Asia, but very rare on the UAE mainland (Feulner et al. 2021).

Latitude may influence not only the plant and animal species that are present, but also their behavior. For example, animals that hibernate or are inactive in winter in Northern Arabia do not necessarily hibernate in the UAE. Examples include Bosc's Fringed-Toed Lizard *Acanthodactylus boskianus* (Roobas and Feulner 2013) and butterflies such as the Desert White *Pontia glauconome* (Feulner et al. 2021).

An Oman-Makran distribution is a recognized biogeographical phenomenon (Kürschner 1986; Léonard 1989; Feulner 2011). Examples include the common Mountain Spurge *Euphorbia larica* (Euphorbiaceae) (although an isolated occurrence is recorded from Yemen; G.M. Brown, pers. comm.) and the plant genera *Pteropyrum*, *Phagnalon* and *Schweinfurthia* (Zohary 1963, 1973). However, a number of relatively common Oman-Makran species are absent from the northernmost UAE mountains. Examples include the Dwarf Palm *Nannorrhops ritchieana* (Arecaceae), the Wild Olive *Olea europaea* (Oleaceae) and the tropical Afro-Indian butterflies *Colotis danae* (Scarlet Tip), and *Colotis liagore* (Desert Orange Tip) (Feulner et al. 2021). This emphasizes the geographical and climatic distinctiveness of the northern mountains.

Somewhat more surprisingly, at least a few familiar plant species, when scrutinized more closely, appear to display unexpected and so far unexplained anomalies in distribution between the east and west flanks of the Hajar Mountains in the UAE. For example, the often abundant west flank annuals *Erucaria hispanica* (Brassicaceae) and *Sclerocephalus arabicus* (Caryophyllaceae) were not recorded in the drainage areas of Hajar Mountain wadis debouching to the East Coast during the period of a two-year survey there (Feulner 2016). The same is true of the perennial bulrush *Juncus socotranus* (Juncaceae), although the latter is common in a "wet" wadi draining from the southern edge of the Ru′us Al Jibal into Wadi Fay in the eastern half of the Dibba Zone.

6.3.2 *Temporal Gradients: Winners and Losers from Human Activities*

The pace of human activity adds a temporal element to ecosystem change in the UAE, beyond the recognized phenomenon of global climate change. Landscapes can be changed and habitats created or obliterated, seemingly overnight.

Human activities are seldom neutral from the point of view of natural environments and the ecosystems they host, but neither are they uniformly negative (see Chap. 23). The most common problem is that they disturb the natural dynamic equilibrium of local ecosystems in ways which too often work in favor of a small number of native or (more often) introduced species at the expense of many other species.

As just one example, over the past 25 years the construction of dams has proliferated in UAE mountain environments and has come to include most mountain wadis (Fig. 6.48). The advantages and disadvantages of dams at various scales and for various purposes have been the subject of debate internationally for decades. In the UAE, birdwatchers often consider dams a positive contribution, facilitating the passage of migrants and incidentally concentrating the birds for easy viewing. Naturalists more concerned about preserving existing wadi habitats and native species, or about groundwater levels in downstream areas and the alluvial plains beyond, generally have a different view.

A recent survey provides a snapshot of the diverse plant species found at more than 60 mountain region dams and water breakers (Mahmoud et al. 2018). These settings are "seed traps" for all the seeds that flow downstream during a rain, and evidently the fine, damp, clay-rich sediment deposited behind dams after periodic flooding creates good habitat for at least the initial propagation of many species, including both locally rare and exotic ones.

Historical experience allows us to add context to many names on the "dams" list. Some examples include the following: (i) The prickly amaranth *Amaranthus albus* (Amaranthaceae), first noticed in late 1999 in a newly plowed field in Wadi Maydaq (Jongbloed et al. 2003), is now common and conspicuous in silt at many dams and

Fig. 6.48 In recent decades, dams and sumps have been created in mountain areas on many scales: (**a**) Wadi Wurayah dam, successor to an earlier 1980s incarnation. (**b**) A bulldozed sump below Kadra dam in Wadi Asfani. (**c**) A shallow temporary pond in Wadi Hala, created by a graded road crossing. Photo credits: Gary Feulner

Fig. 6.49 Some plant species that have been expanding their UAE presence, facilitated by dams and sumps: (**a**) A large stand of *Amaranthus albus*, thriving at a sump beside a major pipeline route. (**b**) *Tephrosia nubica* has been expanding northwards for more than a decade, exploiting silt deposited behind dams and at other places where normal wadi drainage has been impeded. Possibly its spread has been facilitated by global warming. The tall, inverted conical shape of the plant is characteristic and helps to distinguish it from the much more common *T. apollinea*. (**c**) A stand of *Cyperus rotundus* (foreground) beside the Qashash Dam near Kadra. Photo credits: Gary Feulner

sumps in mountain wadis (Fig. 6.49a). (ii) *Tephrosia nubica* (Fabaceae) is very similar to the much more common *T. apollinea* in gross appearance, but is taller and thinner, with fuzzy, sub-ovate fruits (Fig. 6.49b). Once largely restricted to the mountains south of the Hatta Road, in the past decade or so this species has been expanding its range northward into the UAE, particularly where dam-induced flooding has deposited silt (Feulner pers. obs., N. Asmita pers. comm.). (iii) *Cyperus rotundus* (Cyperaceae) (Fig. 6.49c) is an aquatic sedge that favors damp, silty pond margins. Once limited to a few sites with year-round surface water, it is now locally common in silt behind several dams along the western mountain front. (iv) The carpetweed *Glinus lotoides*, a regional species, was first recorded in the UAE in 2016 (Mahmoud et al. 2018); it is now a dominant species behind many dams, where it boosts the populations of a few local butterflies and moths that can exploit it.

Apart from dams, the hand of man can sometimes turn rare endemics into locally more pedestrian species. Two uncommon UAE/Oman endemics—the gangly annual daisy *Launaea omanensis* (Asteraceae) (Fig. 6.50a) (N. Asmita, pers. comm.) and the prostrate *Schweinfurthia imbricata* (Scrophulariaceae) (Fig. 6.50b)—have been shown to be effective colonizers of ground disturbed by bulldozing and grading along roads and tracks. Even the much more common endemic *Pteropyrum scoparium* (Polygonaceae) is seen to prosper along the low gravel berms beside graded wadi tracks in harzburgite terrane.

It is instructive to attempt to monitor such phenomena, because they teach us how our various ecosystems respond to change. It is also potentially important, because it allows us to recognize and intervene in the event of genuinely undesirable or threatening outcomes. But in reporting results such as these, it is essential that the non-professional public should not be misled to think that the discovery of new species or the proliferation of rare species under such conditions is in any way a positive contribution to genuine biodiversity or to ecosystem health, or that they represent anything other than a disruption of the long-term natural order, with consequences that should be suspect in the first instance.

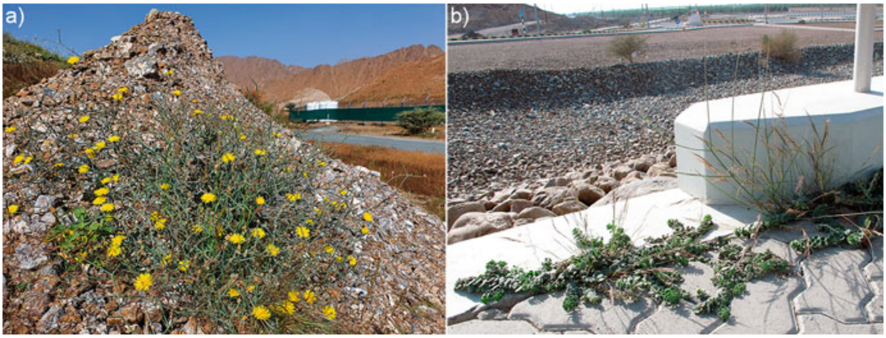


Fig. 6.50 Rare UAE/Oman endemic plants in prosaic anthropogenic locations: (**a**) *Launaea omanensis* along a bulldozed berm in Wadi Wurayah National Park. (**b**) *Schweinfurthia imbricata* among decorative paving stones on a promenade at Siji Dam. Photo credits: Nuri Asmita (a); Gary Feulner (b)

6.4 Conclusions

The mountain regions of the UAE constitute a complex biogeographical unit featuring a distinctive flora and fauna and a multitude of interrelated ecosystems. They remain, however, *terra incognita* to most biological researchers and to the general public, primarily due to limited vehicular access and the arduous and potentially dangerous nature of extended expeditions on foot. The results of the author's explorations and investigations over more than three decades are presented here in order to put that information more securely in the public record. The effort has been made to highlight items that might provoke further inquiry.

The author has been privileged to enjoy residence in the UAE during a time when his activities were welcomed and encouraged, and joins in congratulating the country on more than 50 prosperous years of federation. Regrettably, the world has moved on in some respects. In an era of heightened security concerns, the perceived need for increased regulation of individual initiatives, and the commoditization of human interactions with the natural environment, it would be much more difficult for current researchers to undertake efforts of similar scope. That makes it all the more important to give the foregoing account.

6.5 Recommended Reading

Flora of the Ru'us Al Jibal (Feulner 2011) and *Flora of Wadi Wurayah National Park* (Feulner 2016) are copiously illustrated accounts of those two fundamental but contrasting UAE mountain environments (the carbonate sediments of the Musandam versus the ultrabasic ophiolite of the Hajar Mountains) including geographical, geological, climate, ecological and historical information and regional comparisons, as well as annotated lists of the plant species recorded.

Jongbloed et al. (2003) remains the most comprehensive, authoritative and well illustrated account of the flora of the UAE generally. Its precursor, Western (1989), contains valuable introductory descriptions of the country's different plant environments and associations, especially for coastal areas that have been lost to development in the intervening years.

Feulner (2014) introduces the Olive Highlands, an elevated 'island' of biodiversity within the gabbro terrane of the Hajar Mountains, again with many illustrations. Brown and Sakkir (2004) present the distinctive environment of Jebel Hafeet from a botanical perspective.

Feulner (2006) reviews and discusses basic precipitation data for the UAE over the preceding few decades. Parker (2009) presents a very readable summary account of the climatic history of the UAE and northern Oman over the past 350,000 years, as inferred from the geological record.

The map of wadi fish distribution in Feulner (1998), although not fully comprehensive, has often been used as a surrogate for a census of the UAE and northernmost Oman wadis that sustain permanent surface water.

Almost all of the foregoing references are now available online.

References

Allen DJ, Westrip JRS, Puttick A, Harding KA, Hilton-Taylor C, Ali H (2021) UAE national red list of vascular plants. Technical Report. Ministry of Climate Change and Environment, United Arab Emirates, Dubai

Anacker BL (2011) Phylogenetic patterns of endemism and diversity. In: Harrison S, Rajakaruna N (eds) Serpentine: The evolution and ecology of a model system. Univ Calif Press, Berkeley, CA, pp 49–70

Babocsay G (2004) A new species of saw-scaled viper of the *Echis coloratus* complex (Ophidia: Viperidae) from Oman, Eastern Arabia. Syst Biodivers 1(4):503–514

Brown G, Sakkir S (2004) Flora and vegetation of Jebel Hafit. In: Aspinall S, Hellyer P (eds) Jebel Hafit, a natural history. Emirates Natural History Group, Abu Dhabi

Burriel-Carranza B, Els J, Carranza S (2022) Reptiles & amphibians of the Hajar Mountains. Consejo Superior de Investigaciones Cientificas, Madrid, pp 1-22

Carranza S, Simó-Riudalbas M, Jayasinghe S, Wilms T, Els J (2016) Microendemicity in the northern Hajar Mountains of Oman and The United Arab Emirates with the description of two new species of geckos of the genus *Asaccus* (Squamata: Phyllodatylidae). PeerJ 4:e2371. https://doi.org/10.7717/peerj.2371

Carranza S, Els J, Burriel-Carranza B (2021) Field guide to the reptiles of Oman. Consejo Superior de Investigaciones Cientificos, Madrid, pp 1-224

Cunningham PL, Feulner GR (2001) Notes on the distribution and ecology of the Dhofar toad *Bufo dhufarensis* Parker 1931, in the Musandam region (UAE and Sultanate of Oman). Tribulus 11(2):9–13

El-Keblawy A (2011) Plant community structure and diversity of Wadi Helo protected area: a floral database for future management. Environment and Protected Areas Authority – Sharjah, in collaboration with the University of the United Arab Emirates, pp 1-150

El-Keblawy AA, Khedr AA, Khafaga TA (2016) Mountainous landscape vegetation and species composition at Wadi Helo: a protected area in Hajar Mountains, UAE. Arid Land Res Manag. https://doi.org/10.1080/15324982.2015.1136970

Emirates Wildlife Society–WWF (2006) Establishment of a mountain protected area in Wadi Wurayah, Fujairah Emirate, United Arab Emirates. EWS-WWF, Dubai, pp 1-83

Feulner GR (1997) First observations of *Olea* cf. *europaea* (the wild olive) and *Ehretia obtusifolia* in the United Arab Emirates. Tribulus 7(1):12–14

Feulner GR (1998) Wadi fish of the UAE Tribulus 8(2):16–22

Feulner GR (1999a) A mountain wadi that flows to both the Arabian Gulf and the Gulf of Oman. Tribulus 9(2):26–28

Feulner GR (1999b) Annotated list of plants observed at Jebel Hafeet. Unpublished report to the Emirates Natural History Group – Abu Dhabi re field excursions between December 1997 and October 1999, covering the lower and intermediate slopes of the western ascent wadi, the lower slopes of two southwest flank wadis, the summit ridge, the north and south summit wadis, the lower slopes of an east flank wadi, the plains east of the jebel, and Wadi Tarabat, pp 1-7

Feulner GR (2004) Tail signaling in the semaphore gecko *Pristurus celerrimus*. Tribulus 14(1): 18–22

Feulner GR (2006) Rainfall and climate records from Sharjah airport: historical data for the study of recent climatic periodicity in the UAE. Tribulus 16(1):3–9

Feulner GR (2007) An unexpected resident butterfly of northern Oman: the Arabian grizzled skipper *Spialia mangana* (Lepidoptera: Hesperiidae). Tribulus 17:99–101

Feulner GR (2011) The flora of the Ru'us al-Jibal – the mountains of the Musandam peninsula: an annotated checklist and selected observations. Tribulus 19(4):4-153

Feulner GR (2014) The Olive Highlands: a unique "island" of biodiversity within the Hajar Mountains of the United Arab Emirates. Tribulus 22:9–34

Feulner GR (2016) The flora of Wadi Wurayah National Park, Fujairah, United Arab Emirates: an annotated checklist and selected observations on the flora of an ultrabasic environment in the northern Hajar Mountains. Report of a baseline survey conducted for Emirates Wildlife Society–WWF and sponsored by HSBC. Tribulus 24:8–84

Feulner GR, Green SA (1999) Freshwater snails of the UAE. Tribulus 9(1):5–9

Feulner GR, Green SA (2003) Terrestrial molluscs of the United Arab Emirates. Mitteilungen der Deutschen Malakologischen Gesellschaft 69(70):23–34

Feulner GR, Roobas BR (2014) An unexpected resident butterfly of northern Oman: the Arabian grizzled skipper *Spialia mangana* (Lepidoptera: Hesperiidae). Tribulus 22:41–44

Feulner GR, Roobas BR (2015) Spiders of the United Arab Emirates: an introductory catalogue. Tribulus 23:4–98

Feulner GR, Reimer RW, Hornby RJ (2007) An updated illustrated checklist of dragonflies and damselflies of the UAE. Tribulus 17:37–62

Feulner GR, Roobas BR, Hitchings V, Otto HHH, Campbell O, Roberts HGB, Hornby RJ, Howarth B (2021) Butterflies of the United Arab Emirates including northern Oman. Motivate Publishing, Dubai, pp 1-521

Freyhof J, Els J, Feulner GR, Hamidan NA, Krupp F (2020) Freshwater fishes of the Arabian Peninsula. Motivate Publishing, Dubai, pp 1-272

Garcia-Porta J, Simó-Riudalbas M, Robinson M, Carranza S (2017) Diversification in arid mountains: biogeography and cryptic diversity of *Pristurus rupestris rupestris* in Arabia. J Biogeogr 44:1694–1704. https://doi.org/10.1111/jbi.12929

Ghazanfar SA (1999) A review of the flora of Oman. In: Fischer M, Ghazanfar SA, Spalton JA (eds) The natural history of Oman: a festschrift for Michael Gallagher. Backhuys Publishers, London, pp 29–63

Glennie KW (1991) Sand dunes in the Emirates. Tribulus 1(1):14–17

Glennie KW (1996) Geology of Abu Dhabi. In: Osborne PE (ed) Desert ecology of Abu Dhabi. Pisces Publications, Newbury, pp 16–35

Glennie KW (2001) Evolution of the Emirates' land surface: an introduction. In: Ghareeb E, Al Abed I (eds) Perspectives on The United Arab Emirates. Trident Press, London. Reprinted in Al Abed I, Hellyer P (eds) United Arab Emirates: a new perspective. Trident Press, London, pp 9–27

Glennie KW, Boeuf MGA, Hughes-Clarke MW, Moody-Stuart M, Pilaar WFH, Reinhardt BM (1974) Geology of the Oman Mountains. Verhandelingen Koninklijke Nederland Geologisch Mijnbouwkundig Genootschap 31:1-423 + figures (3 parts)

Goodall TM (1994) The Sabkhat Matti – a forgotten Wadi system? Tribulus 4(2):10–13

Harrison SP, Kruckeberg AR (2008) Garden on the rocks. Nat Hist 117(4):40–44

Insall D (1999) A review of the ecology and conservation status of the Arabian Tahr *Hemitragus jayakari*. In: Fisher M, Ghazanfar SA, Spalton JA (eds) The natural history of Oman: a festschrift for Michael Gallagher. Backhuys Publishers, Leiden, pp 129–146

Jongbloed MVD, Feulner GR, Böer BB, Western AR (2003) The comprehensive guide to the wild flowers of the United Arab Emirates. Environmental Research and Wildlife Development Agency, Abu Dhabi, pp 1–576

Kay KM, Ward KL, Watt LR, Schemske DW (2011) Plant speciation. In: Harrison S, Rajakaruna N (eds) Serpentine: The evolution and ecology of a model system. Univ Calif Press, Berkeley, CA, pp 49–70

Kirchner S, Kruckenhauser L, Pichler A, Borkenhagen K, Freyhof J (2020) Review of the *Garra* species of the Hajar Mountains in Oman and the United Arab Emirates with the description of two new species (Teleostei: Cyprinidae). Zootaxa 4751(3):521–545

Kürschner H (1986) Omanisch-Makranische Disjunktionen Ein Beitrag zur pflanzengeographischen Stellung und zu den florengenetischen Beziehungen Omans. Botanische Jahrbücher für Systematik 106:541–562

Larsen TB (1983) Insects of Saudi Arabia – Lepidoptera; Rhopalocera (A Monograph of the Butterflies of the Arabian Peninsula). Fauna of Saudi Arabia 5:334–478

Larsen TB (1984) The zoogeographical composition and distribution of the Arabian butterflies (Lepidoptera; Rhopalocera). J Biogeogr 11:119–158

Larson DW, Matthes U, Kelly PE (2000) Cliff ecology: pattern and process in cliff ecosystems. Cambridge University Press, Cambridge

Léonard J (1989) Considerations phytogeographiques sur les phytochores irano-touranienne, saharo-sindienne et de la Somalie-pays Masai. Contribution à l'étude de la flore et de la vegetation des deserts d'Iran. Jardin Botanique Nationale Belgique, Brussels, pp 1-123

Llewellyn-Smith RE (2002) The Ru'us al-Jibal mountains of Ras al-Khaimah – considerations for and against establishing a protected area. Tribulus 12(1):15–19

Mahmoud T, Shabana HA, Gairola S (2018) First report on the flora of dams and water breakers in an arid desert of the United Arab Emirates. Pak J Bot 50(6):2301–2310

McClure HA (1984) Late quaternary palaeoenvironments of the Rub' Al Khali. PhD dissertation, Dept of Geography, Univ College London, pp 1-245

Melnikov DA, Ananjeva NB, Papenfuss TJ (2013) A new species of *Pseudotrapelus* (Agamidae: Sauria) from Nizwa, Oman. Russ J Herpetol 20(1):79–84

Moores EM (2011) Serpentine and other ultramafic rocks: Why they are important for earth's history and possibly for its future. In: Harrison S, Rajakaruna N (eds) Serpentine: The evolution and ecology of a model system. Univ Calif Press, Berkeley, CA, pp 1–28

Munton PN (1985) The ecology of the Arabian tahr (*Hemitragus jayakari* Thomas 1894) and a strategy for conservation of the species. J Oman Stud 8(1):11–48

Nazarov R, Melnikov D, Melnikova E (2013) Three new species of *Ptyodactylus* (Reptilia: Squamata: Phyllodactyllidae) from the Middle East. Russ J Herpetol 20(2):147–162

Neubert E (1998) Annotated checklist of the terrestrial and freshwater molluscs of the Arabian peninsula with descriptions of new species. Fauna of Arabia 17:333–461

Parker AG (2009) Chapter 3: Pleistocene climate change in Arabia: developing a framework for hominin dispersal over the last 350 ka. In: Petraglia MD, Rose JI (eds) The evolution of human

populations in Arabia, vertebrate paleobiology and paleoanthropology. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-2719-1_3
Parker A, Eckersley L, Smith MM, Goudie AS, Stokes S, White K, Hodson MJ (2004) Holocene vegetation dynamics in the northeastern Rub' al-Khali desert, Arabian peninsula: a pollen, phytolith and carbon isotope study. J Quat Sci 19:665–676
Parker AG, Preston GW, Parton A, Walkington H, Jardine PE, Leng MJ, Hodson MJ (2016) Low-latitude Holocene hydroclimate derived from lake sediment flux and geochemistry. J Quat Sci 31(4):286–299
Parton A, Farrant AR, Leng MJ, Telfer MW, Groucutt HS, Petraglia MD, Parker AG (2015) Alluvial fan records from Southeast Arabia reveal multiple windows for human dispersal. Geology 43(4):95–98
Pichler A, Ahnelt H, Kirchner S, Sattmann H, Haring E, Handschuh S, Freyhof J, Victor R, Kruckenhauser L (2018) The morphological diversity of *Garra* barreimiae (Teleostei: Cyprinidae). Environ Biol Fish 101:1053–1065
Reimer RW, Feulner GR, Hornby RJ (2009) Errata and addenda: updated illustrated checklist of dragonflies of the UAE. Tribulus 18:28–36
Roobas B, Feulner GR (2013) A population of Bosk's fringe-toed lizard *Acanthodactylus boskianus* (Daudin, 1802) in the Hajar Mountain foothills of the UAE. Tribulus 21:24–37
Roobas B, Feulner GR, Thakur Y (2014) Bosk's fringe-toed lizard *Acanthodactylus boskianus*: follow-up study of a population in the Hajar Mountain foothills of the UAE. Tribulus 22:35–40
Ross Z, Burt J (2015) Unusual canopy architecture in the umbrella thorn acacia, *Vachellia tortilis* (= *Acacia tortilis*), in the United Arab Emirates. J Arid Environ 115:62–65
Sanlaville P (1992) Changements climatiques dans la Péninsule Arabique durant le Pléistocène supérieur et l'Holocène. Paléorient 18(1):5–25
Sanlaville P (1998) Les changements dans l'environnement au Moyen-Orient de 2,000 BP a 6,000 BP. Paléorient 23(2):249–262
Simó-Riudalbas M, Metallinou M, de Pous P, Els J, Jayasinghe S, Péntek-Zakar E et al (2017) Cryptic diversity in *Ptyodactylus* (Reptilia: Gekkonidae) from the northern Hajar Mountains of Oman and the United Arab Emirates uncovered by an integrative taxonomic approach. PLoS One 12(8):e0180397. https://doi.org/10.1371/journal.pone.0180397
Tourenq C, Brook M, Knuteson S, Shuriqi MK, Sawaf M, Perry L (2011) Hydrogeology of Wadi Wurayah, United Arab Emirates, and its importance for biodiversity and local communities. Hydrol Sci J 56(8):1407–1422. https://doi.org/10.1080/02626667.2011.631139
United Arab Emirates University (1993) The National Atlas of The United Arab Emirates. United Arab Emirates University, Al Ain
van Harten A (ed) (2008) Arthropod Fauna of the United Arab Emirates, vol. 1. Dar Al Ummah, Abu Dhabi, pp 1–754
van Harten A (ed) (2009) Arthropod Fauna of the United Arab Emirates, vol. 2. Dar Al Ummah, Abu Dhabi, pp 1–786
van Harten A (ed) (2010) Arthropod Fauna of the United Arab Emirates, vol. 3. Dar Al Ummah, Abu Dhabi, pp 1–700
van Harten A (ed) (2011) Arthropod Fauna of the United Arab Emirates, vol. 4. Dar Al Ummah, Abu Dhabi, pp 1–832
van Harten A (ed) (2014) Arthropod Fauna of the United Arab Emirates, vol. 5. Department of the President's Affairs, Abu Dhabi, pp 1–744
van Harten A (ed) (2017) Arthropod Fauna of the United Arab Emirates, vol. 6. Department of the President's Affairs, Abu Dhabi, UAE, pp 1–775
Western AR (1989) The flora of the United Arab Emirates: an introduction. UAE University, Al Ain, pp 1–188
Zohary M (1963) On the geobotanical structure of Iran. Bull Res Counc Israel 11D:1–113
Zohary M (1973) Geobotanical foundations of the Middle East. Gustav Fischer Verlag, Stuttgart, 2 vols, pp 1–739

Chapter 7
Mangrove Ecosystems of the United Arab Emirates

Guillermo Friis and Mary E. Killilea

7.1 UAE Mangroves in a Global Context

Mangroves are a taxonomically diverse group of halophytic (salt-tolerant) shrubs and trees that occur in the space between the high and low tides on tropical and subtropical coastlines, a harsh and highly dynamic environment that presents exceptional challenges to the species that inhabit it (Hogarth 2015; Primavera et al. 2018; Spalding et al. 2010; Tomlinson 2016). The term mangrove has been also used to refer to the broader intertidal communities formed by these trees plus their associated biota, which are referred to as 'mangrove ecosystems' hereafter. Mangrove plants that are exclusively restricted to intertidal habitats are defined as "true mangroves", and they form forests often consisting of monospecific patches or bands fringing muddy shores, predominately occurring in areas of gentle wave conditions such as bays, deltas and estuaries (Hogarth 2015; Nagelkerken et al. 2008). Mangroves act as ecosystem engineers, stabilizing the soil and creating a habitat that is exploited by a range of other organisms, from microbial communities to diverse assemblages of fauna and flora. Mangrove trees and associates are uniquely adapted to conditions that include alternating desiccation and submergence across tidal cycles, low oxygen concentrations in the water, variable and often high salinity, and high air and sea temperatures inherent to the tropics.

Despite sharing several, complex morphological and physiological adaptations enabling survival in this environment, mangroves species did not evolve from a single common ancestor. In fact, true mangroves are a polyphyletic group (*i.e.* have

G. Friis (✉)
Center for Genomics and Systems Biology, New York University – Abu Dhabi, Abu Dhabi, United Arab Emirates

M. E. Killilea
Departments of Biology and Environmental Studies, New York University, New York, NY, USA

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_7

evolved from multiple evolutionary ancestors) composed by around 70 species from up to 20 families, in which distinct mangrove types have likely evolved independently at least 16 times (Hogarth 2015; Primavera et al. 2018). Of all the mangrove species described, only the gray mangrove (*Avicennia marina*) naturally occurs in the coasts of the UAE. The genus of *A. marina* is named after the Muslim philosopher and father of modern medicine Ibn Sīnā (commonly known as Avicenna in the West; 981–1037 CE), and is locally referred to as 'Al Qurum' in the countries of the Arabian Peninsula.

7.2 Mangrove Ecology and Distribution in the UAE

Different species of mangrove occur throughout the tropics, as well as in a few warm subtropical areas. They can survive air temperatures as low as 5 °C, but are intolerant of frost. Mangrove distribution, however, correlates most closely with sea temperature, rarely occurring outside of areas where average daily temperatures fall below 20 °C (Hogarth 2015). Of all mangrove species, the gray mangrove has the broadest latitudinal and longitudinal distribution (Spalding et al. 2010; Tomlinson 2016), extending across the entire Indian Ocean and into the West Pacific as far as Japan and New Zealand (Fouda and AI-Muharrami 1996; Khalil 2015; Sheppard et al. 2010; Spalding et al. 2010). The broad geographic distribution of the gray mangrove is reflected in its presence across diverse environmental gradients (e.g. temperature, freshwater, sediment and nutrient supply, salinity, tidal range) and spatial settings (e.g. open coastlines, coastal lagoons, estuaries, deltas, coral fringes) (Duke 1990; Quisthoudt et al. 2012). The Arabian Peninsula represents one of the northernmost edges of the species' distribution (Duke 1991; Spalding et al. 2010; Tomlinson 2016), as well as an environmentally stressful habitat characterized by extreme temperatures, aridity, and often extreme salinity (see Chaps. 3 and 4), factors known to be limiting for mangrove growth (Ball 1988; Lovelock et al. 2016; Sheppard et al. 1992).

Mangroves ecosystems represent the only evergreen forests in the UAE, covering approximately 156 km^2 of land along the coasts of the country (Fig. 7.1; Killilea and Burt, in prep). Coastal topography plays a major role in the patchy and scattered pattern of mangroves throughout the coasts of the UAE. Sheltered lagoons house approximately half of the mangroves in the nation. Remaining stands consist of relatively linear communities occurring across intertidal areas bordering a number of bays, islands and tidal creeks from the westernmost coasts of the UAE near Al Ruwais throughout Abu Dhabi coasts, Ras Al Khaimah and Umm Al Quwain in the north; Dubai's single mangrove population consists of the planted stand at Ras Al Khor. Outside the Arabian Gulf, in the Sea of Oman, lies the only mangrove forest on the UAE's east coast, in the Khor Kalba reserve near the border with Oman (Fig. 7.2; Al Habshi et al. 2007; Almahasheer 2018; Moore et al. 2014; Saenger et al. 2002; Saito et al. 2003).

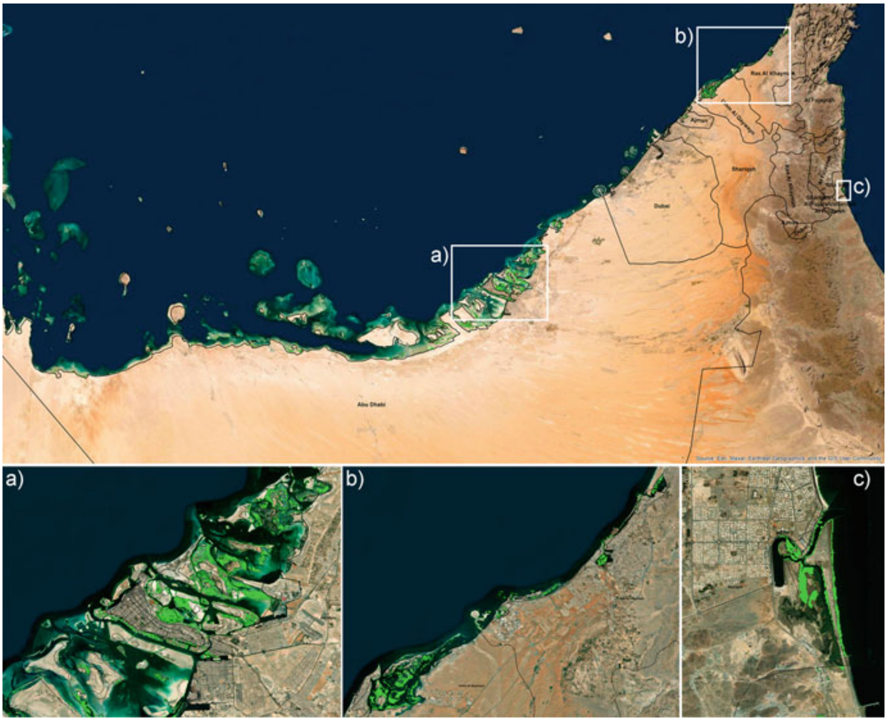


Fig. 7.1 Mangroves distribution. Top panel: Distribution of mangroves, shown in green, of the UAE created using GEEMMM in Google Earth Engine with Landsat imagery collected between 2020 and 2022 (method from Yancho et al. 2020). Bottom panel: provides detailed view of the areas indicated in the top panel (**a**) Abu Dhabi mangroves. (**b**) Ras Al Khaimah and Umm Al Quwain mangroves. (**c**) Khor Kalba mangroves. Basemap courtesy of ESRI “World Imagery” [basemap]. Accessed 20 March 2023 from https://www.arcgis.com/apps/mapviewer/index.html?layers=10df2279f9684e4a9f6a7f08febac2a9 per the ESRI data use policy

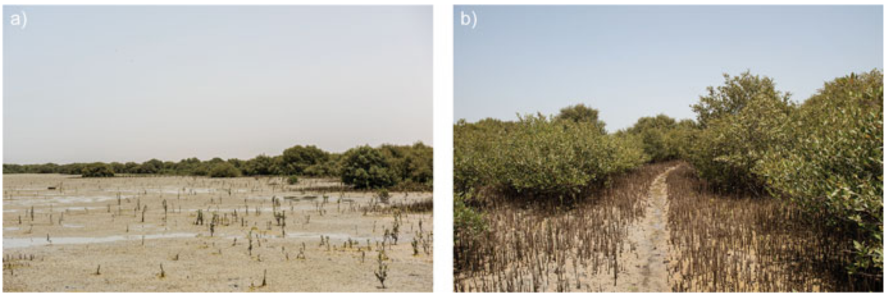


Fig. 7.2 Mangrove stands distribution in Ras Al Khaimah. (**a**) Linear mangrove stand fringing shoreline mudflats during low tide. (**b**) Mangroves growing along an inland tidal creek. Image credits: Vidhyaa Chandramohan

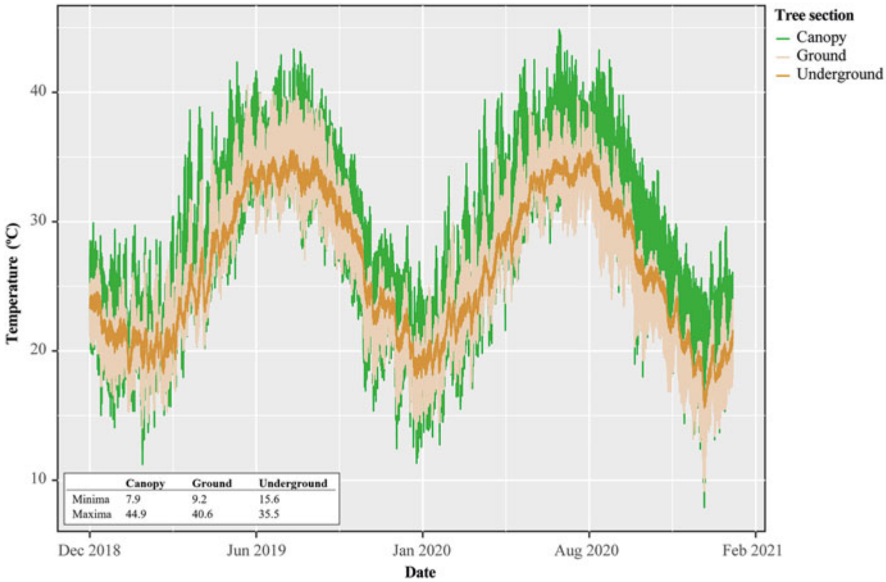


Fig. 7.3 Temperature variability through seasons in the mangroves of the UAE. Temperature records from ten different mangrove trees at Ras Ghurab, Abu Dhabi, measured at different heights through 2 years. Source: G. Friis, unpubl. Data

Distribution of contemporary populations of mangroves in the nation is not only limited by the coastal topography. Three main environmental factors constrain the occurrence of mangroves along UAE coastlines: wide seasonal variation in temperatures, high seawater salinity, and poor soil conditions (Al Habshi et al. 2007). Due to its geographic location in the northern subtropical high-pressure zone, the climate of the UAE is characterized by extreme aridity, with <150 mm of annual rainfall common across the country, and many areas experiencing <100 mm yr.$^{-1}$ (Al Habshi et al. 2007) (See also Chap. 3). The limited cloud cover results in high solar irradiance, causing land surface temperatures in many places to exceed 50 °C during summer days, with winter nighttime temperatures plunging below 8 °C due to the limited availability of vegetation and soil moisture to modulate temperatures (Patlakas et al. 2019). Coastlines of the UAE inhabited by mangroves are no stranger to these extremes. Two-year monitoring of temperatures at ten mangrove trees in a stand at Ras Ghurab Island, Abu Dhabi, revealed annual temperature ranges of 37, 30 and 25 °C in the canopy, on ground level and underground (~ 15 cm depth), respectively, with minimum and maximum temperatures ranging from 8 to 45 °C (Fig. 7.3). These records are highly congruent with previously reported thermal profiles in mangrove stands from the UAE (Al Habshi et al. 2007; Embabi 1993). Limited freshwater input and high evaporation rates also result in extreme salinity on the UAE's enclosed Arabian Gulf coast (Vaughan et al. 2019). Sheltered areas preferred by mangroves such as lagoons and bays present particularly high salinity levels, especially in summer. Generally, mangroves can grow when salt concentrations stay below 45 to 50 ppm, yet there are records of salinity maxima in UAE mangrove stands ranging from 65 to 70 ppm in places such as Al Dabbiya, Khor Al Khuwair or Umm Al Quwain (Al Habshi et al. 2007; Shriadah 2000). High salinity is known to have significant impacts in the development and structure of mangroves, often resulting in stunted 'dwarf' trees, so that gray mangroves in the UAE rarely exceed the 5–7 m (Embabi 1993; Moore et al. 2014), while they can reach the 14 m in tropical environments. Only the mangrove system of the Khor Kalba reserve escapes this impact, to some extent. In contrast with the Arabian Gulf, the eastern coast of the UAE, bordered by the Sea of Oman, has normal oceanic salinity, and summer temperatures that are buffered by cold-water upwelling as a result of the Indian Ocean monsoon, resulting in a more moderate and less variable environment (Claereboudt 2019; Sheppard et al. 1992). Finally, studies on soil characteristics and chemistry revealed that mangroves of the UAE are restricted to substrates formed mostly by fine sand (95%) but with presence of silt and clay (5%), and are not observed on rocky soils or on pure sand beaches (Al Habshi et al. 2007). Nutrients such as nitrogen (N), phosphorus (P) and iron (Fe) known to be relevant for mangrove growth and survivorship (Almahasheer et al. 2016; Naidoo 2009) also occur in short supply in the soils of the UAE (Al Habshi et al. 2007; Moore et al. 2014), and their availability further determine the occurrence of mangrove ecosystems throughout the western and eastern coasts of the country.

Gray mangroves present several adaptative traits that enable their survival in the harsh environment of the intertidal zones of the UAE. As other mangroves species, they have mechanisms for salt uptake and excretion through specialized glands in the underside of the leaves (Howari et al. 2009). They also feature pencil-like roots of about 20 cm height, known as pneumatophores, which grow up above the ground to allow gas exchange for the mangrove roots to compensate for the anaerobic soils in which they grow. The root system of the gray mangrove is generally shallow, running horizontally and radially for several meters from the tree (Purnobasuki and Suzuki 2005), providing support to the substrate. Gray mangroves also produce buoyant seeds that can remain dormant for up to a year until they establish in a suitable environment (Alsumaiti et al. 2017). While these traits are shared by gray mangroves throughout their entire distribution, populations from the UAE, and in particular those occurring on its western Arabian Gulf coast, have seemingly developed specific adaptations to the local environmental conditions, such as more complex cuticular waxes coating the leaf surfaces to protect against water loss (Dodd et al. 1999) or genetically-based changes in physiological traits to cope with aridity, temperature and salinity extremes (Friis et al. 2022).

7.3 Ecological Importance and Diversity Supported by UAE Mangrove Forests

7.3.1 Ecological Functions, Interactions and Productivity of Mangrove Trees in Coastal Ecosystems of the UAE

Mangrove trees modify the conditions of their habitat by maintaining a relatively stable balance between deposition and erosion in intertidal zones. Anatomical structures such us pneumatophores and other kinds of aerial roots provide hard substrata in otherwise soft-sediment soils, creating an environment that is, in turn, exploited by a range of fauna and flora occurring not only at mangrove forests themselves, but across multiple, interconnected marine and terrestrial habitats (ElAmry 1998; Nagelkerken et al. 2008; Primavera et al. 2018). They are also major contributors of energy flow to detritus-based marine food webs (Jennerjahn and Ittekkot 2002), and provide several important functions such as shelter areas, nurseries, breeding and nesting grounds and feeding habitat (ElAmry 1998; Nagelkerken et al. 2008).

Although it is reasonable to assume that the ecological functions of mangroves in the Emirates are comparable to those in other tropical and subtropical regions, the specific mechanisms and relevance of UAE mangroves in the coastal biological systems remain relatively understudied. Little is known, for example, about insect species potentially involved in mangrove pollination in the UAE. Documented pollinators of *A. marina* in other parts of its distribution, such as the honeybee (*Apis mellifera*) or the oriental blue fly (*Chrysomya megacephala*), occur in the UAE, but studies confirming the role of these or other species in mangrove pollination are lacking. In terms of productivity, UAE mangroves have strikingly high biomass and primary productivity rates considering the harsh environment they inhabit. The standing biomass can reach 110 tons per hectare in dense mangroves (Saito et al. 2003). Litter fall estimates range from 5.1 to 8.5 tons per hectare per year depending on the height of the surveyed stands (Spalding et al. 2010), a highly significant input of inshore organic matter in this arid region where primary productivity is so limited (Spalding et al. 2010; See Box 7.2). However, net fluxes of organic matter towards other oceanic or terrestrial ecosystem have not been estimated in the UAE. Despite the lack of information, the role and importance of UAE mangrove as ecosystem engineers is reflected in the diverse biotic communities they support, including arthropods, mollusks, birds, fishes and other plant species. The most relevant and iconic of these species are detailed next.

7.3.2 Crabs

Brachyuran crustaceans, commonly known as crabs, are an important, often dominant element within the faunal assemblages of the intertidal habitats of the Arabian

Fig. 7.4 Crabs and mollusks in UAE mangrove ecosystems. (**a**) *Metopograpsus messor* and *llyograpsus paludicola* crabs forage by mangrove pneumatophores, Umm Al Quawain. (**b**) Mud snails *Cerithidea cingulata* crowd in the sediments of a mangrove forest, Umm Al Quawain. (**c**) Barnacles on a dead mangrove branch in the Eastern Mangroves Park, Abu Dhabi. (**d**) The giant mudcreeper (*Terebralia palustris*), a locally endangered species that can only be found in the mangroves of Khor Kalba in the UAE. Images credit a–c: Vidhyaa Chandramohan. Image credit d: From Fig. 7.2 in Lieb et al. (2010), reproduced under the terms of the Creative Commons Attribution License (CC BY 2.0)

Gulf, including those covered by mangroves (Apel and Turkay 1999). Like mangrove trees themselves, crabs play a key role in the ecosystem, promoting nutrient recycling and shaping the structure of mangrove forests (Nobbs and Blamires 2015). Their activity affects the availability of resources for other mangrove-associated organisms through burrow construction and maintenance, shredding of plant litter, and by modifying the activity and distribution of the sediment microbiota (Nobbs and Blamires 2015). Along the UAE's Arabian Gulf coast, crab communities in the mangrove ecosystems are dominated by species of the families Ocypodidae (16 species) and Grapsidae (4 species), with as well as representation by the families Portunidae (like the mangrove crab, *Scylla serrata*), Majidae, Xanthidae, and Leucosiidae (Al-Ghais and Cooper 1996; Apel and Turkay 1999; Cooper 1997). Most commonly seen species are the grapsids *Metopograpsus messor* and *llyograpsus paludicola* (Fig. 7.4). Crab diversity is seemingly higher in the northeast of the UAE coasts inside the Arabian Gulf according to the most complete survey published to date (Apel and Turkay 1999), due to the conspicuous absence of fiddler crabs (genus *Uca*) in the southern and western Gulf (Apel and Turkay 1999). In addition, a diversity survey conducted in the Khor Kalba reserve (Aspinall et al.

2002) revealed the presence of two other species absent within the Gulf: *Clibanarius longitarsus* and *Perisesarma guttatum*.

7.3.3 Mollusks

Several species of marine mollusks (clams, snails, whelks, etc.) can be found in the soft sediments and flats inhabited by the mangroves of the UAE, yet their general distribution is only partially determined by the presence of mangrove trees (Grizzle et al. 2018). Bivalves occurring in high densities in mangrove forests include the hooded oyster (*Saccostrea cuccullata*) and the Venus clam (*Circenita callipyga*). Among other gastropods we can find the crown turban snail (*Lunella coronata*), the mud snail species *Cerithidea cingulata* (Fig. 7.4) or the sea snail species *Hexaplex kuesterianus* (Grizzle et al. 2018). Barnacles are occasionally present on the pneumatophores, mostly *Euraphia withersi* but also *Balanus amphitrite* and *B. trigonus* (John and George 2004). In addition, in the Khor Kalba mangroves of the east coast we can find the giant mudcreeper (*Terebralia palustris*, Fig. 7.4). This gastropod was once common in the western coasts of the country, as well as an important food resource for local human communities, as proven by its presence in shell middens found by prehistoric settlements (Aspinall et al. 2002; See Sect. 4). However, habitat destruction and other environmental pressures likely drove the giant mudcreeper to the extinction in the southern Arabian Gulf (Aspinall et al. 2002).

7.3.4 Fishes

Mangrove ecosystems are also known to play an important role in sustaining different fish species through various ecological functions. The specific relevance of mangroves for fish diversity in the UAE is, however, not well characterized, and potential connections between mangroves ecosystems and fish-exploited habitats such as seagrass and reefs remain understudied in the region. A fish population survey conducted in mangrove swamps in Abu Dhabi, Umm Al Quwain and Ras Al Khaimah (Al-Ghais 1993) identified two evenly distributed, dominant species in this habitat: the Arabian toothcarp (*Aphanius dispar*) and the common silver-biddy (*Gerres oyena*). A large number of juveniles were also recorded, some of which were species of high economic interest such as *Lutjanus fulviflama*, *Liza macrolepis*, *Sparus sabra*, *Pseudohombus javanicus* or *Cynoglossus* sp. Small bottom-dwelling fish such as blennies and gobies were also found, sometimes in large numbers (Al-Ghais 1993).

7.3.5 Birds

The coasts of the UAE serve as an essential breeding and non-breeding area for vast numbers of birds (Aspinall 1996; Shah et al. 2018). Mangrove habitats in particular support a rich diversity of avian life, yet the importance of mangrove ecosystems to the avifauna has not been documented in depth in this region. Two UAE resident species of heron are known to heavily rely on mangroves: the western reef heron (*Egretta gularis*, Fig. 7.5a) and the striated heron (*Butorides striata*). These species use the mangrove forest as foraging habitats and for nesting, yet they are not restricted to them (Shah et al. 2018). In the east coast, the mangroves and mudflats

Fig. 7.5 Birds in UAE mangrove ecosystems. (**a**) Western reef herons (*Egretta gularis*) perching in the Eastern Mangroves Park, Abu Dhabi. (**b**) Kalba white-collared kingfisher (*Halcyon chloris kalbaensis*). (**c**) Greater flamingos (*Phoenicopterus roseus*) in Bul Syayeef. Image credits: Oscar Campbell

of Khor Kalba are critical to the survival of an endemic subspecies of the white-collared kingfisher, the *Halcyon chloris kalbaensis* (Fig. 7.5b), which breeds nowhere else in the world (Aspinall et al. 2002). The white-collared kingfisher nests in holes in mangrove trees, and feeds on crabs present in the mudflats and from among the mangrove's pneumatophores during low tides (Aspinall et al. 2002). Khor Kalba is also the only place of the UAE where we can find the Sykes's warbler (*Hippolais rama*), although it is not rare in other regions of the world (Aspinall et al. 2002). A celebrated bird species in the UAE is the greater flamingo (*Phoenicopterus roseus*, Fig. 7.5c). An usual winter visitor, it started breeding in Abu Dhabi only three decades ago (S. B. Khan et al. 2017). Since 2009, flamingos have been regularly breeding in Bul Syayeef, a marine area in Abu Dhabi of particular importance due to the presence of large stretches of inter-tidal mudflats, mangroves and salt marshes. Other winter visitors include species of interest like the Western Marsh Harrier (*Circus aeruginosus*) from Central Asia, or the Greater Spotted Eagle (*Clanga clanga*), a species of global conservation concern. Up to 20 of them can be seen each winter at Ras al Khor in Dubai (Oscar Campbell, *pers. comm.*). The Western Cattle Egret (*Bubulcus ibis*) also winters in Abu Dhabi, and every night they fly to the mangroves to roost. Other species in the UAE use mangroves for roosting, including the iconic Purple Sunbird (*Cinnyris asiaticus*) or various dove species.

7.3.6 Plants

Only a reduced number of plant species are able to cope with the environmental conditions found in the mangrove habitats, beside *A. marina* itself. The most common is the amaranth shrub *Arthrocnemum macrostachyum*, easily found along the inland limits of mangrove bands (Böer and Saenger 2006). The parasite plant *Cistanche tubulosa* (Fig. 7.6b), known as the dessert Hyacinthus, is also common, and easy to spot during its reproductive period in March and April. The species *Salicornia europaea*, cultivated for oilseed and as a fodder crop in various parts of the world, grows along with mangrove trees on the edge of the large Khor Al Beida in Umm Al Quwain (Shahid 2017). At some mangrove stands across the UAE, pneumatophores often appear shrouded by curtain-like growths of green filamentous algae, principally *Chaetomorpha linum* and *Cladophora nitellopsis* (John and George 2004).

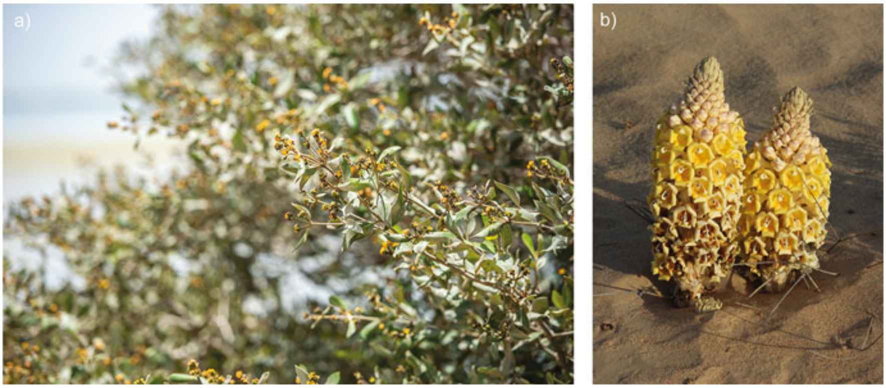


Fig. 7.6 Plant associates in UAE mangrove ecosystems. (**a**) Flower detail of a mangrove tree, Ras Al Khaimah. (**b**) Dessert Hyacinthus (*Cistanche tubulosa*). Images credit a: Vidhyaa Chandramohan. Images credit b: Cistanche tubulosa Huqf 2.jpg by Diorit, reproduced under the Creative. Commons Attribution-Share Alike 4.0 International license (CC-BY-SA-4.0)

7.4 Cultural and Economic Importance of the Mangrove Ecosystem in UAE

Mangrove ecosystems in the UAE have historically been an important cultural and economic resource (Uerpmann and Uerpmann 1996; Beech and Kallweit 2001; Beech and Hogarth 2002), while in other parts of the world they had been viewed as having limited economic or cultural value (Lugo and Snedaker 1974). There is extensive archeological evidence of mangrove ecosystems being an important regional food resource. Mangrove associated mollusks (*Terebralia palustris*, Fig. 7.5) have been found in the middens of archeological sites in Ras al Khaimah dating back to the Stone Age, and in Kalba dating back to the Bronze Age (Beech and Kallweit 2001; Goudie et al. 2000; Lindauer et al. 2017). Three other archeological sites across the UAE have found remains of mangrove crabs (*Scylla serrata)* in middens providing further support regarding the importance of mangrove ecosystems as a food resource (Beech and Hogarth 2002). Additional archeological sites, from 6000 ybp in Ras al Khaimah, found fish bones and oyster shells with mangrove root impressions further supporting a long history of mangrove ecosystems economically supporting the Arabian Gulf region (Uerpmann and Uerpmann 1996).

Direct uses of mangroves include timber and camel fodder. Camels have been observed eating mangrove leaves and it has been suggested that they were historically used as camel fodder (Lieth and Lieth 1993; Llewellyn-Smith 2012). The presence of mangrove stumps provide evidence of harvesting the trees (Goudie et al. 2000), and the wood was an important resource for home construction and boat building in the region (Beech and Hogarth 2002).

The discovery of oil and changing economy of the twentieth century resulted on less direct dependence on coastal ecosystems, and an increase in coastal development and environmental pressure on mangrove ecosystems. In the late 1970s H.H. Sheikh Zayed bin Sultan al Nahyan, President of the UAE., initiated plantings of both native and introduced species of mangroves in the UAE and restricted the harvesting of mangroves (Lieth and Lieth 1993; Saenger et al. 2002). Ultimately, *A marina*, the local mangrove species was the only species that successfully established in the UAE (Lieth and Lieth 1993). During the 1980s and 1990s, there was scientific and economic interest in creating plantations of halophytic species to create agricultural benefits without straining freshwater resources which included a research conference in Al Ain in December 1990 that resulted in several research papers on mangroves (Lieth and Al Masoom 1993).

The twenty-first century brought a change in the cultural and economic value of mangrove ecosystems from agricultural ecosystems, where resources are extracted, to ecosystems that need protection. Through protection and planting programs developed in the previous decades there was a near doubling in the extent of mangroves in the UAE. Recent interest in mangroves has been focused on their environmental and recreational value.

In 1995 0.96% of the UAE gross national product was from tourism this increased to 9.2% in 2019 which corresponds with 20 million more visitors per year ("Tourism in the United Arab Emirates" 2022). Mangrove parks provide an opportunity for visitors to experience the natural resources of the UAE. Kayaking tours are a popular way to explore the Mangrove National Park in Abu Dhabi and the mangrove ecosystems in Ras al Khaimah. Ras al Khor in Dubai provides a walkway and hides where tourists can observe flamingos, while in 2011 their logs only included 950 tourists they represented 88 different countries (Ryan et al. 2012). These sites not only attract international tourists but also provide educational opportunities for local schools. The link between education, tourism and conservation were highlighted during a visit to the UAE by Prince William in February 2022 when his schedule included planting mangroves in Jubail Mangrove Park, which opened in January 2020 to help protect biodiversity and raise awareness of the UAEs mangrove ecosystems (Forster and Maxwell 2022).

While mangroves provide eco-tourism opportunities, the economic growth of the region has led to habitat loss and environmental degradation in some areas. At the same time there is an increasing interest by residents of the UAE to protect these ecosystems. The majority of residents recently surveyed in Ras al Khaimah supported preservation of the mangroves over economic development, but this desire to protect these ecosystems does not seem to be driven by a knowledge of the ecosystem services they provide (Assaf et al. 2022). Whether or not the general public can clearly identify the environmental and economic value of these ecosystems there has been an increased interest in seeing these ecosystems continue to thrive.

Box 7.1 Evolution and Diversity of Arabian Mangroves

The evolutionary processes that led to the colonization and adaptation by *Avicennia marina* to the harsh environment of the western coasts of the UAE and the rest of the Arabian Gulf represent a fascinating mystery for evolutionary biologists. The diversification of the different varieties of *Avicennia marina* has been dated at approximately 3 million years ago (Li et al. 2016), with the variety *A. m. marina* occupying the largest fraction of the species distribution, from the coasts of East Africa and the Arabian Peninsula to the southern coast of Japan and the Western and Northern coasts of Australia, throughout the Indian Ocean to the South of China. However, the Arabian Gulf is a very young sea. Being as shallow as 36 m on average, the Arabian Gulf was completely drained during the peak of the last glaciation, which encompassed the period from 115,000 to 12,000 years ago, approximately. It was not until 12,500 years ago that the infilling of the southern basin of the Gulf started, and present shorelines were not reached until just 6000 years ago (Lambeck 1996). It was assumed, therefore, that the gray mangrove populations of the Arabian Gulf were the result of a recent colonization that followed the formation of the enclosed sea after the last glacial maximum, an extraordinarily short period of time in evolutionary terms during which, nevertheless, the mangroves were able to adapt to the exceptionally stressful environment of the region. However, analyses based on genetic data suggest an alternative, unexpected scenario. Phylogenetic analyses reconstructing the evolutionary relationships among mangroves of the UAE both inside and outside the Arabian Gulf reveals that these populations are highly differentiated, and that the differentiation process started around 32,000 years ago, before the last glaciation peak (Friis et al. 2022). In other words, mangrove populations from the Arabian Gulf are older than the Gulf itself, and they seemingly survived in relict 'marine swamps' during the last glacial period, a pattern never documented before for any marine taxa in this region. Genetic indices such as nucleotide diversity and heterozygosity, reveal higher levels of genetic diversity in the mangroves of the east coast compared to those within the Arabian Gulf, where the reduced habitat availability during the glaciation seemingly resulted in more genetically depauperate populations. Furthermore, the Tajima's D index, a parameter that correlates with recent

(continued)

Box 7.1 (continued)
demographic growth, shows a more pronounced pattern of population expansion in the UAE populations from within the Gulf, congruent with a demographic recovery following the end of the glaciation and rise of the sea levels (Fig. 7.B1.1).

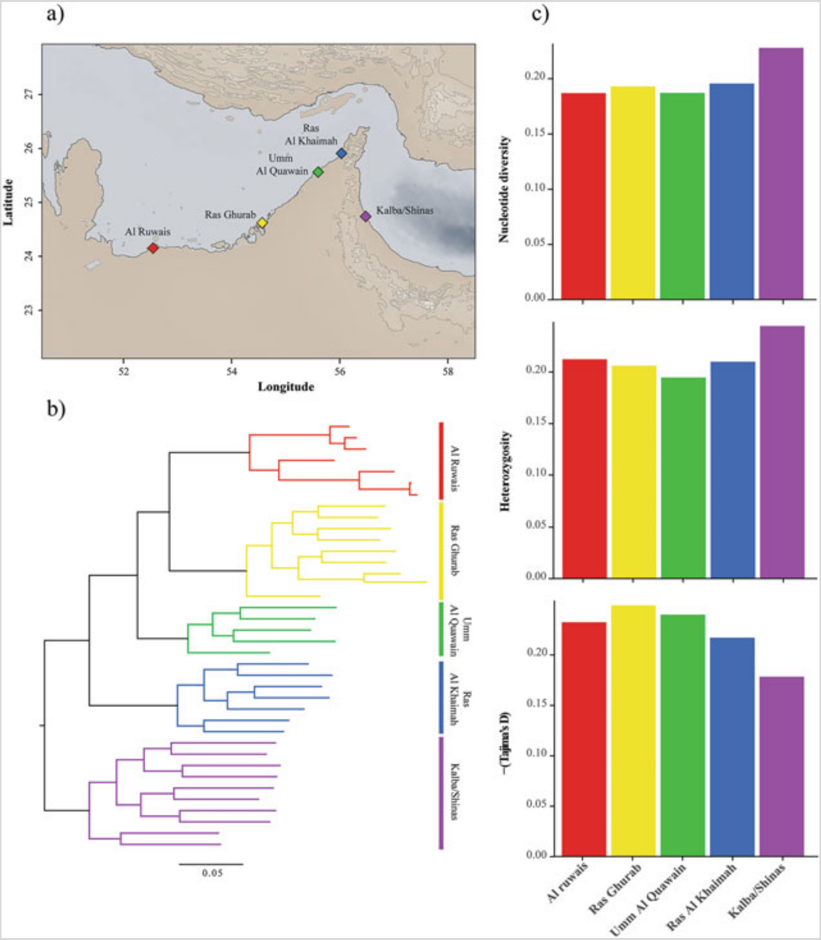


Fig. 7.B1.1 Evolutionary history and genetic diversity in UAE mangroves. (**a**) Geographic location of the analyzed mangrove populations. (**b**) Phylogenetic tree. Each terminal branch represents an individual, colored by population of origin. Internal branches represent evolutionary relationships among mangrove populations. Branch lengths depict genetic distance among individuals (substitutions per site). (**c**) Estimates of genetic diversity (nucleotide diversity and heterozygosity) and demographic expansion (Tajima's D). Data source: G. Friis, unpubl. Data

Box 7.2 Mangroves as Blue Carbon Ecosystems

Measurements of global average atmospheric carbon dioxide (CO_2) provided by the National Oceanic and Atmospheric Administration (NOAA) hit its highest ever peak in May 2022 at an average of more than 420 parts per million, a 50% higher concentration than in pre-industrial times. Along with mitigation strategies to reduce emissions derived from fossil fuel combustion, approaches to fight against climate change include nowadays strategies supporting CO_2 uptake and storage in what have been named 'blue carbon' ecosystems, *i.e.,* ecosystems with high carbon sequestration rates through plant growth and accumulation of organic matter in the soil. Vegetated coastal ecosystems present significant potential for organic carbon storage (Donato et al. 2011; Mcleod et al. 2011). Mangroves are among the most carbon-rich forests in the tropics, conspicuously contributing to carbon sequestration along with other oceanic and coastal ecosystems such as seagrasses, algae, salt marshes and other plants in coastal wetlands (Chmura et al. 2003; Donato et al., 2011). Dynamics of carbon sequestration and storage have been well documented in humid and tropical climates, but they have drawn less attention in arid regions such as Arabia. A recent study led by Schile et al. (2017) measured whole-ecosystem carbon stocks in multiple sites across the UAE in natural and planted mangroves, as well as in salt marshes, seagrass beds, microbial mats, and coastal sabkha. The study reports that naturally occurring mangroves held significantly more carbon than other vegetated ecosystems in the Emirates, both in terms of biomass and soil organic matter, for an average of 218 tons of carbon per hectare overall, a storage capacity 64% higher than the next blue carbon ecosystem in the region (the microbial mats) and a 106% higher than planted mangroves. Schile et al.'s work reveals UAE mangrove ecosystems as critical for carbon sequestration compared to other blue carbon ecosystems in the region, and provides evidence that mangrove restauration programs may not consistently promote the successful establishment of mature mangrove ecosystems. Given the UAE's interest in carbon reduction (e.g. hosting COP-28 in 2023 and aiming for net-zero emissions by 2050), conservation of local mangrove forests is therefore of key importance in supporting the national goals for combatting climate change (Fig. 7.B2.1).

Fig. 7.B2.1 Activities to increase carbon storage capacities of ecosystems in Abu Dhabi. (**a**) Participants of a plantation event in the Jubail Island Park. (**b**) Recently planted mangrove trees a part of an afforestation program. Image credits: Vidhyaa Chandramohan

7.5 Threats

The global area of mangroves is decreasing. Forests that once extended across three-quarters of the tropical and subtropical coastlines have been reduced in area by as much as 25% to 50% worldwide since 1980 (Giri et al. 2011; Hamilton and Casey 2016; Spalding et al. 2010; Thomas et al. 2017), with profound consequences for biodiversity and for the services and goods provided by these ecosystems (Carugati et al. 2018; Nagelkerken et al. 2008). Estimates of annual mangrove loss range from 0.16% to 2% (Alongi 2015; Hamilton and Casey 2016), mostly due to coastal urbanization and agricultural expansion, dredging, eutrophication or pollution, as well as changes related to global warming.

The UAE is not a stranger to these environmentally harmful processes. The coastal areas of the country have undergone remarkable modifications over the past half-century, with rapid economic and population growth following the 1970s oil boom leading to intense urban development, particularly in coastal zones that now support sprawling mega-cities (Burt 2014; Van Lavieren et al. 2011). While much of the early urbanization resulted in the growth of cities behind the coastline, since the early 2000s there has also been a dramatic increase of reclamation and infilling into coastal seascapes for creation of high-end waterfront real estate (Friis and Burt 2020). Today, the 50 km length of natural coastline in Dubai has expanded to over 250 km when including the perimeter of man-made islands (Burt et al. 2009), where real estate development occurred along with extensive dredging and infilling to support coastal port and oil infrastructures (Burt 2014; Burt et al. 2017; Burt et al. 2016). Such changes have resulted in substantial degradation and loss of diverse coastal ecosystems, including mangroves (Burt 2014). Khan and Kumar (2009), for instance, documented mangrove cover losses at specific sites of the UAE ranging from 49 to 618 ha between 1972 to 2000, a 20% decline from the original area, as a result of extensive land reclamation for coastal infrastructure development. In turn, surveyed sites unaltered by human constructions registered significant increases of mangrove cover over the same period. Direct modification and destruction of the habitat due to infrastructure development and land reclamation are not the only threats for mangrove forests derived from coastal urbanization. Different reports show that mangroves in the UAE have suffered negative impacts due to other changes, such as hypoxic conditions resulting from the discharge of untreated wastewater, structures interfering with natural sedimentation processes and water circulation, or depletion of fresh water resources (Khan and Kumar 2009; Lokier et al. 2018; Paleologos et al. 2019).

Sea level rise as a consequence of global warming also represents a threat for mangrove forests (Lovelock and Ellison 2007), including the mangrove ecosystems in the shallow Arabian Gulf, and particularly along the low-lying UAE coast (Alsumaiti et al. 2017). It has been argued that intertidal communities could migrate vertically in response to changes in sea level. However, mangrove trees cannot keep pace if the rate of change in elevation of sediment surfaces suitable for rooting and growth is exceeded by the rate of change in relative sea levels (Gilman et al. 2008). Hard infrastructure such as seawalls and roads bordering the coasts can also prevent the landward migration of mangroves and their associated biota. Under this scenario, sea level rise is likely to cause recurrent, long-term inundations of the lagoons and bays favored by mangrove forests, modifying the level and conditions of the intertidal zone inhabited by mangroves, which include changes in sedimentation processes and coastal morphology. An interesting study conducted by Lokier et al. (2018) focused on the effects of contemporary sea level rise on sedimentary systems and shoreline morphology in a specific site of Abu Dhabi, near Khor Qantur. Among other processes, they documented the formation of higher-level sand bars that isolated, buried and ultimately destroyed several mangrove stands in the locality. Arguably, the events observed during the study can be extrapolated to the foreseeable scenarios of sea level rise due to global warming. Indeed, eustatic changes projections reported by the Environment Agency of Abu Dhabi (2009) revealed that the effects of sea level rise may flood the totality of the current mangrove area by 2100.

Changes in temperature and precipitation of anthropogenic origin are also widely affecting mangrove ecosystem in the UAE and around the world (Gilman et al. 2008; Lovelock and Ellison 2007; Lovelock et al. 2016). Arabian mangroves already experience some of the highest temperatures registered across their tropical and subtropical distribution during the summer, as well as highly limiting cold temperatures in winter, revealing a remarkable tolerance of the local populations to extreme thermal stress. However, increasing temperatures will likely have a negative impact in the mangroves of the UAE, and while globally, it may favor the expansion of the species polewards, it can also result in the local disappearance of the species in the region if critical physiological limits are met (Lovelock et al. 2016; Osland et al. 2017; Peer et al. 2018). Temperatures exceeding 35 °C negatively affect the patterns of flowering, fruit development and root formation, and photosynthesis is highly impeded when leaf temperatures reach the 38 to 40 °C for most mangroves species (Alsumaiti et al. 2017; Gilman et al. 2008). In addition, climate change is also likely to result in lower levels of precipitation for the subtropical dry regions. Reduced rainfall in an already super-arid environment, along with increased evaporation and higher salinity, will lead to decreased net primary productivity, growth and seedling survival (Gilman et al. 2008). Indeed, genetic analyses reveal parameters such as maximum temperature of the warmest month, annual precipitation or salinity maxima as the most important ecological pressures driving local adaptation in Arabian mangroves (Friis et al. 2022), which suggests that drastic changes in such variables can easily result in severe, negative impacts on these ecosystems.

7.6 Management and Conservation Status

Mangrove management and conservation has led to a net increase in mangrove area in the UAE, especially over the last 20 years (Fig. 7.7). Coastal development benefitted mangroves in some areas by decreasing salinity and increasing nutrients and other areas were built on (Embabi 1993). In response the pressures put on mangroves by development and overexploitation, H.H. Sheikh Zayed bin Sultan al Nahyan, President of the UAE, temporarily banned the harvesting of mangroves and initiated several programs to plant mangroves (Lieth and Lieth 1993; Saenger et al. 2002). By the late 1980s, there were 17 mangrove stands mapped in the UAE, but the actual area was not provided (Embabi 1993). Additionally, the Ras a Khor mangrove

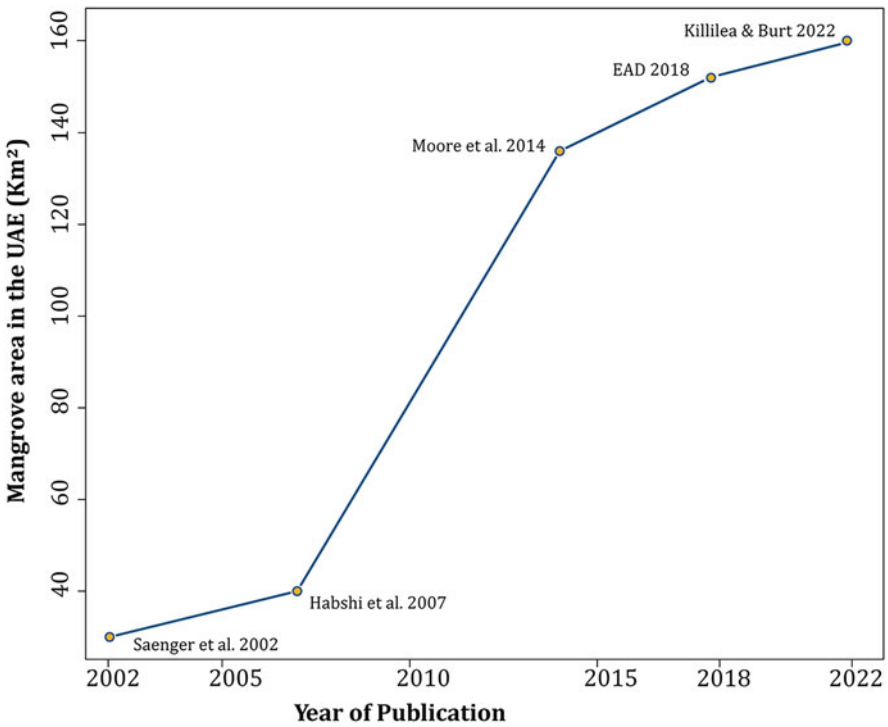


Fig. 7.7 Historic changes in mangrove cover in the UAE. Growth of mangrove cover as a result of the afforestation programs undertaken in the last 20 years. Data assembled from: Saenger et al. (2002), Al Habshi et al. (2007), Moore et al. (2014), Environment Agency Abu Dhabi (EAD, 2018), Killilea and Burt (*in prep*)

wetland in Dubai, was developed and planted in the 1980s and is a designated Ramsar Site due to its ecological importance.

Today, the UAE has five wetlands that include mangroves and have been designated as internationally important Ramsar Sites. There are also nationally protected sites such as the Mangrove National Park in Abu Dhabi. The UAE Ministry of Climate Change and the Environment is responsible for preserving biodiversity and developing policies and programs to mitigate climate change. In 2020, the Ministry implemented a marine environment rehabilitation program, that supports the cultivation of 100,000 mangrove seedlings to help restore degraded habitats as well as to plant new mangrove forests ("Ministry of Climate Change and Environment Implements Marine Environment Rehabilitation Program" 2020).

The majority of mangrove forests are either managed by the government of the local emirate or private landowners. For example, Ras al Khor is protected by the Dubai municipality (Ryan et al. 2012). Three of Ras al Khaimah's mangrove sites are owned by the Ras al Khaimah government, and the fourth is primarily owned by a real estate development that is protecting the site (Llewellyn-Smith 2012). The Environment Agency of Abu Dhabi protects several existing sites in Abu Dhabi and partnered with the Tourism Development and Investment Company (TDIC) to plant 750,000 saplings of mangroves on Saadiyat island (Alsumaiti and Shahid 2019). While formal protection status may be limited, the extensive resources going into planting and protecting mangroves is having a positive impact on these ecologically important ecosystems.

7.7 Recommended Readings

Additional information on the mangroves of the UAE can be found in Dodd et al. (1999); Friis and Burt (2020); Friis et al. (2022); Friis et al. (2021); Spalding et al. (2010).

Acknowledgements The authors are grateful to Vidhyaa Chandramohan (Photojournalist, https://vidhyaa.visura.co) who kindly provided pictures to illustrate this chapter. We also thank Oscar Campbell and Mathew Mitchell for assisting with the characterization of birds and fish inhabiting the UAE mangrove ecosystems.

References

Al Habshi A, Youssef T, Aizpuru M, Blasco F (2007) New mangrove ecosystem data along the UAE coast using remote sensing. Aquat Ecosyst Health Manage 10(3):309–319. https://doi.org/10.1080/14634980701512525

Al-Ghais SM (1993) Distribution of fish in mangrove swamp located along UAE coast of Arabian Gulf. J King Abdulaziz Univ 17:45–55

Al-Ghais SM, Cooper RT (1996) Brachyura (Grapsidae, Ocypodidae, Portunidae, Xanthidae and Leucosiidae) of Umm Al Quwain mangal, United Arab Emirates. Trop Zool 9(2):409–430. https://doi.org/10.1080/03946975.1996.10539320

Almahasheer H (2018) Spatial coverage of mangrove communities in the Arabian Gulf. Environ Monit Assess 190(2):85. https://doi.org/10.1007/s10661-018-6472-2

Almahasheer H, Duarte CM, Irigoien X (2016) Nutrient limitation in Central Red Sea mangroves. Front Mar Sci 3:271. https://doi.org/10.3389/fmars.2016.00271

Alongi DM (2015) The impact of climate change on mangrove forests. Curr Clim Change Rep 1(1): 30–39

Alsumaiti TS, Shahid SA (2019) Mangroves among most carbon-rich ecosystem living in hostile saline rich environment and mitigating climate change–a case of Abu Dhabi. J Agric Crop Res 7(1):1–8

Alsumaiti TS, Hussein K, Al-Sumaiti AS (2017) Mangroves of Abu Dhabi emirate, UAE, in a global context: a review. Int Environ Sci 6(4):110–121

Apel M, Turkay M (1999) Taxonomic composition, distribution and zoogeographic relationships of the Grapsid and Ocypodid crab fauna of intertidal soft bottoms in the Arabian Gulf. Estuar Coast Shelf Sci 49:131–142. https://doi.org/10.1016/s0272-7714(99)80018-3

Aspinall S (1996) Status and conservation of the breeding birds of The United Arab Emirates. Hobby Publications, Liverpool

Aspinall S, Böer B, Ziolkowski M, Hogarth P, Beech M (2002) Biosphere reserve study, Sharjah, UAE. Environment and Protected Areas Authority, Sharjah

Assaf H, Idwan S, Jallad AH, Ammari MZ, Al Chaar A, Kouja M (2022) Public values regarding an urban mangrove wetland in The United Arab Emirates. J Environ Eng Landsc Manage 30(1): 114–123

Ball MC (1988) Ecophysiology of mangroves. Trees 2(3):129–142

Beech M, Kallweit H (2001) A Note on the Archaeological and Environmental remains from Site JH57, a 5 th-4 th Millennium BC shell midden in Jazirat al-Hamra. Ra's al-Khaimah Tribulus (Journal of the Emirates Natural History Group) 11(1):17–20

Beech, M., & Hogarth, P. (2002). An archaeological perspective on the development and exploitation of mangroves in the United Arab Emirates. Research and Management Options for Mangrove and Salt Marsh Ecosystems. Abu Dhabi, UAE: ERWDA, 196–198

Böer B, Saenger P (2006) The biogeography of the coastal vegetation of the Abu Dhabi gulf coast. In: Khan et al (eds) Sabkha ecosystems: tasks for vegetation science, vol 42. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-5072-5_3

Burt JA (2014) The environmental costs of coastal urbanization in the Arabian Gulf. City 18(6): 760–770

Burt JA, Bartholomew A, Usseglio P, Bauman A, Sale P (2009) Are artificial reefs surrogates of natural habitats for corals and fish in Dubai, United Arab Emirates? Coral Reefs 28(3):663–675

Burt JA, Smith EG, Warren C, Dupont J (2016) An assessment of Qatar's coral communities in a regional context. Mar Pollut Bull 105(2):473–479

Burt JA, Ben-Hamadou R, Abdel-Moati MAR, Fanning L, Kaitibie S, Al-Jamali F, . . ., Warren CS (2017) Improving management of future coastal development in Qatar through ecosystem-based management approaches. Ocean Coast Manag 148:171–181. https://doi.org/10.1016/j.ocecoaman.2017.08.006

Carugati L, Gatto B, Rastelli E, Martire ML, Coral C, Greco S, Danovaro R (2018) Impact of mangrove forests degradation on biodiversity and ecosystem functioning. Sci Rep 8(1):13298

Chmura GL, Anisfeld SC, Cahoon DR, Lynch JC (2003) Global carbon sequestration in tidal, saline wetland soils. Glob Biogeochem Cycles 17(4)

Claereboudt MR (2019) Oman. In: Sheppard C (ed) World seas: an environmental evaluation. Elsevier, Amsterdam, pp 25–48

Cooper RT (1997) Mangal-associated Brachyura (Ocypodidae, Grapsidae, Portunidae, Majidae, Xanthidae and Leucosiidae) from the northeastern coastal islands of Abu Dhabi, United Arab Emirates. Crustaceana 70:155–179. https://doi.org/10.1163/156854097X00807

Dhabi EAA (2009) Climate change impacts, vulnerability & adaptation. EAD, Abu Dhabi

Dodd RS, Blasco F, Rafii ZA, Torquebiau E (1999) Mangroves of The United Arab Emirates: ecotypic diversity in cuticular waxes at the bioclimatic extreme. Aquat Bot 63(3–4):291–304

Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M, Kanninen M (2011) Mangroves among the most carbon-rich forests in the tropics. Nat Geosci 4(5):293–297

Duke N (1990) Phenological trends with latitude in the mangrove tree *Avicennia marina*. J Ecol:113–133

Duke N (1991) A systematic revision of the mangrove genus *Avicennia* (Avicenniaceae) in Australasia. Aust Syst Bot 4(2):299–324

ElAmry M (1998) Population structure, demography and life tables of *Avicennia marina* (Forssk.) Vierh. At sites on the eastern and western coasts of The United Arab Emirates. Mar Freshw Res 49(4):303–308. https://doi.org/10.1071/MF97144

Embabi NS (1993) Environmental aspects of geographical distribution of mangrove in The United Arab Emirates. In: Lieth H, Al Masoom A (eds) Towards the rational use of high salinity tolerant plants. Springer, Dordrecht, pp 45–58

Environment Agency Abu Dhabi (2018) Abu Dhabi State of Environment Report:2017

Forster S, Maxwell C (2022) Prince William visit: Abu Dhabi announces major mangrove conservation project. The National. https://www.thenationalnews.com/uae/environment/2022/02/10/prince-william-visit-abu-dhabi-announces-major-mangrove-conservation-project/. Accessed 10 Oct 2022

Fouda M, AI-Muharrami M (1996) Significance of mangroves in the arid environment of the Sultanate of Oman. J Agric Mar Sci 1:41–49

Friis G, Burt JA (2020) Evolution of mangrove research in an extreme environment: historical trends and future opportunities in Arabia. Ocean Coast Manag 195:105288. https://doi.org/10.1016/j.ocecoaman.2020.105288

Friis G, Vizueta J, Smith EG, Nelson DR, Khraiwesh B, Qudeimat E et al (2021) A high-quality genome assembly and annotation of the gray mangrove, *Avicennia marina*. G3 11(1):jkaa025. https://doi.org/10.1093/g3journal/jkaa025

Friis G, Smith EG, Lovelock CE, Ortega A, Marshell A, Duarte CM, Burt JA (2022) Isolation in cryptic glacial refugia and extreme environmental conditions drive rapid lineage diversification in Arabian gray mangroves. Authorea. https://doi.org/10.22541/au.165451878.80994363/v3

Gilman EL, Ellison J, Duke NC, Field C (2008) Threats to mangroves from climate change and adaptation options: a review. Aquat Bot 89(2):237–250

Giri C, Ochieng E, Tieszen LL, Zhu Z, Singh A, Loveland T et al (2011) Status and distribution of mangrove forests of the world using earth observation satellite data. Glob Ecol Biogeogr 20(1):154–159

Goudie AS, Parker A, Al-Farraj A (2000) Coastal change in Ras al Khaimah (United Arab Emirates): a cartographic analysis. Geogr J 166(1):14–25

Grizzle RE, Bricelj VM, AlShihi RM, Ward KM, Anderson DM (2018) Marine molluscs in nearshore habitats of The United Arab Emirates: decadal changes and species of public health significance. J Coast Res 34(5):1157–1175. https://doi.org/10.2112/jcoastres-d-17-00119.1

Hamilton SE, Casey D (2016) Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21). Glob Ecol Biogeogr 25(6):729–738

Hogarth PJ (2015) The biology of mangroves and seagrasses. Oxford University Press, Oxfordshire

Howari FM, Jordan BR, Bouhouche N, Wyllie-Echeverria S (2009) Field and remote-sensing assessment of mangrove forests and seagrass beds in the Northwestern part of The United Arab Emirates. J Coast Res 25(1):48–56. https://doi.org/10.2112/07-0867.1

Jennerjahn TC, Ittekkot V (2002) Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. Naturwissenschaften 89(1):23–30

John DM, George JD (2004) Intertidal and subtidal benthic communities in Abu Dhabi, United Arab Emirates. In: Anon (ed) Marine atlas of Abu Dhabi. Emirates Heritage Club, Abu Dhabi, pp 94–123

Khalil ASM (2015) Mangroves of the Red Sea. In: Rasul NMA, Stewart ICF (eds) Red Sea: the formation, morphology, oceanography and environment of a Young Ocean basin. Springer, Dordrecht, pp 585–597

Khan MA, Kumar A (2009) Impact of "urban development" on mangrove forests along the west coast of the Arabian Gulf. Earth Sci India 2:159–173

Khan SB, Javed S, Ahmed S, Shah JN, Al Hammadi AA, Al Hammadi EA (2017) Greater flamingo (*Phoenicopterus roseus*): important wintering sites and breeding records in The United Arab Emirates. Zool Middle East 63(3):194–201

Lambeck K (1996) Shoreline reconstructions for the Persian Gulf since the last glacial maximum. Earth Planet Sci Lett 142(1):43–57. https://doi.org/10.1016/0012-821X(96)00069-6

Li X, Duke NC, Yang Y, Huang L, Zhu Y, Zhang Z, Shi S (2016) Re-evaluation of phylogenetic relationships among species of the mangrove genus Avicennia from indo-West Pacific based on multilocus analyses. PLoS One 11(10):e0164453

Lieb B, Gebauer W, Gatsogiannis C, Depoix F, Hellmann N, Harasewych MG, Strong EE, Markl J (2010) Molluscan mega-hemocyanin: an ancient oxygen carrier tuned by a ~550 kDa polypeptide. Front Zool 7:14. https://doi.org/10.1186/1742-9994-7-14

Lieth H, Al Masoom A (1993) Towards the rational use of high salinity tolerant Plants, vol I of the Proc. Of the Al Ain conference 1990, T: VS 27, 521 p. Dordrecht, Boston, London, Kluwer academic publisher, In

Lieth H, Lieth A (1993) Seawater irrigation studies in The United Arab Emirates—an introduction to the Al Ain conference. In: Lieth H, Al Masoom A (eds) Towards the rational use of high salinity tolerant plants. Springer, Dordrecht, pp 1–10

Lindauer S, Marali S, Schöne BR, Uerpmann HP, Kromer B, Hinderer M (2017) Investigating the local reservoir age and stable isotopes of shells from southeast Arabia. Radiocarbon 59(2):355–372. https://doi.org/10.1017/RDC.2016.80

Llewellyn-Smith RE (2012) Coastal wetlands in Ra's al-Khaimah, United Arab Emirates: an update on their status, biodiversity, values and protection. Tribulus 20:24–36

Lokier SW, Court WM, Onuma T, Paul A (2018) Implications of sea-level rise in a modern carbonate ramp setting. Geomorphology 304:64–73. https://doi.org/10.1016/j.geomorph.2017.12.023

Lovelock CE, Ellison J (2007) Vulnerability of mangroves and tidal wetlands of the great barrier Reef to climate change. Coral Reefs 26(4):831–834

Lovelock CE, Krauss KW, Osland MJ, Reef R, Ball MC (2016) The physiology of mangrove trees with changing climate. In: Goldstein G, Santiago LS (eds) Tropical tree physiology. Springer, Dordrecht, pp 149–179

Lugo AE, Snedaker SC (1974) The ecology of mangroves. Annu Rev Ecol Syst 5(1):39–64

Mcleod E, Chmura GL, Bouillon S, Salm R, Björk M, Duarte CM et al (2011) A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Front Ecol Environ 9(10):552–560

Ministry of Climate Change and Environment Implements Marine Environment Rehabilitation Program. (2020). MOCCAE News. https://www.moccae.gov.ae/en/media-center/news/27/7/2020/ministry-of-climate-change-and-environment-implements-marine-environment-rehabilitation-program.aspx#page=1. Accessed 10 Oct 2022

Moore GE, Grizzle RE, Ward KM, Alshihi RM (2014) Distribution, pore-water chemistry, and stand characteristics of the mangroves of The United Arab Emirates. J Coast Res 31(4):957–963. https://doi.org/10.2112/jcoastres-d-14-00142.1

Nagelkerken I, Blaber S, Bouillon S, Green P, Haywood M, Kirton L et al (2008) The habitat function of mangroves for terrestrial and marine fauna: a review. Aquat Bot 89(2):155–185

Naidoo G (2009) Differential effects of nitrogen and phosphorus enrichment on growth of dwarf *Avicennia marina* mangroves. Aquat Bot 90(2):184–190

Nobbs M, Blamires S (2015) Spatiotemporal distribution and abundance of mangrove ecosystem engineers: burrowing crabs around canopy gaps. Ecosphere 6(5):1–13

Osland MJ, Day RH, Hall CT, Brumfield MD, Dugas JL, Jones WR (2017) Mangrove expansion and contraction at a poleward range limit: climate extremes and land-ocean temperature gradients. Ecology 98(1):125–137

Paleologos E, Welling B, Amrousi M, Masalmeh H (2019) Coastal development and mangroves in Abu Dhabi, UAE. Paper presented at the IOP Conf Ser Earth Environ Sci 344:012020. https://doi.org/10.1088/1755-1315/344/1/012020

Patlakas P, Stathopoulos C, Flocas H, Kalogeri C, Kallos G (2019) Regional climatic features of the Arabian peninsula. Atmos 10(4):220

Peer N, Rajkaran A, Miranda N, Taylor R, Newman B, Porri F et al (2018) Latitudinal gradients and poleward expansion of mangrove ecosystems in South Africa: 50 years after Macnae's first assessment. Afr J Mar Sci 40(2):101–120

Primavera JH, Friess DA, Van Lavieren H, Lee SY (2018) The mangrove ecosystem. In: Sheppard C (ed) World seas: an environmental evaluation, Volume III: The Indian Ocean to the Pacific. Academic Press, Cambridge, MA, pp 18–51

Purnobasuki H, Suzuki M (2005) Functional anatomy of air conducting network on the pneumatophores of a mangrove plant, *Avicennia marina* (Forsk.) Vierh. Asian J Plant Sci 4(4):334–347

Quisthoudt K, Schmitz N, Randin CF, Dahdouh-Guebas F, Robert EM, Koedam N (2012) Temperature variation among mangrove latitudinal range limits worldwide. Trees 26(6): 1919–1931

Ryan C, Ninov I, Aziz H (2012) Ras Al Khor-eco-tourism in constructed wetlands: post modernity in the modernity of the Dubai landscape. Tour Manag Perspect 4:185–197. https://doi.org/10.1016/j.tmp.2012.08.006

Saenger P, Blasco F, Youssef AM, Loughland R, Wrydani S (2002) The mangrove vegetation of The United Arab Emirates, with particular emphasis on those of the Abu-Dhabi emirate. Proceedings of the 2nd international symposium and workshop on arid zone environments: research and management options for mangrove and saltmarsh ecosystems. ERWDA, Abu Dhabi

Saito H, Bellan MF, Al-Habshi A, Aizpuru M, Blasco F (2003) Mangrove research and coastal ecosystem studies with SPOT-4 HRVIR and TERRA ASTER in the Arabian Gulf. Int J Remote Sens 24(21):4073–4092. https://doi.org/10.1080/0143116021000035030

Schile LM, Kauffman JB, Crooks S, Fourqurean JW, Glavan J, Megonigal JP (2017) Limits on carbon sequestration in arid blue carbon ecosystems. Ecol Appl 27(3):859–874. https://doi.org/10.1002/eap.1489

Shah JN, Javed S, Khan S, Al Hammadi AA, Al Hammadi EA, Soorae PS et al (2018) Distribution and temporal trends of western reef heron (*Egretta gularis*) populations along the Arabian Gulf coast of Abu Dhabi, United Arab Emirates. Waterbirds 41(4):376–383. https://doi.org/10.1675/063.041.0401

Shahid M (2017) Two populations of *Salicornia europaea* in The United Arab Emirates. Tribulus 25:71–75

Sheppard C, Price A, Roberts C (1992) Marine ecology of the Arabian region: patterns and processes in extreme tropical environments. Academic Press, London

Sheppard C, Al-Husiani M, Al-Jamali F, Al-Yamani F, Baldwin R, Bishop J et al (2010) The Gulf: a young sea in decline. Mar Pollut Bull 60(1):13–38. https://doi.org/10.1016/j.marpolbul.2009.10.017

Shriadah MA (2000) Chemistry of the mangrove waters and sediments along the Arabian Gulf shoreline of The United Arab Emirates. Indian J Mar Sci 29(3):224–229

Spalding M, Kainuma M, Collins L (2010) World atlas of mangroves. Routledge, Oxfordshire

Thomas N, Lucas R, Bunting P, Hardy A, Rosenqvist A, Simard M (2017) Distribution and drivers of global mangrove forest change, 1996–2010. PLoS One 12(6):e0179302

Tomlinson PB (2016) The botany of mangroves. Cambridge University Press, Cambridge

Tourism in the United Arab Emirates (2022). https://www.worlddata.info/asia/arab-emirates/tourism.php. Accessed 10 Oct 2022

Uerpmann M, Uerpmann H-P (1996) Ubaid pottery in the eastern Gulf–new evidence from Umm al-Qaiwain (UAE). Arab Archaeol Epigr 7(2):125–139

Van Lavieren H, Burt J, Feary D, Cavalcante G, Marquis E, Benedetti L et al (2011) Managing the growing impacts of development on fragile coastal and marine ecosystems: lessons from the Gulf. United Nations University - Institute for Water, Environment, and Health, Hamilton, Canada

Vaughan GO, Al-Mansoori N, Burt JA (2019) The Arabian Gulf. In: Sheppard C (ed) World seas: an environmental evaluation. Elsevier, Amsterdam, pp 1–23

Yancho JMM, Jones TG, Gandhi SR, Ferster C, Lin A, Glass L (2020) The Google earth engine mangrove mapping methodology (GEeMMM). Remote Sens 12(22):3758

Chapter 8
Coastal Lagoons (*Khors*) of the Emirates

Daniel Mateos-Molina, Simon J. Pittman, Marina Antonopoulou, Stephen Carpenter, Mona Möller, Sabir Bin Muzaffar, and Ivonne Bejarano

8.1 Coastal Lagoons (Khors)

The Arabic word *khor* refers to coastal lagoons, bays and inlets, as well as to seasonal terrestrial watercourses, and is thought to have origins in the Arabic word *ḵawr* meaning "a low land between two stretches of higher ground". In the United Arab Emirates (UAE), *khors* are typically low-lying tidal lagoons that exist in various shapes and sizes along the coastline and in some areas have been modified by urban development in recent decades. These structurally complex and dynamic land-sea ecosystems are hotspots of ecological connectivity that support high biological diversity and generate ecosystem services and benefits that are crucial for sustaining human wellbeing.

Lagoons are shallow-water transitional environments located at the edge of the ocean, forming the front-line in responding to urbanization pressures and to climate change where rising sea level, heatwaves and storms challenge and shape lagoonal ecology. As such, coastal lagoons are defined as areas of relatively shallow water

D. Mateos-Molina (✉) · M. Antonopoulou · S. Carpenter · M. Möller
Emirates Nature - WWF, Dubai, United Arab Emirates
e-mail: dmateos@enwwf.ae

S. J. Pittman
Oxford Seascape Ecology Lab, School of Geography and the Environment, University of Oxford, Oxford, UK

Seascape Analytics, Plymouth, UK

S. B. Muzaffar
Biology Department, United Arab Emirates University, Abu Dhabi, United Arab Emirates

I. Bejarano
Department of Biology, American University of Sharjah, Sharjah, United Arab Emirates

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_8

that have been partly or wholly enclosed from the sea by the formation of depositional barriers such as islands and spits (Bird 1994). Kjerfve (1994) defined three broad categories of coastal lagoons as: (1) *choked lagoons* with a single narrow inlet; (2) *restricted lagoons* with several inlets and good circulation; and (3) *leaky lagoons* with many inlets, wide channels and strong tidal and wind driven circulation and flushing). The most common lagoon type in UAE is the *choked lagoons*, however, the UAE has examples of each of the three types of coastal lagoon (see the Distribution section below).

All coastal lagoons in the UAE have formed as a result of rising sea level during the Holocene epoch (i.e., during the past ~11,700 years) where coastal barriers were built by marine erosion and depositional processes. This was followed by a period of sediment deposition on the landward side of barriers resulting in a localized drop in sea level (Schneider 1975). The influence of the sea on lagoonal form and function is determined largely by the size and depth of inlets (and by dredged channels), the tidal range and the prevailing direction of currents. In the UAE strong moisture-laden winds from the northwest (*shamals*) create waves that reshape the coastal barrier dunes and support growth of halophytes (salt-tolerant plants) on dune ridges (Chap. 4). When combined with spring tides; the winds can bring sediments onto tidal flats where cyanobacterial mats thrive. These highly dynamic and ever-changing hydrodynamic and wind driven processes create the dendritic networks of channels delivering and removing sediments, nutrients, and organisms throughout the lagoonal circulation system that is constantly in flux.

Unlike the adjacent open ocean, tidal mixing and salinity can vary dramatically within and between lagoons. Lagoonal plants and animals are adapted to the highly variable daily conditions (sea water inundation, salinity and day-night temperature changes), and can also tolerate seasonal extremes of natural physicochemical fluctuations, yet these organisms remain vulnerable to human impacts. The tidal regime is of critical importance to organisms living between the high and low water marks because they need to survive periods of inundation during high tide, and exposure to intense solar radiation and desiccation during low tide. The complex tidal regime and the associated circulation system of lagoons epitomizes a homeostatic, or self-regulating, process with feedback that maintains a dynamic equilibrium providing sufficient stability for life to thrive.

Coastal lagoons provide a geomorphological setting for wetlands to thrive, where halophytic plants trap and bind inorganic sediments and organic matter to enhance stability of the land barriers and shallow sediments. In the UAE, topography shaped by coral and oyster reefs, oceanic carbonate sedimentation and windblown materials (Evans et al. 1964) and the interplay with biotic elements have generated gradients in environmental conditions and mosaics of habitat patches within these systems. Coastal lagoons promote high marine primary productivity from seagrass, algae and cyanobacteria that thrive in the photic zone where light can penetrate through the water column to allow photosynthesis. The complex patterns of coastal lagoons can

Fig. 8.1 The entire khor at Umm al Quwain as seen from space showing barrier islands, inlets and channels (including dredged), constructed land, urban areas and extensive wetlands. Image captured at low tide on 2nd July 2023. Source: PlanetScope imagery © 2023 Planet Labs Inc. and shared under their Terms of Service for Education and Research

be observed from above, where the intricacies of the hydrological network, with both its wetlands and drylands, can be clearly seen (Fig. 8.1).

In the UAE, inner lagoons are typically hypersaline environments with salinity that can exceed 60 PSU (compared with 36 PSU in normal oceanic water) and are characterized by containing large areas of halophytic (salt tolerant) plants and microorganisms in intertidal and supratidal areas (Mateos-Molina et al. 2020, 2021a). Above the high tide are extensive supralittoral salt-flats called coastal *sabkha* where the salinity of groundwater is many times greater than seawater (Schneider 1975). The primary drivers of hypersalinity in UAE lagoons are the arid conditions and high rates of evaporation, low freshwater inflow and limited exchange with oceanic waters experienced by coastal lagoons.

Coastal lagoons also export materials, nutrients and biota to oceanic waters, fuelling food webs beyond their borders. Where powerful ebb channel flows occur, depositional sand deltas are created on the seaward side of land barriers. These outward-draining flows also transport nutrient-rich waters from the inner lagoon system to the outer more nutrient-poor oceanic water creating ecologically important nutrient subsidies, with potential benefits to outlying ecosystems and offshore fisheries.

8.2 Distribution of the Different Types of Coastal Lagoon in the Emirates

Coastal lagoons constitute a common coastal environment, occupying 13% of coastal areas worldwide (Kjerfve 1994). In the Emirates, the coastal lagoons are far more common and occupy approximately 27% of the coastline. The intricate geomorphology expands the intertidal and supratidal area along both coasts of the UAE, primarily in the low-lying Arabian Gulf coast, but with Khor Kalba being a remaining notable example on the east coast (Figs. 8.2 and 8.3).

All three geomorphological types of coastal lagoon described by Kjerfve (1994) exist in the UAE. In the southwest of the emirates, close to the town of Mirfa in Abu

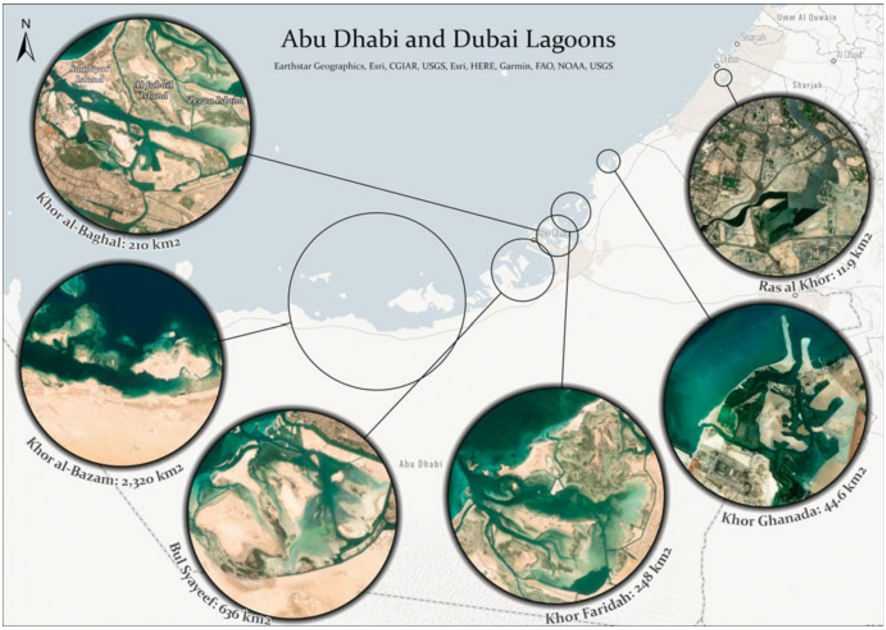


Fig. 8.2 Distribution of lagoons in the emirates of Abu Dhabi and Dubai. Map created using ESRI ArcGIS Pro 3.0

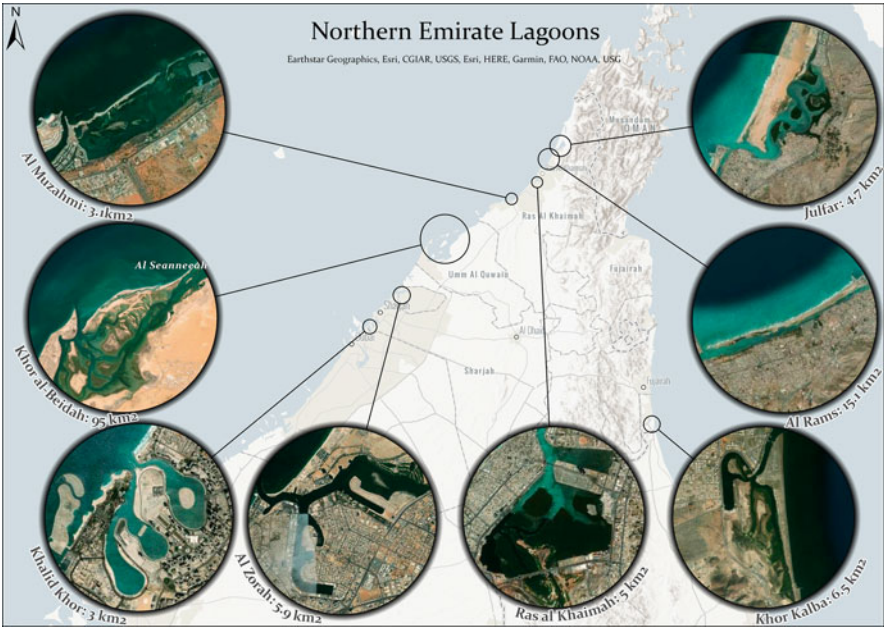


Fig. 8.3 Distribution of lagoons in the northern emirates. Map created using ESRI ArcGIS Pro 3.0

Dhabi, lies Khor al Bazam, a leaky lagoon, which includes several connections to the open sea, where strong winds from the north maintain a highly flushed system (Fig. 8.2). More restricted lagoons are present on both sides of Abu Dhabi city, with several 'drumstick' or 'T' shaped barrier islands (Fig. 8.3). These barrier islands form the 'T' structure seaward and perpendicular to the prominent wind direction (*shamal*) (see Chap. 3). These are characterised as low to moderate wave energy systems with fine-grained sediments and brackish lagoonal marshes.

Large wave-driven dune formations along the coast of the UAE result in numerous barrier lagoons associated with low-lying areas in the lee of the dunes and abundant sediment that often builds into intertidal islands and spits. Hence, the tails of the barrier islands frequently extend south away from the direction of the shamal winds, which transport sands back towards the lagoon and restrict circulation. The consequence of this process can be visualised on Halat Al Bahrani Island, in Khor Bul Syayeef in Abu Dhabi (Fig. 8.4).

The Khor Faridah and Khor al-Baghal complex near the Abu Dhabi capital city is made up of approximately 400 km^2 of coastal lagoons, split by several natural and artificial or modified barrier islands, including Saadiyat, Al Jubail and Zeraa islands, that form 'T' shaped structures perpendicular to the prevailing winds (Fig. 8.2). Further north, Khor Ghanada lagoon near the Dubai border is restricted to two main channels that distribute tidal waters into the mangrove-dominated ecosystem. Here, numerous artificial channels have been created, flushing out highly saline waters and promoting mangrove growth.

Fig. 8.4 Halat Al Bahrani Island forming a T-shaped structure of the Khor Bul Syayeef, Abu Dhabi. Source: ESRI World Imagery basemap using 0.5 m WorldView-2 (Maxar) satellite imagery

In the northern emirates (Fig. 8.3), the prevailing wind changes to be more oblique to the direction of the coast, resulting in lagoons that are often stretched wide, parallel to the coast, and exhibiting more restricted connection to the ocean (i.e., choked systems). Khor al-Beidah at Umm al Quwain is the largest (~127 km^2) and remains one of the most undisturbed lagoons in the Northern Emirates. The dominant wind force has transported barrier island sands alongshore on Siniya Island, which has extended the sand-spit feature over 600 m along the coast between 1984 and 2020.

Because of their sheltered nature, most of the lagoons in the UAE have been modified or dredged to accommodate local ports and related infrastructure. Al Khan, Khalid (locally referred to as *Al-Buhaira*) and Al Mamzar are highly modified lagoons in Sharjah that are widely used for recreation and commercial boating. Notwithstanding these modifications, each coastal feature is orientated north-east, reflecting the effect of the dominant shamal wind direction from the NNW. This effect is further exaggerated further north along the coast, where there are a series of lagoons in Ras al-Khaimah including Khor al Rams, Julfar and Khor al Muzahmi (Fig. 8.3). These three lagoons form over 22.9 km^2 of biodiverse wetlands that are highly valuable to the ecotourism and fisheries industries. This has been recognised by an area of Al Muzahmi that has been designated with reserve status to ensure its conservation. Khor al Rams consists of a large barrier island (known as the Saraya Islands) and extends over 7 km along the shore. Ras al Khor in Dubai is another lagoon which has been significantly modified by development. This choked lagoon once had a singular narrow connection with the sea, but was heavily modified by the dredging of the main creek and the then-new Rashid Port in the 1960s, followed by expanded dredging further into the Ras Al Khor area in later years (Köstem 2021); the khor has now been linked to the sea through the Jumeirah area with the dredging of the Business Bay through the 2010s (Hammad 2019).

8.3 Biodiversity in Coastal Lagoons

Coastal lagoons in the UAE are highly productive ecosystems that support rich biodiversity and provide important ecosystem services. These coastal lagoons have been identified as priority areas for conservation due to the presence of key coastal habitats for threatened and locally important species and their life cycles (for example, species that utilize them as nursery habitats before moving out to open sea) (Ben Lamine et al. 2020; Mateos-Molina et al. 2021a, b). Coastal habitat mapping on the UAE coast of the Arabian Gulf revealed the coexistence of multiple important habitat types (sabkha, halophytes, mangroves, seagrasses, saltmarshes, etc.) forming an interconnected mosaic of different intertidal and subtidal habitats in the coastal lagoons (Mateos-Molina et al. 2020, 2021b). The composition and spatial arrangement of habitat types, together with hydrology, influence the ecological connectivity among those habitats and their organisms in coastal lagoons. This ecological interplay creates unique seascapes where the value of the whole ecosystem is more than the sum of its individual habitat types (Fig. 8.5). For that reason, it is critical to understand these complex seascapes and their ecological functions as whole social-ecological systems in order to design effective conservation actions.

Coastal lagoons in the UAE are important areas for carbon sequestration, the process of capturing and storing ‘blue carbon’, where carbon captured by marine living organisms gets trapped in sediments, potentially reducing atmospheric carbon dioxide (Nellemann et al. 2010). Coastal lagoons contain a variety of habitats associated with carbon capture, including mangroves, seagrasses and saltmarshes, and also coastal sabkha and microbial mats that are common in the region (Schile et al. 2017, Schile-Beers et al. 2018; Alsumaiti and Shahid 2019). Field measurements from dominant coastal habitat types in the UAE indicate that microbial mats, which support no emergent vegetation, exhibit the second highest carbon storage values after mature mangroves (Schile et al. 2017). Saltmarsh, coastal sabkha and seagrass also function as important blue carbon stocks. Thus, the conservation value of these ecosystems extends beyond their high biodiversity to their importance to climate change mitigation, an important feature given the UAE’s 2050 carbon neutrality goals.

Fig. 8.5 Seascape of Umm Al Quwain coastal lagoon with the presence of multiple habitats, including dense mangrove forest, saltmarsh stands, mudflats and sabkha. (Photo: Daniel Mateos-Molina)

Unlike terrestrial environments that are limited to sequester carbon through photosynthesis, habitats in coastal lagoons can accumulate carbon by encouraging the deposition of carbon dioxide into sediments in coastal waters. Suspended sediment from land runoff and erosion elsewhere along the coast gets trapped along with dead plant biomass in coastal lagoon environments which makes them hotspots for carbon burial. Furthermore, a lack of oxygen in water results in slower decomposition of carbon, therefore promoting long term sequestration (Campbell et al. 2015).

The coastal zones of the United Arab Emirates and the greater Arabian Gulf are characterized by relatively high levels of productivity due to nutrients originating on land (Nezlin et al. 2007; Muzaffar et al. 2017a). This makes the coastal lagoons and inlets fertile feeding areas for large shoals of 'forage' fish such as anchovies, sardines, herrings and scads (Muzaffar et al. 2017a, b) and a variety of juvenile individuals of larger fish species such as trevallies and barracudas. Anchovies and sardines undertake migrations along the coastal areas, making them seasonally abundant at different times along the coast. Collectively these small forage fish serve as an important food for larger fish, sharks, dolphins and seabirds (Muzaffar et al. 2017b). Numerous threatened coastal and marine species such as green and hawksbill turtles, halavi guitarfish, greater flamingo, socotra cormorant (see Box 8.1), and greater spotted eagle among many others use this habitat as a feeding, breeding and/or roosting ground (Fig. 8.6) (Whelan et al. 2017, 2019; https://ebird.

Fig. 8.6 Presence of threatened species in a coastal lagoon. (**a**) Black tip reef shark, (**b**) Halavi Guitarfish and (**c**) Green Turtles. (All photos: Daniel Mateos-Molina)

org). Lagoon ecosystems are also home to extremely thermally tolerant corals (Smith et al. 2017) and are important seascapes for birds (including many globally threatened migratory species), particularly for feeding, breeding and roosting (Muzaffar 2020; Ben Lamine et al. 2020).

Box 8.1 UAE Lagoons as Critical Habitat for Socotra Cormorant
Socotra Cormorants are classified as globally vulnerable and geographically restricted in their distribution, occurring only in the Arabian Gulf and the adjoining Gulf of Oman, extending into the Gulf of Aden (BirdLife International 2018; Muzaffar 2020). The largest and most well-studied colony within the Arabian Gulf breeds on Siniya Island in Umm Al Quwain Khor (Fig. 8.7). Up to 26,000–41,000 pairs have been estimated to nest on this island, with an annual presence of around 150,000–200,000 individuals (Muzaffar et al. 2017a). They form gregarious breeding colonies between August and January (Muzaffar et al. 2017a; Muzaffar 2020). For the rest of the year, they disperse throughout the Arabian Gulf.

As the searing hot summer begins, vast flocks of Socotra Cormorants start arriving at the northern sand banks of Siniya Island (Muzaffar et al. 2017a; Muzaffar 2020). Initially, they roost on the islands while scoping out the terrain and assessing the nearby fish stocks. Thus, as the Socotra cormorants initiate nesting, they have a steady supply of forage fish in the nearby waters.

Every morning, many cormorants gather near the shoreline, flexing their wings and getting ready for a morning of fishing (Muzaffar et al. 2017b). Then, as if by some unknown signal, individuals start flying in large groups towards the fishing areas, sometimes as much as 40 km away from

(continued)

Fig. 8.7 (**a**) A breeding colony of Socotra Cormorants (*Phalacrocorax nigrogularis*) showing adults (black) and chicks (white) on Siniya Island, Umm Al Quwain Khor; (**b**) an early morning congregation of adults and juveniles getting ready to fly off to fishing grounds; (**c**) a pre-departure 'raft' of cormorants; and (**d**) a feeding frenzy at one of the foraging sites. All photos: Sabir Muzaffar

Box 8.1 (continued)
the colony. Eventually, both the adults and juveniles leave Siniya Island mostly making their way along the coastline west towards offshore islands.

The relative abundance of forage fish in coastal waters indicates a healthy, functioning marine ecosystem. Socotra Cormorant populations have declined overall in the Arabian Gulf, although they appear to have increased within the United Arab Emirates (Khan et al. 2018). Overfishing and development in the coastal zones threaten the complex food web that supports the cormorant populations (Muzaffar et al. 2017a, b; Muzaffar 2020). The establishment of coastal marine protected areas that protect coastal lagoons and surrounding shallow waters of these islands is urgent to ensure the preservation of marine biodiversity and healthy flourishing ecosystems.

8.4 Socio-cultural Importance of the Coastal Lagoons

Coastal lagoons provide numerous and diverse ecosystem services for society such as fisheries (e.g., commercial fish species), regulation and protection of coastlines from floods and storms, regulation of climate change and purification of water among many others (Basset et al. 2013; Lopes and Videira 2013; Newton et al. 2014, 2018) (Fig. 8.8). Coastal lagoons also support tourism and recreational activities such as recreational fishing and boating, leisure and water sports in the

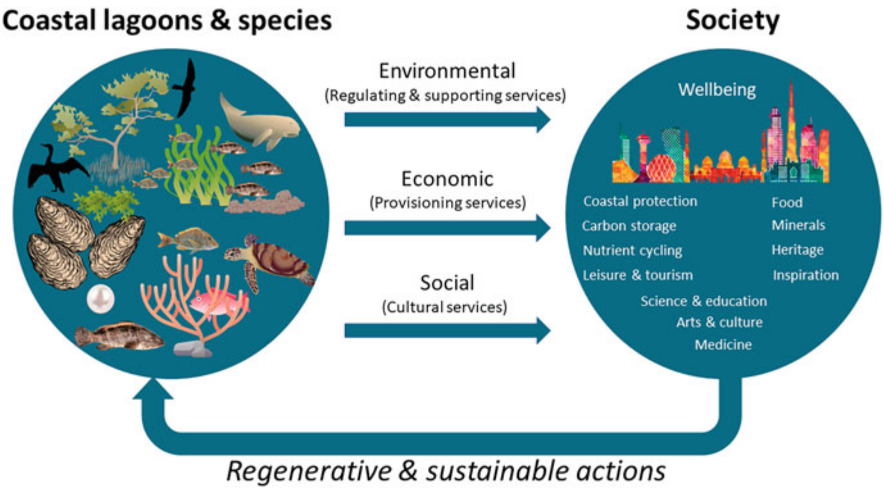


Fig. 8.8 Coastal lagoons support important ecosystem services. Modified from Fig. 1 in Pittman et al. (2022) and reused under Creative Commons (CC-BY 4.0)

Fig. 8.9 Traces of human occupation in coastal lagoons. (**a**) Dugong bone mound and (**b**) the rostra of animals and the skulls placed in anatomical position, aligned ribs in Siniya Island, Umm Al Quwain. Source: Méry et al. (2009), reproduced with permission (license: 5514780773472)

United Arab Emirates. In addition, the historical nature of humanity's relationship with coastal lagoons places lagoons as important for societal, archaeological, and heritage values (Craig 2006; Lasserre 1979).

Several archaeological sites of human settlements have been discovered around coastal lagoons in the Emirates demonstrating the socio-cultural value of these ecosystems. The findings at archaeological sites showcase the historic importance of lagoons in food security and livelihoods (Fig. 8.9). At the Kalba coastal lagoon on the east coast, mangrove wood from nearby *Avicennia marina* forests were burned in the fireplace, while small finds such as fish bones and molluscs were also identified. The site is thought to have had strategic importance in maritime trade (Schwall and Jasim 2020). At Jazirat Al Hamrah, Ras Al Khaimah, pottery shards originating from the western Mediterranean, Mesopotamia, and Indo-Pakistani borderlands reveal the presence of the lagoonal settlements for commercial maritime trade (Potts et al. 2003; Mutin 2012). At Khor Al Beidah, Umm Al Quwain, the Ed-Dur Site is one of the largest archaeological sites in the UAE, with settlements over several periods, including the Ubaid period (3800–6500 BC), Bronze Age, Stone Age, Iron Age, and Pre-Islamic periods (Carter and Philip 2010). In fact, the development of modern day Umm Al Quwain began when a tribe of people led by Sheikh Majid bin Rashid Al Mualla moved from Siniya Island in Khor Al Beidah to the mainland (Government of Umm Al Quwain 2015). Food waste such as discarded oyster shells and fish skeletons indicate that fishing took place within the lagoon itself, though some fishing (for example tuna), may have occurred outside of the lagoon (Charpentier and Méry 2008).

More recently, lagoons may have been used as boat shelters for trade and pearling. For example, from the late thirteenth century Julfar al-Mataf in Ras Al Khaimah was fabled as a commercial trading centre but declined over time due to the continuous siltation of the lagoon that had previously formed the natural harbour. As a result, people relocated closer to what is modern-day Ras Al Khaimah (Velde 2012).

In the early 1900s, many villages subsisted on fishing and pearl-diving, and some lagoons became important areas for local inhabitants involved in these two professions. For example, Abu Dhabi's Bateen village, which lies close to Khor Al Batin, was noted to have 50 pearl-diving boats to export pearls and import a variety of commodities, including rice and coffee (Lorimer 1908).

8.5 Human Impacts on Coastal Lagoons

UAE's coastal lagoons have played an important role in supporting human settlements for centuries from small coastal trading towns and neolithic fishing communities (Lidour et al. 2021) to the modern cities of today (Chap. 22). Consequently, the human footprint on coastal lagoons is considerable and diverse. Coastal urbanization including construction of new islands, creation of small artificial coastal lagoons and modifications to the hydromorphology of existing lagoons through the dredging of new channels has accelerated the loss of some coastal habitats and species whilst benefiting others (Chap. 23; Burt 2014). The city seascapes have also changed the physical structure of the coastline with construction of seawalls, breakwaters, jetties, piers, marinas, ports and related infrastructure having replaced the softer shorelines (Chap. 23; Burt and Bartholomew 2019). In addition, sheltered lagoonal coastlines are prime real estate for residential developments and for locating critical urban infrastructure such as marine storage and transport facilities (ports, marinas, storage depots), desalination plants, sewage treatment works and marine transport.

Over the past several decades new channels have been dredged to allow safe and efficient navigation between lagoons and to the open ocean in many of the coastal

Fig. 8.10 A portion of the northern Khor Faridah lagoon (Abu Dhabi) in (**a**) December 1984 and (**b**) 36 years later in December 2020 showing artificial channels, land creation and modifications, extensive urbanization, as well as expansion of wetland vegetation in 2020 (dark green areas). Source: Google Earth, based on Landsat/Copernicus imagery, reused per Google Terms of Service

lagoons across the UAE (Fig. 8.10). These channels have reduced the environmental differences between the open ocean and coastal lagoons (e.g., water temperature and salinity), and therefore could be argued to have made the lagoon environment more amenable to life.

Some lagoons have become less hypersaline where dredging has deepened channels and widened inlets to the ocean resulting in increased tidal flushing with lower salinity sea water (~38‰). In some areas, increased flushing and lowering of salinity together with nutrient runoff from land is thought to have improved habitat suitability for grey mangroves (*Avicennia marina*) allowing the recent expansion of existing and newly planted mangroves in several UAEs lagoons since 1990 (Elmahdy et al. 2020). The densest mangroves typically grow between tidal channels and the edges of mudflats. The ecological characteristics including human uses of coastal lagoons influence the capacity of a lagoon for carbon sequestration and storage (i.e., blue carbon), the delivery of a range of other ecosystem services and the suitability of its habitats to support biodiversity.

However, dredging results in the suspension of sediments that can increase turbidity that reduces water quality for light-sensitive organisms such as seagrasses and corals (Erftemeijer and Shuail 2012; Duck and da Silva 2012). Subsequently, there are consequences for species that rely on these habitats to survive (e.g., turtles). Dredging also results in increased water flow that can reduce soil stability for seagrass and mangrove seedling growth.

However, the changes to channel depth and complexity can benefit some highly mobile species. For example, research in Australia (Borland et al. 2022) found that functional diversity in fish assemblages was highest in urban estuaries where dredged channels were small (i.e. <1% of the estuary) and where channel slope orientation promoted light penetration to the seafloor. For most lagoons globally, however, our understanding of the direct and long-term indirect ecological consequences of channel modifications through dredging is insufficient to support effective ecosystem-based management, and this topic has yet to be well studied in the Emirates.

8.5.1 Marine Vessel Traffic

Marine vessels have multiple types of impact on marine environments that include underwater noise known to disturb marine animals, the potential for chemical pollution, the erosion of channel banks from bow-waves, collisions with the seabed (e.g. propellor scars in seagrass and groundings), and collisions with large air-breathing marine animals (turtles, dugongs and cetaceans) (Duarte et al. 2021). Marine vessels are a widespread and chronic source of underwater noise pollution. The underwater sound from vessels propagates over great distances (Fig. 8.11). As a

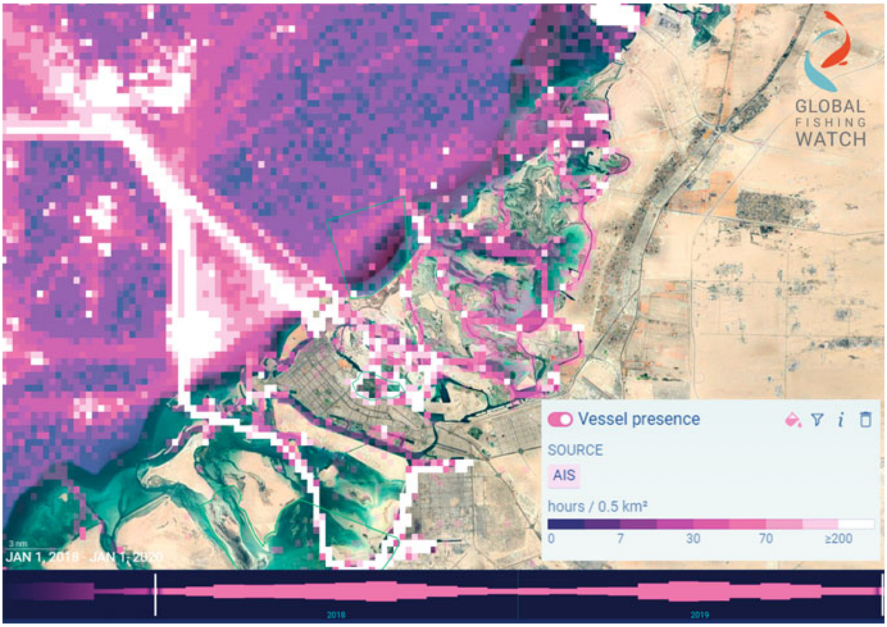


Fig. 8.11 Vessel traffic intensity within the Khor Faridah lagoon recorded using vessel locations/hours from the Automatic Identification System during a 2-year period (January 2018 to January 2020). The presence of a vessel is determined by taking one position per day per vessel from the positions transmitted by the vessel's AIS. Only large vessels are required to use AIS. Source: Global Fishing Watch shared under Creative Commons license (CC BY 4.0)

result, vessels have altered marine soundscapes with high traffic areas suffering from chronic exposure to noise, especially in surrounding urban areas. Vessel noise overlaps with the audible frequencies of many marine mammals, turtles, fish and some invertebrates which can disrupt their orientation, communication, socializing, predator avoidance, settlement cues and rest. Therefore, a reduction in vessel noise can reduce cumulative pressure on marine species (Merchant 2019). In addition, in shallow water, vessel wakes disturb sediments leading to sediment resuspension and redistribution particularly where unvegetated soft sediments exist, such as lagoon channel banks. Wakes can propagate far into shallow-water areas, creating turbulence and erosion that increase turbidity and reduce water quality for plants and injure or displace juvenile fish (Zaggia et al. 2017).

Vessel impact abatement policies and regulations are crucial for limiting their disturbance to lagoonal ecosystem. Vessel speeds and routes can be controlled to reduce impacts in biologically sensitive areas, solar-electric recreational boats and passenger ferries can be incentivised, and safe boating practices can be promoted to minimise collisions. Furthermore, technological solutions to vessel design and schemes can reduce impacts and infrastructural standards, such as green marina schemes, low impact moorings and initiatives to reduce waste disposal and chemical pollution.

8.5.2 Urban Light Pollution

Urbanization of coastal lagoons increases light pollution from streetlights, building and ports, altering the natural regime of night-time sky brightness. Artificial night lights impact a wide range of organisms including marine species in shallow water, insects and birds by disrupting fundamental processes such as circadian rhythms, energetics, movement orientation, reproduction and predator-prey relationships (Davies et al. 2014). The reported impacts, including disruption to molecular and cellular processes, are most severe for nocturnally active animals (Tidau et al. 2021). Light-induced mortality occurs with seabirds. White LEDs are now widely used as an energy efficient light source, but many marine organisms are sensitive to the short wavelengths they emit (Tamir et al. 2017).

Light-related impacts can be mitigated by changing the light source to a less biologically responsive wavelength or using barriers to reduce light spillage (i.e., from white to amber LED, filtered and shielded light sources) (Longcore et al. 2018). For example, The State of Florida prohibits lighting for new construction near beaches to emit wavelengths less than 560 nm to protect sea turtles. These changes are required if we are to transition to nature-positive urban environments that allow other species to coexist with us in the urban seascape. Comparison of urban night-light intensity measured by the VIIRS satellite (Visible Infrared Imaging Radiometer Suite—Day/Night Band DNB) (lightpollutionmap.info) revealed that night time irradiance across Umm al Quwain lagoon fluctuated between 2012 and 2017 and then increased by >40% from 2017 to 2022 (Fig. 8.12). A deeper scientific

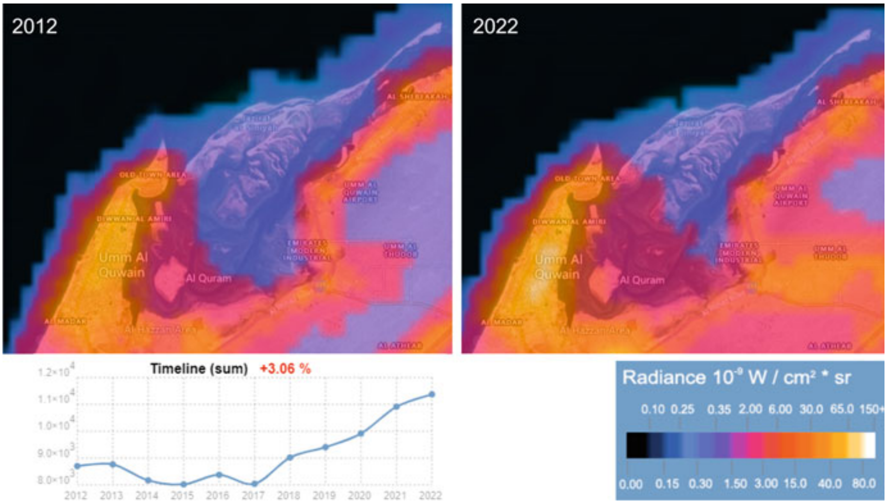


Fig. 8.12 Artificial light at night (vertical radiance) measured from 2012 by the Visible and Infrared Imaging Suite (VIIRS) sensor on board NASA Joint Polar-Orbiting Satellites. Source: Data derived from NASA's VIIRS/NPP Lunar BRDF-Adjusted Nighttime Lights Yearly composites and shared under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC)

understanding of horizontal irradiance and the biological impacts of artificial lights on coastal lagoons needs to be conducted in collaboration with energy companies and urban municipalities.

8.5.3 Water Pollution

Coastal lagoon waters and sediment quality are susceptible to contaminants and nutrients due to runoff from land, outflows of wastewater, and seepage from ground water that often occurs in urban and agricultural areas. This problem is further exacerbated by low flushing, sheltered waters and abundant depositional environments. Low rainfall in the UAE reduces the occurrence of land-based sources of pollution entering the marine waters, although the limited freshwater input also means flushing is entirely tidally driven. Water and sediment samples in UAE lagoons and urban creeks have been shown to have exceedances with some sediment-associated heavy metals (e.g., manganese, zinc, copper) (Shriadah 1998; Samara et al. 2020) and through bioaccumulation in fish (Cunningham et al. 2019). Little is known about the scale of the threat from engineered products such as discarded fishing gear and other sources of marine plastics, but as a global problem it must be considered as a priority in the management towards healthy coastal lagoons (Stöfen-O'Brien et al. 2022).

8.5.4 Implications of Climate Change for UAE Lagoons

Global climate change caused by greenhouse gas emissions are predicted to produce even more extreme conditions (e.g., higher salinities, higher temperatures, lower oxygen levels) in UAE's coastal lagoons.

The Arabian Gulf holds the world's warmest ocean water. Thermal expansion of the oceans and melting polar ice due to accelerated global warming are increasing sea levels, and this is projected to continue for centuries and potentially drive intertidal and shallow water species and habitats inland seeking more favourable conditions (Lauchlan and Nagelkerken 2020). IPCC projections of global mean SLR by 2100 range from 0.61 to 1.10 m (RCP 8.5) with some models predicting scenarios of over 2 m by 2100 due to large uncertainties in the stability of Greenland and Antarctic ice sheets (IPCC 2019). For the north-western Arabian Gulf, tidal gauge data indicated a relative sea-level rise of 2.2 ± 0.5 mm per year between 1979 and 2007 (Alothman et al. 2014) and publicly available coastal inundation maps for 2050 using moderate projections suggest that considerable changes in the intertidal habitats will occur (Melville-Rea et al. 2021; https://www.climatecentral.org/).

Submergence of 20–78% of coastal wetlands globally has been predicted to occur by 2100 while, simultaneously, some intertidal habitats may keep pace with sea level rise and expand landward (Spencer et al. 2016). Where hard barriers to landward shifts occur, such as seawalls and elevated relief, the phenomenon of 'coastal squeeze' will result in temporary loss of habitat (Mills et al. 2016). Efforts to conserve and expand natural intertidal habitats will serve to buffer the coastline from waves and inundation. As sea level rises, increasing wave action will erode low-lying sandy beaches and barrier islands that allowed lagoons to form, and creeks will begin to silt up and become more homogeneous as they transform into subtidal flats. On the landward edge, sea level rise may increase seawater intrusion into groundwater, reducing the inflow of freshwater to the lagoons and reducing the suitability of water for vegetation (Tully et al. 2019). Potential evapotranspiration has been predicted (SSP2–4.5) to increase throughout the region by up to 0.37 mm per year during the middle of the twenty-first century (2021–2050), likely creating harsher hyper-arid conditions and hyper-salinity for many coastal plants and animals (Ajjur and Al-Ghamdi 2021). Models based on RCP 8.5 scenario predict local extinctions of marine species due to decline in habitat suitability and a $>$ 40% drop in potential fisheries production in UAE waters by 2090 (Wabnitz et al. 2018), although such estimates may be underestimated as the models did not include other human impacts or hard-to-predict processes such as predator-prey interactions. Organisms such as oysters, a wide range of shallow water sedentary species, and vulnerable juvenile fishes are expected to suffer from prolonged exposure to elevated temperatures, deoxygenation and acidification (i.e., ocean water becoming less alkaline and hindering calcification) (Weatherdon et al. 2016). Such changes are likely to have cascading effects through the lagoonal food web impacting birds and the food availability for marine fauna (Lincoln et al. 2021). These changes may allow ecological space for non-native species to become invasive nuisance species (e.g., some phytoplankton) while others will decline in threat (Clarke et al. 2020).

Impacts to lagoonal ecosystems from human activity are likely to have cumulative and unanticipated interactions accruing across scales in time and varying in space across the lagoons. The high biodiversity, diverse ecosystem services and vulnerability of coastal lagoons to climate change suggest that these fascinating formations can serve as priority locations for nature-based solutions (e.g., protection, climate adaptation, restoration) (Pittman et al. 2022). Considerable knowledge gaps exist in our understanding of how multiple interacting local and global stressors will influence species and habitats and the structure and function of the lagoons in the region (Melville-Rea et al. 2021). Strengthening relationships for data diplomacy, data sharing and collaboration among scientists of the region could facilitate accelerating our understanding of the impact of stressors in the UAE and the Gulf (Fawzi et al. 2022) Ecoengineering solutions and identifying areas for managed retreat will be important adaptation strategies with potential to increase coastal wetland area (Burt and Bartholomew 2019; Schuerch et al. 2018). It is clear that the structure and function of UAEs lagoons are profoundly intertwined with human activity.

8.6 Management and Conservation

The specific characteristics and spatial arrangement of coastal lagoons, where individual habitat types often intermingle with each other in a configuration of 'seascape' mosaics, point to the need for a whole-site and ecosystem-based approach for conservation and management. Such an integrated approach focuses on the integrity of the interconnected ecosystems, rather than individual habitat types, and focused on the ecological functioning and resilience of an area to maintain biodiversity and the flow and quality of ecosystem services. Considering the vulnerability of the coastal seascapes to human pressures, ecosystem-based management can strengthen the synergies between ecological and biodiversity conservation with key socio-economic challenges and needs.

To address the Kunming-Montreal Global Biodiversity Framework (GBF) targets that include 30% of land-sea protection by 2030 (CBD 2022), future plans to expand the current protected areas in the UAE can draw from the recommendations of local scientific studies, as well as global guidance by IUCN and the Convention of Biological diversity (CBD) calling for a science-based design of ecologically representative and interconnected protected area networks (i.e., Aichi Target 11). Following the definition on Areas of Particular Importance for Biodiversity (APIBs) by CBD, a recent study in the UAE identified a number of coastal lagoons as Marine 'APIBs' considering habitat richness and their critical role in different life-stages of endangered species, among other criteria (Ben Lamine et al. 2020). These Marine APIBs are underrepresented within the existing UAE national designation of Marine Protected Areas (MPAs) with an estimated gap between current and desired protection of approximately 78% (Ben Lamine et al. 2020). Continual coastal development and ecosystem fragmentation points to the urgent need to expand the extent of protection in the coastal and intertidal zones along the UAE's waters and particularly coastal lagoons.

Increasing protection of coastal ecosystems is recognized as a key strategy for the UAE that not only supports biodiversity, but also safeguard the nation's largest blue carbon sinks that, if lost or degraded, can in turn release additional Green House Gas Emissions (GHGs) (IPCC 2019; Hilmi et al. 2021). The UAE National Determined Contribution (NDC, MOCCAE 2020) under the United National Framework Convention on Climate Change makes explicit reference to the initiatives that aim to conserve or restore blue carbon habitats as an adaptation measure with mitigation co-benefit.

Moving forward, greater collaboration between scientific research and policy making is critical to support compiling comprehensive blue carbon ecosystem inventories. It is highly important to measure the carbon storage and long-term emissions removal by coastal ecosystems, including coastal lagoons that typically are higher due to the dynamic environmental conditions, habitat maturity and biodiversity richness present in these areas. Such comprehensive inventories can form the basis of robust design, implementation, and reporting of blue carbon projects in the future. Science-based efforts to protect and restore blue carbon ecosystems are recognized as credible 'Nature-based solutions' supporting national climate plans to achieve Net-Zero by 2050 with measurable positive long-term climate mitigation and biodiversity outcomes (SBTi 2021; IUCN 2020).

The UAE's coastal lagoons are at the heart of the economic activity of each emirate, with multiple stakeholders, such as tourism, real estate, ports and shipping, fishing, and recreation, benefiting from the ecosystem services of these coastal ecosystems, while often engaging in activities that sometimes have a negative environmental impact. These complex interconnections of natural and socio-economic systems can offer an opportunity to integrate protected areas into broader economic and social development plans and strategies for the UAE. Moreover, the rise of ecosystem valuation and natural capital studies have demonstrated a clear link between oceans and economic development (Hoegh-Guldberg 2015), therefore natural capital accounting can further support integrated management decisions in the future.

Progress is being made in the implementation of commercial and government sector guidance for social and environment safeguarding and for the realization of environmental net gain (Hooper et al. 2021). An integrated approach to coastal management can support effective biodiversity conservation in areas that fall outside of formally recognized protected areas (e.g., private land). The Kunming-Montreal GBF include specific targets of 'Other Effective Conservation Measures' (OECMs) recognizing that governance and management mechanisms other than protected areas can positively contribute to ecosystem and biodiversity conservation (IUCN-WCPA Task Force on OECMs 2019).

Designating protected areas within coastal lagoon seascapes and OECMs would ultimately need to be integrated into broader decision-making and land-sea use planning guided by national or sub-national Marine Spatial Planning (MSP) and/or

Integrated Coastal Zone Management (ICZM). MSP and ICZM are broadly recognized by government, private sector and the scientific community as credible planning tools that can enable dialogue and engagement across multiple sectors to help identify optimum scenarios for activities (Katsanevakis et al. 2011; Santos 2019). Where ecosystem-based approaches are central, effective spatial planning can safeguard biodiversity and ecosystem resilience (WWF 2017). Key learnings from the increasing empirical knowledge on MSP and integrated ocean management implementation can offer valuable insights for the UAE decision makers. MSP and coastal management can benefit from natural capital studies and environmental impact assessments that are becoming increasingly important not only for development agencies, but also for financing institutions that are becoming more aware of their dependence on natural capital and the risks associated with biodiversity loss (TNFD 2022; DNB 2020).

Coastal wetlands and lagoons play a key role in global biodiversity persistence, so their effective management can elevate the national and international status of a designation. More than half of the currently listed Important Bird Areas (IBAs) in the UAE are coastal/marine (BirdLife International 2022) and at least three coastal lagoons have received recognition as Ramsar sites under the Ramsar Convention on Wetlands (Ramsar 2022). Three of the four protected areas in the UAE recognized by the prestigious IUCN Green List are coastal wetlands (https://iucngreenlist.org/explore/green-list-sites). Further expanding IBAs, Ramsar Sites, UNESCO World Heritage sites of cultural and natural importance in the UAE can offer a wide range of opportunities for scientific research, guidance on sustainable management of the coastal zone including MPAs, MSP, OECMs, as well as raising awareness among the public.

Given the proximity of coastal lagoons to urban environments, an integrated approach to managing these areas should also include citizen science and community programs that gather local knowledge, enable field activities contributing to science and conservation efforts, while creating environmentally-conscious behavior. Protected areas in coastal lagoons can also provide a platform for citizens to learn and enhance their physical and mental wellbeing as they interact with nature (Brymer et al. 2019). Ultimately, engagement of local communities and the public as well as citizen science initiatives are fundamental elements that can help advance the 'science we need for the ocean we want' as stated in the Implementation Plan for the United Nations Decade of Ocean Science for Sustainable Development (United Nations 2021).

References

Ajjur SB, Al-Ghamdi SG (2021) Evapotranspiration and water availability response to climate change in the Middle East and North Africa. Clim Chang 166(3):1–18

Alothman AO, Bos MS, Fernandes RMS, Ayhan ME (2014) Sea level rise in the north-western part of the Arabian Gulf. J Geodyn 81:105–110

Alsumaiti TS, Shahid SA (2019) Mangroves among most carbon-rich ecosystem living in hostile saline rich environment and mitigating climate change – a case of Abu Dhabi. J Agric Crop Res 7(1):1–8

Basset A, Elliott M, West RJ, Wilson JG (2013) Estuarine and lagoon biodiversity and their natural goods and services. Estuar Coast Shelf Sci 132:1–4

Ben Lamine E, Mateos-Molina D, Antonopoulou M, Burt JA, Das HS, Javed S et al (2020) Identifying coastal and marine priority areas for conservation in The United Arab Emirates. Biodivers Conserv 29(9):2967–2983

Bird EC (1994) Physical setting and geomorphology of coastal lagoons. In: Kjerfve B (ed) Coastal lagoon processes, Elsevier oceanography series, vol 60. Elsevier, Amsterdam, pp 9–39

BirdLife International (2018) *Phalacrocorax nigrogularis*. The IUCN Red List of threatened species 2018: e.T22696802A132594449. https://doi.org/10.2305/IUCN.UK.2018-2.RLTS.T22696802A132594449.en. Accessed 09 Mar 2023

BirdLife International (2022) Country profile: United Arab Emirates. http://www.birdlife.org/datazone/country/united-arab-emirates. Accessed 9 Mar 2023

Borland HP, Gilby BL, Henderson CJ, Connolly RM, Gorissen B, Ortodossi NL et al (2022) Dredging transforms the seafloor and enhances functional diversity in urban seascapes. Sci Total Environ 831:154811

Brymer E, Freeman E, Richardson M (2019) One health: the well-being impacts of human-nature relationships. Front Psychol 10:1611. https://www.frontiersin.org/articles/10.3389/fpsyg.2019.01611/full. Accessed 10 Sept 2022

Burt JA (2014) The environmental costs of coastal urbanization in the Arabian Gulf. City 18(6): 760–770

Burt JA, Bartholomew A (2019) Towards more sustainable coastal development in the Arabian Gulf: opportunities for ecological engineering in an urbanized seascape. Mar Pollut Bull 142:93–102

Campbell JE, Lacey EA, Decker RA, Crooks S, Fourqurean JW (2015) Carbon storage in seagrass beds of Abu Dhabi, United Arab Emirates. Estuar Coasts 38(1):242–251

Carter RA, Philip G (2010) Beyond the Ubaid: transformation and integration in the late prehistoric societies of the Middle East (no. 63). Oriental Institute of the University of Chicago, Chicago

CBD (2022) Zero draft of the post-2020 global biodiversity framework. Convention on biological diversity, Kunming, China. https://www.cbd.int/doc/c/efb0/1f84/a892b98d2982a829962b6371/wg2020-02-03-en.pdf. Accessed 10 Sept 2022

Charpentier V, Méry S (2008) A neolithic settlement near the strait of Hormuz: Akab Island, United Arab Emirates. Proc Seminar Arabian Stud:117–136

Clarke SA, Vilizzi L, Lee L, Wood LE, Cowie WJ, Burt JA et al (2020) Identifying potentially invasive non-native marine and brackish water species for the Arabian Gulf and Sea of Oman. Glob Chang Biol 26(4):2081–2092

Craig RK (2006) Valuing coastal and ocean ecosystem services: the paradox of scarcity for marine resources commodities and the potential role of lifestyle value competition. J Land Use Environ Law 22:355

Cunningham PA, Sullivan EE, Everett KH, Kovach SS, Rajan A, Barber MC (2019) Assessment of metal contamination in Arabian/Persian Gulf fish: a review. Mar Pollut Bull 143:264–283

Davies TW, Duffy JP, Bennie J, Gaston KJ (2014) The nature, extent, and ecological implications of marine light pollution. Front Ecol Environ 12(6):347–355

DNB (2020) Indebted to nature Exploring biodiversity risks for the Dutch financial sector. https://www.dnb.nl/media/4c3fqawd/indebted-to-nature.pdf. Accessed 10 Sept 2022

Duarte CM, Chapuis L, Collin SP, Costa DP, Devassy RP, Eguiluz VM et al (2021) The soundscape of the Anthropocene Ocean. Science 371(6529):eaba4658

Duck RW, da Silva JF (2012) Coastal lagoons and their evolution: a hydromorphological perspective. Estuar Coast Shelf Sci 110:2–14

Elmahdy SI, Ali TA, Mohamed MM, Howari FM, Abouleish M, Simonet D (2020) Spatiotemporal mapping and monitoring of mangrove forests changes from 1990 to 2019 in the Northern

Emirates, UAE using random forest, Kernel logistic regression and Naive Bayes Tree models. Front Environ Sci 8:102
Erftemeijer PL, Shuail DA (2012) Seagrass habitats in the Arabian Gulf: distribution, tolerance thresholds and threats. Aquat Ecosyst Health Manag 15:73–83
Evans G, Kinsman DJJ, Shearman DJ (1964) A reconnaissance survey of the environment of recent carbonate sedimentation along the Trucial Coast, Persian Gulf. In: van Straaten L (ed) Developments in sedimentology, vol 1. Elsevier, Amsterdam, pp 129–135
Fawzi NAM, Fieseler CM, Helmuth B, Leitão A, Al-Ainsi M, Al Mukaimi M et al (2022) Diplomacy for the world's hottest sea. Science 376(6600):1389–1390
Government of Umm Al Quwain (2015) Siniya Island. Archaeological sites. https://ahd.uaq.ae/en/about-us/archaeology/siniya-island.html. Accessed 27 June 2022
Hammad A (2019) Business bay – Dubai creek extension – construction management, challenges and results part II – project details. J Eng Arch 7:100. https://doi.org/10.15640/jea.v7n1a11
Hilmi N, Chami R, Sutherland MD, Hall-Spencer JM, Lebleu L, Benitez MB, Levin LA (2021) The role of blue carbon in climate change mitigation and carbon stock conservation. Front Clim 3. https://doi.org/10.3389/fclim.2021.710546
Hoegh-Guldberg O (2015) Reviving the ocean economy: the case for action – 2015. WWF International, Gland
Hooper T, Austen M, Lannin A (2021) Developing policy and practice for marine net gain. J Environ Manag 277:111387
IPCC (2019) IPCC special report on the ocean and cryosphere in a changing climate. IPCC Intergovernmental Panel on Climate Change, Geneva
IUCN (2020) Guidance for using the IUCN global standard for nature-based solutions. A user-friendly framework for the verification, design and scaling up of nature-based solutions. IUCN, Gland
IUCN-WCPA Task Force on OECMs (2019) Recognising and reporting other effective area-based conservation measures. IUCN, Gland. https://portals.iucn.org/library/sites/library/files/documents/PATRS-003-En.pdf
Katsanevakis S, Stelzenmüller V, South A, Sørensen TK, Jones PJS et al (2011) Ecosystem-based marine spatial management: review of concepts, policies, tools, and critical issues. Ocean Coast Manag 54:807–820
Khan S, Javed S, Ahmed S, Al Hammadi EA, Al Hammadi AA, Al Dhaheri S (2018) Does a recent surge in Socotra cormorant *Phalacrocorax nigrogularis* nesting population and establishment of new breeding colonies ensure long term conservation? Pragmatic assessment of recent augmentation in Abu Dhabi Emirate, UAE. Bird Cons. https://doi.org/10.1017/S0959270918000242
Kjerfve B (1994) Coastal lagoons. In: Kjerfve B (ed) Elsevier oceanography series, vol 60. Elsevier, Amsterdam, pp 1–8
Köstem B (2021) 'The world is sinking:' sand, urban infrastructure, and world-cities. Cult Stud 35: 684–706. https://doi.org/10.1080/09502386.2021.1895244
Lasserre P (1979) Coastal lagoons: sanctuary ecosystems, cradles of culture, targets for economic growth. Nat Res Forum 15:2–21
Lauchlan SS, Nagelkerken I (2020) Species range shifts along multistressor mosaics in estuarine environments under future climate. Fish Fish 21(1):32–46.
Lidour K, Béarez P, Beech M, Charpentier V, Méry S (2021) Intensive exploitation of marine crabs and sea urchins during the middle Holocene in the eastern Arabian peninsula offers new perspectives on ancient maritime adaptations. J Isl Coast Archaeol:1–29
Lincoln S, Buckley P, Howes EL, Maltby KM, Pinnegar JK, Ali TS, Le Quesne WJ (2021) A regional review of marine and coastal impacts of climate change on the ROPME Sea area. Sustainability 13(24):13810
Longcore T, Rodríguez A, Witherington B, Penniman JF, Herf L, Herf M (2018) Rapid assessment of lamp spectrum to quantify ecological effects of light at night. J Exp Zool A Ecol Integr Physiol 329(8–9):511–521

Lopes R, Videira N (2013) Valuing marine and coastal ecosystem services: an integrated participatory framework. Ocean Coast Manag 84:153–162
Lorimer JG (1908) Gazetteer of the Persian Gulf, Oman and Central Arabia. Superintendent Government Print, India
Mateos-Molina D, Antonopoulou M, Baldwin R, Bejarano I, Burt JA, García-Charton JA et al (2020) Applying an integrated approach to coastal marine habitat mapping in the North-Western United Arab Emirates. Mar Environ Res 161:105095
Mateos-Molina D, Lamine EB, Antonopoulou M, Burt JA, Das HS, Javed S et al (2021a) Synthesis and evaluation of coastal and marine biodiversity spatial information in The United Arab Emirates for ecosystem-based management. Mar Pollut Bull 167:112319
Mateos-Molina D, Pittman SJ, Antonopoulou M, Baldwin R, Chakraborty A, García-Charton JA, Taylor OJS (2021b) An integrative and participatory coastal habitat mapping framework for sustainable development actions in The United Arab Emirates. Appl Geogr 136:102568
Melville-Rea H, Eayrs C, Anwahi N, Burt JA, Holland D, Samara F, Paparella F, Al Murshidi AH, Al-Shehhi MR, Holland DM (2021) A roadmap for policy-relevant sea-level rise research in The United Arab Emirates. Front Mar Sci 8:907. https://doi.org/10.3389/fmars.2021.670089
Merchant ND (2019) Underwater noise abatement: economic factors and policy options. Environ Sci Pol 92:116–123
Méry S, Charpentier V, Auxiette G, Pelle E (2009) A dugong bone mound: the neolithic ritual site on Akab in Umm al-Quwain, United Arab Emirates. Antiquity 83(321):696–708. https://doi.org/10.1017/S0003598X00098926
Mills M, Leon JX, Saunders MI, Bell J, Liu Y, O'Mara J, Lovelock CE, Mumby PJ, Phinn S, Possingham HP, Tulloch VJ (2016) Reconciling development and conservation under coastal squeeze from rising sea level. Conserv Lett 9(5):361–368
MOCCAE (2020) In: Pörtner DC, Roberts V, Masson-Delmotte P, Zhai M, Tignor E, Poloczanska et al (eds) Second nationally determined contribution of The United Arab Emirates. https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/SROCC_FullReport_FINAL.pdf. Accessed 1 July 2022
Mutin B (2012) Cultural dynamics in Southern Middle-Asia in the fifth and fourth millennia BC: a reconstruction based on ceramic traditions. Paléorient 38(1):159–184
Muzaffar SB (2020) Seabirds in the Arabian Gulf: ecology, movements and conservation. J Aquat Ecosyst Health Manag 23(2):220–228
Muzaffar SB, Whelan R, Clarke C, Gubiani R, Benjamin S (2017a) Breeding population biology in Socotra cormorants (*Phalacrocorax nigrogularis*) in The United Arab Emirates. Waterbirds 40(1):1–10
Muzaffar SB, Clarke C, Whelan R, Gubiani R, Cook TR (2017b) Short distance directional migration in the threatened Socotra cormorant: link to primary productivity and implications for conservation. Mar Ecol Prog Ser 575:181–194
Nellemann C, Corcoran E, Carlos DM, De Young C, Fonseca LE, Grimsdith G (2010) Blue Carbon: The role of healthy oceans in binding carbon. University of New Hampshire, Center for Coastal and Ocean Mapping
Newton A, Icely J, Cristina S, Brito A, Cardoso AC, Colijn F et al (2014) An overview of ecological status, vulnerability and future perspectives of European large shallow, semi-enclosed coastal systems, lagoons and transitional waters. Estuar Coast Shelf Sci 140:95–122
Newton A, Brito AC, Icely JD, Derolez V, Clara I, Angus S et al (2018) Assessing, quantifying and valuing the ecosystem services of coastal lagoons. J Nat Conserv 44:50–65
Nezlin NP, Polikarpov IG, Al-Yamani F (2007) Satellite-measured chlorophyll distribution in the Arabian Gulf: Spatial, seasonal and inter-annual variability. International Journal of Oceans and Oceanography 2(1):139–156
Pittman SJ, Stamoulis KA, Antonopoulou M, Das HS, Shahid M, Delevaux JMS, Wedding LM, Mateos-Molina D (2022) Rapid site selection to prioritize coastal seascapes for nature-based solutions with multiple benefits. Front Mar Sci 9. https://doi.org/10.3389/fmars.2022.832480

Potts DT, Al Naboodah H, Nābūdah ḤM, Hellyer P (eds) (2003) Archaeology of The United Arab Emirates. Trident Press, London
Ramsar (2022) Ramsar convention country profiles, UAE. https://www.ramsar.org/wetland/united-arab-emirates. Accessed 3 July 2022
Samara F, Solovieva N, Ghalayini T, Nasrallah ZA, Saburova M (2020) Assessment of the environmental status of the mangrove ecosystem in The United Arab Emirates. Water 12(6): 1623
Santos FC (2019) Marine spatial planning in world seas: an environmental evaluation, volume III: ecological issues and environmental impacts. Elsevier, Amsterdam
SBTi (2021) Science based target initiative. SBTi Corporate Net-Zero Standard V1. https://sciencebasedtargets.org/resources/files/Net-Zero-Standard.pdf. Accessed 1 Aug 2022
Schile LM, Kauffman JB, Crooks S, Fourqurean JW, Glavan J, Megonigal P (2017) Limits on carbon sequestration in arid blue carbon ecosystems. Ecol Appl 27(3):859–874. https://doi.org/10.1002/eap.2017.27.issue-310.1002/eap.1489
Schile-Beers L, Megonigal JP, Kauffman JB, Crooks S, Fourqurean JW, Campbell J, Dougherty B, Glavan J (2018) Carbon sequestration in arid blue carbon ecosystems: a case study from the United Arab Emirates. In: Windham-Myers L, Crooks S, Troxler GT (eds) A Blue Carbon Primer. CRC Press, pp 327–339
Schneider JF (1975) Recent tidal deposits, Abu Dhabi, UAE, Arabian Gulf. In: Ginsburg R (ed) Tidal deposits. Springer, Berlin, pp 209–214
Schuerch M, Spencer T, Temmerman S, Kirwan ML, Wolff C, Lincke D, McOwen CJ, Pickering MD, Reef R, Vafeidis AT, Hinkel J (2018) Future response of global coastal wetlands to sea-level rise. Nature 561(7722):231–234
Schwall C, Jasim SH (2020) Assessing Kalba: new fieldwork at a bronze age coastal site on the Gulf of Oman (Emirate of Sharjah, UAE). Proc Sem Arab Stud 50:321–332
Shriadah MA (1998) Metals pollution in marine sediments of The United Arab Emirates creeks along the Arabian Gulf shoreline. Bull Environ Contam Toxicol 60(3):417–424
Smith EG, Vaughan GO, Ketchum RN, McParland D, Burt JA (2017) Symbiont community stability through severe coral bleaching in a thermally extreme lagoon Abstract Scientific Reports 7(1). https://doi.org/10.1038/s41598-017-01569-8
Spencer T, Schuerch M, Nicholls RJ, Hinkel J, Lincke D, Vafeidis AT et al (2016) Global coastal wetland change under sea-level rise and related stresses: the DIVA wetland change model. Glob Planet Chang 139:15–30
Stöfen-O'Brien A, Naji A, Brooks AL, Jambeck JR, Khan FR (2022) Marine plastic debris in the Arabian/Persian Gulf: challenges, opportunities and recommendations from a transdisciplinary perspective. Mar Policy 136:104909
Tamir R, Lerner A, Haspel C, Dubinsky Z, Iluz D (2017) The spectral and spatial distribution of light pollution in the waters of the northern Gulf of Aqaba (Eilat). Sci Rep 7(1):1–10
Tidau S, Smyth T, McKee D, Wiedenmann J, D'Angelo C, Wilcockson D et al (2021) Marine artificial light at night: an empirical and technical guide. Methods Ecol Evol 12(9):1588–1601
TNFD (2022) The TNFD nature-related risk & opportunity management and disclosure framework beta v0.1. https://tnfd.global/publication/nature-related-risk-beta-framework-v01/. Accessed 4 July 2022
Tully K, Gedan K, Epanchin-Niell R, Strong A, Bernhardt ES, BenDor T, Mitchell M, Kominoski J, Jordan TE, Neubauer SC, Weston NB (2019) The invisible flood: the chemistry, ecology, and social implications of coastal saltwater intrusion. Bioscience 69(5):368–378
United Nations (2021) The United Nations decade of ocean science for sustainable development (2021–2030): implementation plan, summary. https://unesdoc.unesco.org/ark:/48223/pf0000376780
Velde C (2012) The geographical history of Julfar. Fifty years of Emirates archaeology. Motivate Publishing, Dubai

Wabnitz CC, Lam VW, Reygondeau G, Teh LC, Al-Abdulrazzak D, Khalfallah M et al (2018) Climate change impacts on marine biodiversity, fisheries and society in the Arabian Gulf. PLoS One 13(5):e0194537
Weatherdon LV, Magnan AK, Rogers AD, Sumaila UR, Cheung WW (2016) Observed and projected impacts of climate change on marine fisheries, aquaculture, coastal tourism, and human health: an update. Front Mar Sci 3:48
Whelan R, Jabado RW, Clarke C, Muzaffar SB (2017) Observations of rays and guitarfish (Batoidea) in shallow waters around Siniya Island, Umm al-Qaiwain, United Arab Emirates. Tribulus 25:76–90
Whelan R, Clarke C, Gubiani R, Muzaffar SB (2019) Sea turtle observations on and around Siniya Island, Umm Al Quwain, United Arab Emirates. Mar Turt Newsl (156):10–12
WWF (2017) Delivering ecosystem-based marine spatial planning in practice: an assessment of the integration of the ecosystem approach into UK and Ireland marine spatial plans, p 1–132
Zaggia L, Lorenzetti G, Manfé G, Scarpa GM, Molinaroli E, Parnell KE et al (2017) Fast shoreline erosion induced by ship wakes in a coastal lagoon: field evidence and remote sensing analysis. PLoS One 12(10):e0187210

Recommended Reading

Pittman SJ, Antonopoulou M, Mateos-Molina D (2020) Policy report: areas of particular importance in the Arabian Gulf. Emirates Nature-WWF, Dubai, United Arab Emirates 66pp
Potts DT, Hellyer P (2014) Fifty years of Emirates archaeology: proceedings of the second international conference on the archaeology of The United Arab Emirates. Tribulus 22:87–89
Wolanski E, Day JW, Elliott M, Ramesh R (eds) (2019) Coasts and estuaries: the future. Elsevier https://www.sciencedirect.com/book/9780128140031/coasts-and-estuaries

Chapter 9
Seagrasses of the United Arab Emirates

Noura Al-Mansoori and Himansu Sekhar Das

9.1 Distribution

9.1.1 Global Distribution

Found in intertidal as well as subtidal zones, seagrass meadows are either fully submerged or occasionally exposed in intertidal areas of the coastline. These marine plants occur in tropical, subtropical, and temperate zones (Fig. 9.1), and typically occur to a depth of 10 m in most of its range (Short et al. 2001), although they can be found to depths of 50 m or more when the water quality and clarity are optimal (Den Hartog 1979). Seagrass occurs in sediment types that range from muddy organic soil to sand with gravel substrates, and are often adjacent to mangrove and coral reef ecosystems (Lamine et al. 2021). Seagrasses are the most common coastal habitat globally, forming underwater meadows that are critical for coastal and marine wildlife and contribute to the primary productivity of the coastal waters (Costanza et al. 1997).

N. Al-Mansoori (✉)
Marine Biology Lab, New York University, Abu Dhabi, United Arab Emirates

Marine Biodiversity Division, Environment Agency Abu Dhabi, Abu Dhabi, United Arab Emirates
e-mail: nouram.almansoori@ead.gov.ae

H. S. Das
Marine Biodiversity Division, Environment Agency Abu Dhabi, Abu Dhabi, United Arab Emirates

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_9

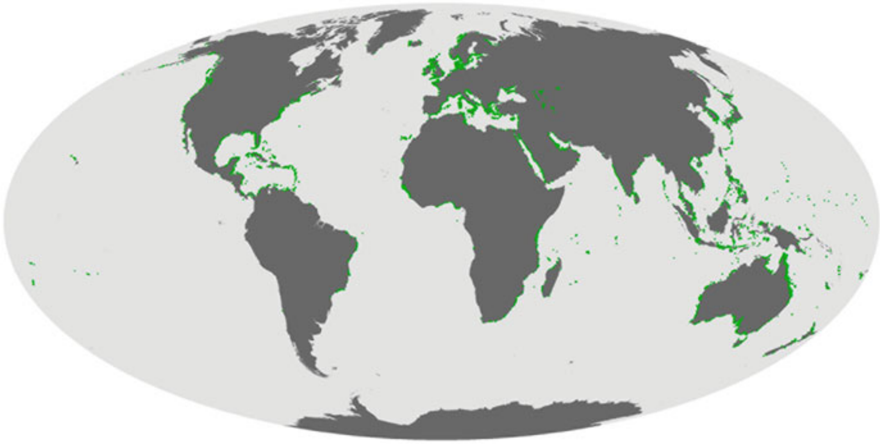


Fig. 9.1 Seagrasses are widely distributed and found along most of the coastlines around the world. Data source: UNEP-WCMC (2021), published per the ENEP-WCMS General Data License

9.1.2 Taxonomy

Seagrasses are marine angiosperms (flowering plants) that represent a small group of species compared with most other marine organisms, yet they hold a vital role in providing habitats to other species. There are about 300,000 species of angiosperms, and only around 60 of them are considered seagrasses. They fall into two families: Potamogetonaceae and Hydrocharitaceae, taxonomic studies of seagrasses are still ongoing with some current knowledge gaps (Hartog and Kuo 2006). With low taxonomic diversity compared to the more than 250,000 terrestrial flowering plants, seagrasses diverged from a lineage of monocot flowering plants (the same group that contains corn, lilies and all of the terrestrial grasses) between 70 and 100 million years back (Les et al. 1997). Research on their taxonomy and distribution is still on-going and questioned despite the limited diversity of seagrass flora (Hemminga and Duarte 2000). Despite of their low species diversity and specialist physiological characteristics, seagrasses have successfully and widely colonized in most coastal regions except the polar regions (Orth et al. 2006a). Seagrasses are a vascular (veinous) plant that produced roots and seeds and has various other adaptations that emerged as this group evolved on land and that they still retain despite moving into the sea; seed dispersal through water currents is one of the abiotic dispersal adaptation that seagrasses utilize as a method of reproduction, in which floating seeds, reproductive fragments or fruits are transported long distances until seeds arrive at the sediment surface as 'seed rain' (Orth et al. 2006b). They should not be confused with the evolutionarily divergent marine algae (seaweeds), which are taxonomically and biologically very distinct and are discussed separately in Chap. 10.

9.1.3 Arabian Gulf Seagrasses

In the relatively young Arabian Gulf in the North-Western Indian Ocean (NWIO) region, seagrasses are representative of Indo-Pacific and subtropical biogeographic conditions. Largest extent of the seagrasses mapped in the Arabian Gulf are found in Abu Dhabi coastal waters (Das 2021), although seagrass meadows have also been mapped from other emirates as well (Table 9.1), namely, Dubai, Umm Al Quwain and Ras Al Khaimah in khors (lagoons), channels and backwaters (Fig. 9.2), with relatively less areal coverage. The seagrasses of the UAE usually inhabit shallow, low wave energy areas up to a depth of 14 m (EAD 2020) in a varied sediment type

Table 9.1 Seagrass area (in km^2) of each emirate and a general description of the seagrasses in each area, with notes on observed occurrences and depths

Area/region	Seagrass area (km^2)	Description	Reference
Sharjah (Northern region)	0	Studies showed little to no significant seagrass beds; coastal waters are deeper here with more hard-bottom habitats not suitable for seagrass growth and recruitment.	Mateos-Molina et al. (2020)
Ajman (Northern region)	0	Studies showed little to no significant seagrass beds; coastal waters are deeper here with more hard-bottom habitats not suitable for seagrass growth and recruitment.	Mateos-Molina et al. (2020)
UAQ (Northern region)	11.10 km^2	Seagrasses here can be found in Khor Beidah, which is a coastal lagoon (coastal lagoons are locally known as 'Khors'. They grow in extreme conditions at depths between 0 and 2 m and colonise mudflats and tolerate being completely exposed to the sun at low tide. They also form sparse seagrass beds at their deeper distribution (7–10 m).	Mateos-Molina et al. (2020)
RAK (Northern region)	10.47 km^2	Seagrasses here are similar to UAQ they can be found in these coastal lagoons: Khor Muzahmi, Khor Ras al Khaimah, Khor Julfar and Khor Hulaylah.	Mateos-Molina et al. (2020)
Dubai (Northern region)	10.5 km^2	Seagrasses in Dubai were recorded around Jebel Ali Protected Area.	Personal com, Dubai Municipality data (2021)
Abu Dhabi (including Western region)	2922 km^2	Abu Dhabi has the largest stretch of coastline along the southern Arabian Gulf in the UAE. It includes vast seagrass meadows, algal beds, and coral reefs. It encompasses Marawah Marine Biosphere reserve and Al Yassat Marine Protected Area, where the second largest population of dugongs occur.	EAD (2020)

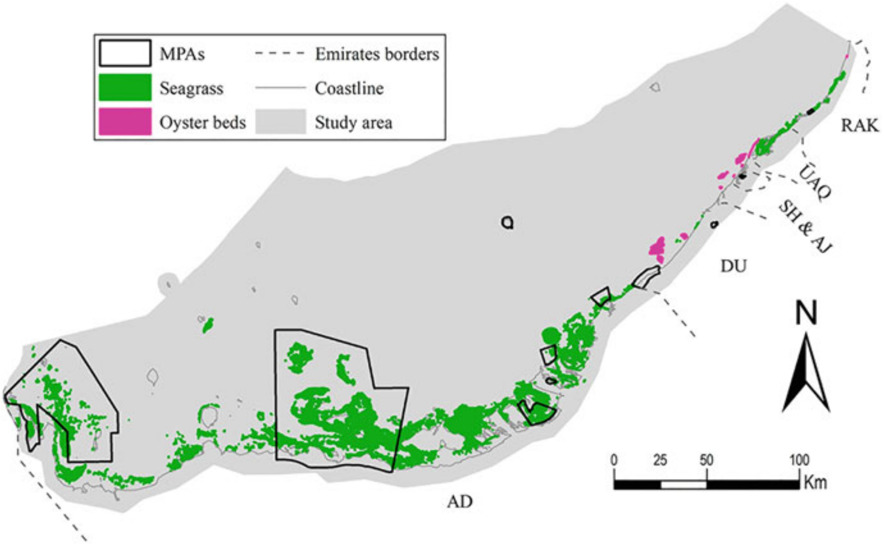


Fig. 9.2 UAE coastline showing seagrass areas, the location of marine protected areas and the occurrence of oyster beds. Source: Fig. 4 in Mateos-Molina et al. (2021), reproduced under Elsevier license 5513570228876

that ranges from sandy substratum to muddy soil with nutrients and organics. The Arabian Gulf contains 6% of the total area of seagrasses around the world, which covers an area of around 6790–7320 km^2 in the Gulf, with ca. 80% of this (i.e. 4% of global total) occur in Abu Dhabi alone (Erftemeijer and Shuail 2012; Lamine et al. 2021), and the most dense meadow could be found in Marawah Marine Biosphere reserve, an MPA established in 2007 to protect the rich ecosystems within (Mateos-Molina et al. 2021) (Fig. 9.2) (see also Chap. 8).

9.1.4 Seagrass in the United Arab Emirates

The seagrass meadows in the UAE coastal waters of the Arabian Gulf are composed of three key habitat forming species of seagrasses: *Halodule uninervis*, the most dominant species that contributes the highest biomass growing in all sediment types, *Halophila ovalis*, the second most dominant species that has a wider distribution and can be found in sand/gravel substrata in deeper waters, and *Halophila stipulacea*, which is has limited abundance and distribution and prefers muddy intertidal habitats with high organic content (Campbell et al. 2015). These meadows can be found as monospecific beds, as well as mixed species assemblages. In several areas in Abu Dhabi, especially during summer, seagrass meadows are intermixed with marine algae such as *Sargassum* spp. and *Harmophysa* spp. that usually grow within and around the seagrass meadows where substratum is dominated by gravel rocks and

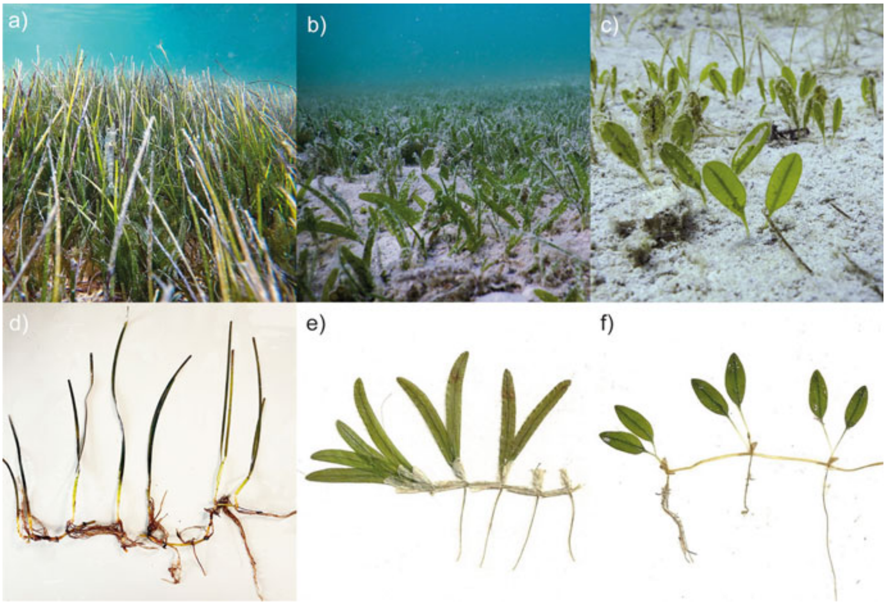


Fig. 9.3 The three seagrass species: (**a**) and (**d**) *Halodule uninervis,* (**b**) and (**e**) *Halophila stipulacea* and (**c**) and (**f**) *Halophila ovalis.* This figure showcases these species in the field how they appear naturally, and then a closer view in the laboratory. Photos: Noura Al-Mansoori (**a**, **d**, **e**, **f**) and Himansu Das (**b**, **c**)

Table 9.2 Depth ranges and substratum types these species prefer

Species	Distribution along the depth gradient (m)											Sediment type			
	1	2	3	4	5	6	7	8	9	10	12	14	Mud	Sand	Sand/coral	Rock/ gravel
Halodule uninervis													X	X	X	X
Halophila ovalis														X	X	
Halophila stipulacea													X	X		

dead coral (see also Chap. 10). Up to 80% of coverage is contributed by *H. uninervis* in most meadows (Fig. 9.3 and Table 9.2).

Seagrass cover of Abu Dhabi coastal waters was estimated to be 5500 km^2 in 2000 using aerial as well as boat-based field surveys (Phillips et al. 2002). In 2021, combining data from remote sensing satellite imageries (Worldview and Sentinel) and data from available online sources and field survey using underwater video rays/ drop camera, the Environment Agency Abu Dhabi mapped approximately 3000 km^2 of seagrass in Abu Dhabi. Considering the survey methods of both the estimates, Abu Dhabi seagrass area may range from 3000 to 5000 km^2 (Fig. 9.2).

The western region of Abu Dhabi as part of south-western Arabian Gulf is a sheltered waterbody with wide areas of shallow depth ($<$15 m) and sediments rich in nutrients and organics. Water circulation in the area is limited in this embayment and turbidity is relatively slow (see Chap. 4). Water depth, circulation, current and sediment types in the central and western region of Abu Dhabi create favorable conditions for seagrass growth, resulting in relatively higher density and wide distribution of seagrass beds. The area has natural channels, sheltered waters, bays and backwaters that supports the seagrass growth.

Due to high sea surface temperatures (SST) during summer, the seasonality of seagrass is apparent in UAE waters. Disappearance of seagrass meadows in very shallow waters (up to 5 m) during peak summer temperatures (July–September, SSTs $>$34 °C) is common, and this is associated with movement of seagrass-feeding marine megafauna to deeper ($>$5 m) waters during this period. Seagrass leaves shed copiously in these shallow depths during summer, leaving roots and rhizomes, with leaves reappearing only after the cessation of summer extremes. At times, seagrass-specializing marine animals such as dugongs will switch to feeding on marine algae during these periods where seagrasses decrease in density (Marsh et al. 1982). By October, when SSTs return to 24–26 °C, seagrass leaves start reappearing (EAD 2020). Similar pattern not observed in waters deeper than 5 m, where the slight difference in depth allows them to remain below physiological thresholds that cause stress, and seagrass beds in these slightly deeper depths can remain dense throughout the summer (Das 2021).

9.2 Diversity

Seagrasses have a wide distribution globally but with a relatively low number of species (~60 species worldwide), and because of their submerged nature they are often overlooked. Yet in comparison to most marine and coastal plants they are widely distributed (Short et al. 2007). Seagrasses have been classified into their respective bioregions in order to better understand their taxonomic distribution and provide a framework for understanding seagrass habitats, their dynamics in a geographic context, and their trophic pathways, while also providing a structure for scientists to compare and contrast species and study them worldwide (Short et al. 2007).

Regional biogeography is an important part of understanding seagrasses, because is based on the geographic range and is used to relate species of temperate and tropical regions. Even though taxonomic and genetic studies are still ongoing, the classification of most species have been well described into six bioregions globally: (1) Temperate North Atlantic (2) Tropical Atlantic, (3) Mediterranean, (4) Temperate North Pacific, (5) Tropical Indo-Pacific (part of which includes the UAE) and, (6) the Temperate Southern Oceans. Of all the tropical and temperate regions, the tropical Indo-Pacific region has the highest diversity of seagrass species, and which includes the Arabian Gulf (Short et al. 2007). Out of 60 known species globally,

Table 9.3 Regional distribution of seagrass species; Arabian Gulf, Sea of Oman, Red Sea, Mediterranean. Data from: (El Shaffai 2016; El-Shaffai et al. 2011; Green et al. 2003; Lipkin et al. 2003)

Bioregion	Description	Richness	Threats	Temperature and salinity range
Arabian Gulf	Low species richness, three species of seagrasses in hypersaline and eutrophic coastal waters with extremely high SST during summer	Three species	Dredging, landfilling, coastal development, discharges from desalination plants and industries,	Summer temperature reaches 36 ° C. Salinity 44–46 PSU
Red Sea	Highest species richness in the region. Water quality and clarity of red sea along with the slow slopes encourages growth and recruitment of seagrass.	12 species	Coastal development, dredging and land filling, maintenance of channels	Depth up to 70 m temp 32–33 °C in summer, Salinity 35–36 PSU
Sea of Oman	Narrow but extensive slope of shallow coastal waters support growth of seagrass.	Four species	Coastal development, monsoon rain that brings silt	Temp 33–34 °C in summer, Salinity 34–36 PSU
Mediterranean Sea	Eastern Mediterranean has suitable habitat for seagrass along its coast that connects Red Sea.	Five species	Coastal development, harbor, and pollution	Depth up to 25 m Temp 30–31 °C in summer, Salinity 39–40 PSU

24 predominantly occur in this bioregion, with only three species known to occur in the Arabian Gulf, presumably because the extreme environmental conditions of this region limit the number of species that are able to survive (Erftemeijer and Shuail 2012). Arabian Gulf seagrass diversity is low compared to the adjacent Red Sea, Northwestern Indian Ocean (NWIO), Western Indian Ocean (WIO) and rest of the Indo-pacific region (Table 9.3). This makes the Arabian Gulf a critical place in terms of climate change effects on these tropical species and hotspot for research to better understand mechanisms that seagrasses use to survive extreme temperature fluctuations.

9.3 Broad Importance of the Ecosystem

9.3.1 Global-Scale Importance

On a global scale, the complex seagrass ecosystems provide physical and biological functions such as stabilizing sediments, reducing sediment resuspension and erosion during storms, in addition to acting as a buffer for wave action. They also serve as a shelter for resident and transient adult and juvenile animals many of which have commercial and recreational importance to traditional fishing communities. Seagrasses and their epiphytes area major marine source of carbon and provide a food source to complex food webs through direct grazing or detrital pathways. They also trap detritus, sediment and nutrients (derived from land runoff) (Coles et al. 2002). Seagrass meadows have an extensive root system that stabilize the sediment and protect against coastal erosion, while also acting as effective carbon sinks for almost 10% of oceanic carbon burial, or 27.4 Tg C in a year (Duarte et al. 2005).

9.3.2 Ecological and Biological Importance: Arabian Gulf/UAE

Along the UAE coastline, seagrass ecosystems hold vital ecological and biological importance. They play a major role in purifying coastal waters, cycling nutrients and contribute to the food web structure (Hemminga and Duarte 2000). Seagrass meadows are known for carbon and nutrient sequestration. Organic carbon in seagrass sediment, known as “blue carbon,” originates from carbon sequestration ability of seagrass species. A study in 2013 suggests 52 tonnes/ha of blue carbon is stored in seagrass beds of Abu Dhabi and due to its large extent the overall blue carbon stock is estimated to be highest in the area out of all other ecosystems (algal mats and mangroves) (Skaalvik et al. 2013) (Fig. 9.4).

Seagrasses of the UAE is biologically critical as it supports at least 3000 dugongs and over 4000 green sea turtles (Das et al. 2021). They serve as important breeding and foraging grounds for the endangered green turtle (*Chelonia mydas*), and to the world’s second largest population of the vulnerable dugong (*Dugong dugon*) (Fig. 9.5) (Sheppard et al. 2010). Since dugongs and adult green sea turtles are herbivorous, seagrass is the staple food for these species. In addition, seagrass meadows are important fish nursery sites. Knowing the resilience of seagrasses to climate change, studies to estimate carbon sequestration capacity of seagrass and other coastal communities such as mangroves and saltmarshes have been undertaken by various research agencies (Elkabbany 2019; Skaalvik et al. 2013).

Seagrass beds are a direct food source for many herbivores while also providing and indirect energy source to the detrital food web. They also provide nursery habitats for a variety of commercially important fishes, pearl oyster (*Pinctada*

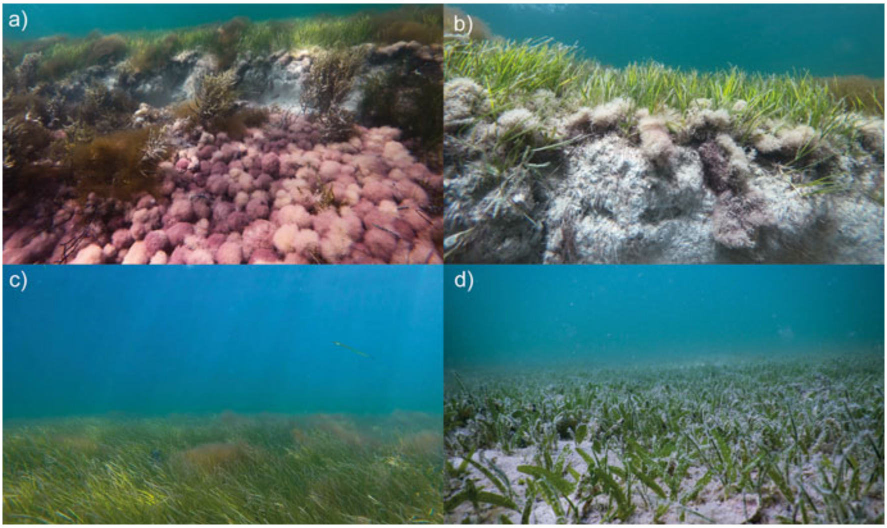


Fig. 9.4 (**a** and **b**) Exposed root system of a seagrass meadow intermixed with algae. (**c**) *Halodule uninervis* monospecific seagrass meadow with some dispersed algae near Marawah Marine Biosphere Reserve in Western Region Abu Dhabi. (**d**) Intermixed seagrass meadow. Photos: Noura Al-Mansoori (**a**–**c**), Himansu Das (**d**)

Fig. 9.5 Aerial view of a herd of Dugongs ((*Dugong dugon)* in the Western Region grazing on a seagrass meadow near Marawah Marine Biosphere Reserve, Abu Dhabi. Photo: Shamsa Al-Hameli

radiata), shrimp (*Penaeus semisulcatus*) and various other species that utilize these beds for food, shelter, and growth (Fig. 9.6).

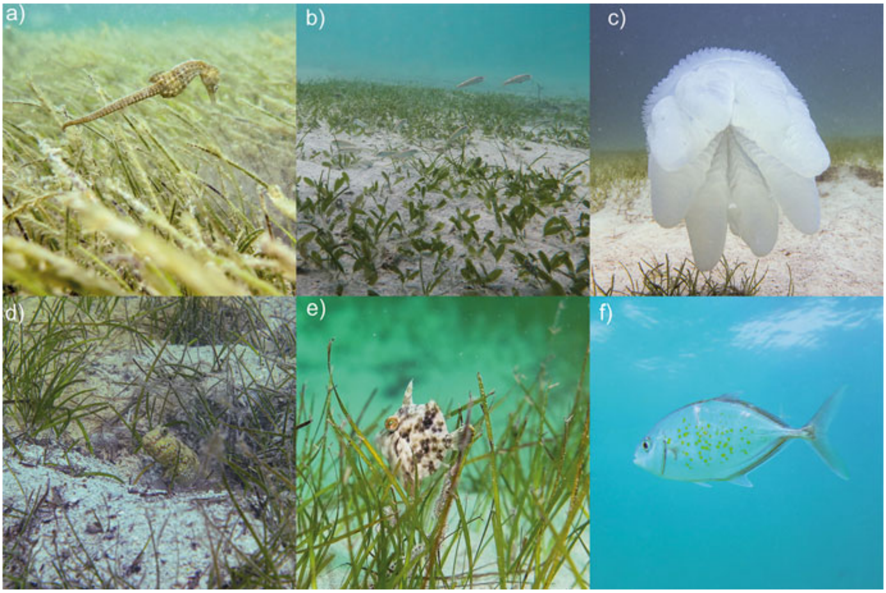


Fig. 9.6 Commonly found associated species that utilize seagrass beds as a habitat: (**a**) Sea Pony (*Hippocampus fuscus*) (**b**) Juvenile fish grazing around seagarsses (**c**) Jellyfish (**d**) Goby fish (*Cryptocentrus lutheri*) burrowing between seagrass (**e**) Seagrass filefish (*Acreichthys tomentosus*) (**f**) Orange spotted trevally (*Carangoides bajad*). Photos: Shamsa Al-Hameli (**a**), Noura Al-Mansoori (**b**–**f**)

9.3.3 Socio-cultural Importance

In terms of socio-cultural importance, seagrass beds have indirectly supported pre-modern communities around this region by providing food and refuge to dugongs. Historically, dugongs served as an important food source for coastal populations, as evidenced by the presence of their bones in UAE archaeological middens extending back as far as 4000 years ago (Lidour and Beech 2020). These coastal communities of the UAE consider seagrass meadows as sites for fish, dugong, and green turtles. In the past, prior to 1970 when there was no regulation for fishing marine megafauna, dugongs and green turtles were captured and meat consumed. The bones and skeletal remains of dugongs and green turtles in several coastal and offshore islands are a testimony of the activities in the past (Beech 2010).

9.4 Threats

Seagrasses occur in nearshore coastal waters, which are often close to human settlements. Therefore, most of the threats originate from human activities. Loss and degradation of seagrass meadows on global scales are often common to causes of seagrass impacts in the UAE and include factors such as eutrophication (Bulthuis 1983; Cambridge and McComb 1984; Neverauskas 1987) and coastal land-use modification through developmental activities such as dredging of navigational channels as well as operation of ports, harbours and industries (Kemp et al. 1983; Short and Wyllie-Echeverria 1996). Dredging and landfilling for coastal and offshore developments causes physical removal and smothering of seagrass meadows as well as deterioration of water clarity which is crucial of growth and recruitment of seagrasses (Erftemeijer and Shuail 2012; Short and Wyllie-Echeverria 1996). Mechanical damage by anchoring and propellor action of boats though common along the coast of offshore island, the threat has not been quantified. These actions not only damage seagrass physically but disturbs sediment to degrade water quality.

As the coastal marine environment of the UAE has experiened extremely rapid urbanization and industrialization since the 1970s (see Chap. 23), with seagrass beds occurring in some of the most heavily modified areas (e.g. lagoons and in shallow environments around oil concessions), pressures on these important ecosystems have been acute. Unfortunately, seagrass surveys only began in the late 1990s, and it is unknown to what extent seagrass beds were impacted by earlier development, particularly the extensive dredging of navigation channels throughout the central and western region of Abu Dhabi from the late 1960s onward, which were constructed to support the nascent oil and gas industry at Ruwais and its associated offshore platforms. Furthermore, after the discovery of oil in 1970, UAE escalated its development mostly along the coast and offshore areas for exploration of oil and gas. This increased developmental pressures resulted in low water clarity in terms of obstruction to penetration of light that may be considered as one of the most significant threat to seagrass growth and recruitment (Short and Wyllie-Echeverria 1996). Eutrophicated water supports growth of phytoplankton and marine algae in and around the seagrass meadows (Neverauskas 1987). This also increased nutrient content in the water column which accelerated macro algae growth and allowed it to dominate over seagrasses by covering the morphologically smaller seagrasses of the Arabian Gulf. Such invasion of macro algae may cause lower rate of photosynthesis (Larkum and West 1990; Walker et al. 1988). The epiphytes that grow in seagrass decreases diffusion of nutrients and gasses to seagrass thus affecting its physiology and growth which in large quantities may cause suffocation of meadows in a large scale (Fig. 9.7) (Borowitzka and Lethbridge 1989).

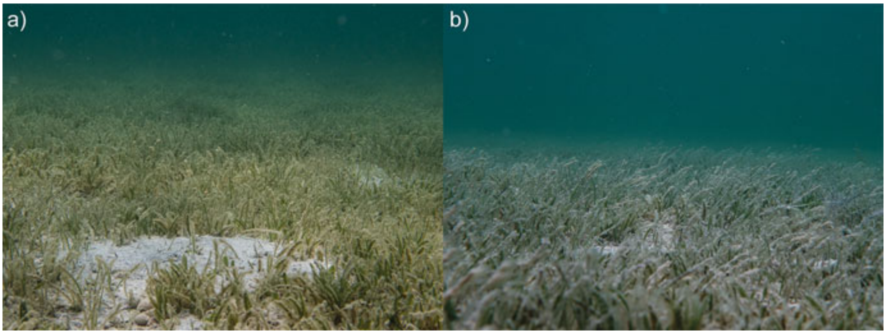


Fig. 9.7 High nutrients and sedimentation may cause overgrowth by opportunistic epiphytic algae on seagrass beds, which may induce light stress and reduced seagrass growth. Figure (**a**) and (**b**) shows a seagrass bed near Mirfa, Abu Dhabi during June 2022, with sediment deposits and epiphytic growth on seagrasses. Photos: Noura Al-Mansoori (**a**), Himansu Das (**b**)

9.5 Management and Conservation

9.5.1 Federal and Government Laws and Regulation

The conservation and management of seagrass meadows are in place in UAE through national and local regulations and laws, species conservation plans, and international and regional conventions and MoUs. The actions to protect seagrass meadows include research and monitoring, identification of threatening processes, development of policies and laws, and declaration of natural parks and protected areas, in addition to restoration of degraded habitats.

Due to its importance as foraging and nursery area for marine wildlife and fish, seagrass meadows have been considered as a critical habitat and protected by Law 23 and 24 (1999). Under International conventions for biological diversity, and the Abu Dhabi 2030 plan, the conservation target for seagrass habitats have been included among other key important marine habitats and associated species, which aids the protection and conservation of seagrass habitats (Mateos-Molina et al. 2021). All developmental project along the coast of Abu Dhabi goes through EIA (Environmental Impact Assessment) to limit impacts to these ecosystems. Five marine protected areas in Abu Dhabi encompass extensive seagrass meadows that are known to support diverse fish assemblages, as well as marine mammals and reptiles. Marawah Marine Biosphere Reserve protects 30% of the UAE seagrasses and contains the largest herd of dugongs after Al Yassat Marine Protected Area (Mateos-Molina et al. 2021).

As part of conservation, (a) regular assessment and mapping of seagrass meadows is crucial to take management actions, (b) mitigating threats, (c) taking actions to improve water clarity and quality, and (d) restoring seagrass in lost and degraded habitats are few of the initiatives that are ongoing or being planned. The value of seagrass for the UAE in terms of supporting marine wildlife and fisheries and rate of carbon sequestration has been realised. Blue carbon assessment program (AGEDI 2013, 2016) includes seagrass beds, along with related ecosystems such as mangroves, algal mat and salt marshes.

Human activities along the coast have sometimes resulted in loss and degradation of seagrass meadows. Keeping ecosystem in mind, and to achieve targets of Abu Dhabi 2030 for protection of coastal communities, seagrass restoration is the applied aspect of recovery of seagrass. However, seagrass restoration by sexual as well as asexual means are not cost-effective. Success of a restoration program depends on several factors (Orth and Moore 1988) such as, (a) site selection (depth, water quality, clarity, and circulation), (b) selection of species (species that has better chance of survival). (c) standard operating protocol for plantation (spacing, patch location). The biggest challenge to the success of the UAE's seagrass restoration is its distribution. Since most of the seagrasses in the UAE grow in sub-tidal region—unlike Southeast Asian countries where seagrasses grow in an intertidal area—planting and monitoring a patch underwater is challenging.

9.5.2 Assessment of Seagrass Meadows of UAE

DPSIR (Driver – Pressure – State – Impact – Response) assessment is a useful tool to asses and investigate the cause-effect within an ecosystem to aid better frameworks for stakeholders, policy makers and governance managers to draft response measures. International Union for Conservation of Nature's (IUCN) Red List of Threatened Species classifies the dugong as 'Vulnerable' and green turtles as "Endangered", indicating that there is a high risk of extinction in the wild in the medium term. The dugong's and green turtle's life cycle and their reliance on seagrass for food make it highly vulnerable to threats. Seagrasses are restricted to shallow, coastal waters where the seabed receives enough light for photosynthesis to occur. These areas are also subject to high levels of human activities, which can have short- and long-term impacts on seagrass ecosystems. The DPSIR analysis indicates a summary and overall situation of seagrass meadows in UAE (Table 9.4).

9.6 Conclusions

Baseline information for seagrass ecosystems in terms of their extent, species composition, biomass and water and sediment characteristics is available for the UAE waters. The gap in research and knowledge includes phenology, seasonality of distribution, interaction of flora and fauna, impact of frugivory, ecosystem values and economic evaluation. To conserve seagrass meadows, we need to respond and manage several challenges such as (a) understanding the importance of value of seagrass, (b) improved knowledge on seagrass ecology and their resilience to climate change, (c) identifying and mitigating threatening processes, (d) developing and

Table 9.4 DPSIR (Driver – Pressure – State – Impact – Response)—summary assessment for Seagrass meadows of UAE

Drivers	Pressure	State	Impact	Response
Urbanization Driver Rapid increase in human population putting pressure on local resources, particularly for coastal development and urbanization. **Climate Change** There are many interactions between climate factors influencing both the magnitude of other stressors and the physiological responses of different seagrass species. Parameters include temperature, light, salinity, nutrients and dissolved oxygen.	Primary pressures on seagrass habitat are mainly from coastal development, island creation, dredging and sedimentation. Climate change (increase in SST) and pollution serve to exacerbate the impacts of these activities. **Destruction / degradation of sea grass habitats** Coastal dredging and landfill physically remove seagrass, increase sedimentation, change physical hydrography, and disturbs grazing behavior of marine megafauna.	A comprehensive global assessment of 215 studies found that seagrasses have been disappearing at a rate of 110 km^2 per year since 1980 and that 29% of the known areal extent has disappeared since seagrass areas were initially recorded in 1879. Furthermore, rates of decline have accelerated from a median of 0.9% per year before 1940 to 7% per year since 1990 (Waycott et al. 2009). Three species of seagrasses occur in UAE waters. *Halodule uninervis* is the dominant species with more than 80% of the cover followed by *Halophila ovalis* and Halophila stipulacea. **Spatial extent:** Seagrass habitat in Abu Dhabi 2922 km^2, which is the most significant in the UAE. Seagrasses in other emirates cover less than 20 km^2 (See Table 9.1) (EAD 2020). **Seasonality**	**Environmental Impacts** The key ecosystem services associated with *Halodules and Halophila sp* (Mtwana Nordlund et al. 2016) in the Tropical Indo-Pacific bioregion (Short et al. 2007) include: • Nursery for fish and fish larvae • Habitat for marine invertebrate • Foraging habitat for marine megafauna • Carbon sequestration • Nutrient cycle • Sediment stabilization • Water purification • Research **Economic Impacts** Economic valuations of seagrasses have not been widespread and not specifically performed for the UAE. One study characterizes a significant role of seagrass in carbon sequestration in AD waters due to its large extent (Campbell et al. 2015). Recent studies highlight the	**International Agreements** UAE is Party to Convention for Migratory Species (CMS), which lists the dugong in its Appendix II, meaning that the conservation of the species would benefit from international cooperative activities organized across its migratory range. UAE is signatory to the CMS Dugong Memorandum of Understanding (MoU) IOSEA sea turtle conservation MoU, which obligate it to study dugongs and sea turtles and their habitats for conservation purposes. **Federal Laws** In summary, Law 23 (1999) and Law 24 (1999) prohibits anchoring in fishing grounds, trawling nets, bottom setting nets, nylon nets and drift nets. Environmental impact of establishments and developments require permits before any work

		Seagrass growth and density increase seasonally in Abu Dhabi waters during November–April, and seasonal growth is not necessarily tied to the same locations. During summer when water temperature increases up to 36 °C, shallow water seagrasses disappear.	importance of derivative-based valuation models that link structure and function of ecosystems to all associated economic services (Dewsbury et al. 2016).	while also providing environmental monitoring. **Enforcement and Compliance** Plan Maritime 2030 provides a vision for coastal development and a coordination mechanism for permitting authorities. EAD permits for project level developments most often require environmental impact assessments to assess project impacts and develop mitigation or compensation plans. **Outreach and Awareness** Outreach programs for seagrass are covered along with Dugong and sea turtle programs.

implementing conservation actions including restoration of lost and degraded areas. Many of these responses requires multidisciplinary approach, regional and international collaborations as well as stakeholder involvement. Seagrass research, conservation and communication in the UAE may continue to be a priority as part of coastal and marine conservation strategies.

9.7 Recommended Readings

For those interested in learning more about the seagrass systems, we recommend World Atlas of Seagrasses (2003) and for a more in depth scientific reference Global Seagrass Research Methods (2001) and Seagrasses: Biology, Ecology and Conservation (2006). We also recommend visiting Seagrasswatch.org to learn about the global seagrass monitoring efforts by scientists and citizens.

Acknowledgments The authors would like to thank the editors of the publication for considering us for this wonderful chapter. The management of New York University Abu Dhabi and the Environment Agency Abu Dhabi are acknowledged for giving us this opportunity to work on seagrass research program. We are grateful to EN-WWF for data and maps from northern emirates of the UAE. We sincerely thank Prof. Dr. John Burt who has been a constant source of inspiration and support for our work.

References

AGEDI (2013) Technical report: local, national regional biodiversity rapid assessment: systematic conservation planning assessments and spatial prioritizations–supporting technical information for the United Arab Emirates (MU000945_F11_02_01). EAD, Abu Dhabi. https://agedi.org/download/11712/?tmstv=1678426645. Accessed 01 July 2022

AGEDI (2016) Final technical report: regional desalination and climate change (report: CCRG/IO). EAD, Abu Dhabi. https://agedi.org/download/15066/?tmstv=1678426791. Accessed 15 July 2022

Beech MJ (2010) Mermaids of the Arabian Gulf: archaeological evidence for the. Int J Naut Archaeol 39(1):32–47

Borowitzka M, Lethbridge R (1989) Seagrass epiphytes. Aquat Bot 34(1–3):177–196

Bulthuis DA (1983) Effects of in situ light reduction on density and growth of the seagrass *Heterozostera tasmanica* (Martens ex Aschers.) den Hartog in Western Port, Victoria, Australia. J Exp Mar Biol Ecol 67(1):91–103

Cambridge M, McComb A (1984) The loss of seagrasses in Cockburn Sound, Western Australia. I. The time course and magnitude of seagrass decline in relation to industrial development. Aquat Bot 20(3–4):229–243

Campbell J, Lacey E, Decker R, Crooks S, Fourqurean J (2015) Carbon storage in seagrass beds of Abu Dhabi, United Arab Emirates. Estuar Coasts 38(1):242–251

Coles R, Lee Long W, McKenzie L, Roder C (2002) Seagrass and marine resources in the dugong protection areas of Upstart Bay, Newry region, Sand Bay, Llewellyn Bay, Ince Bay and the Clairview region, April/May 1999 and October 1999 (technical report no. 43). CRC Reef Research Centre, Townsville. https://hdl.handle.net/11017/353

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387(6630):253–260

Das HS (2021) Mapping and characterisation of seagrass meadows of Abu Dhabi waters, UAE. Internal report of Environment Agency Abu Dhabi. EAD, Abu Dhabi

Das HS, Al-Hameli M, Bugla I, Al-Mansoori A, Al Jailani H, Al Ahbabi W (2021) Aerial survey of marine wildlife, 2021. EAD, Abu Dhabi

Den Hartog C (1979) Seagrasses and seagrass ecosystems, an appraisal of the research approach. Aquat Bot 7:105–117

Dewsbury BM, Bhat M, Fourqurean JW (2016) A review of seagrass economic valuations: gaps and progress in valuation approaches. Ecosyst Serv 18:68–77

Duarte CM, Middelburg JJ, Caraco N (2005) Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences 2(1):1–8

EAD (2020) Terrestrial and marine habitat mapping from high resolution satellite imagery for Emirate of Abu Dhabi. http://enviroportal.ead.geoportal. Accessed 20 June 2022

El Shaffai A (2016) In: Rouphael A, Abdulla A (eds) Field guide to seagrasses of the Red Sea. International Union for the Conservation of Nature, Gland, p 56

Elkabbany MF (2019) Sea level rise vulnerability assessment for Abu Dhabi, United Arab Emirates. MSc Thesis, Lund University, Lund. https://lup.lub.lu.se/student-papers/search/publication/8998495. Accessed 24 May 2022

El-Shaffai A, Hanafy M, Gab-Alla A (2011) Distribution, abundance and species composition of seagrasses in Wadi El-Gemal National Park, Red Sea, Egypt. Indian J Appl Sci 4(3):1–8

Erftemeijer PLA, Shuail DA (2012) Seagrass habitats in the Arabian Gulf: distribution, tolerance thresholds and threats. Aquat Ecosyst Health Manag 15:73–83

Green EP, Short FT, Frederick T (2003) World atlas of seagrasses. Univ of California Press, Berkeley

Hartog C, Kuo J (2006) Taxonomy and biogeography of seagrasses. In: Larkum AWD, Orth RJ, Duarte CM (eds) Seagrasses: biology, ecology and conservation. Springer, Dordrecht, pp 1–23. https://doi.org/10.1007/978-1-4020-2983-7_1

Hemminga MA, Duarte CM (2000) Seagrass ecology. Cambridge University Press, Cambridge

Kemp WM, Twilley RR, Stevenson J, Boynton WR, Means JC (1983) The decline of submerged vascular plants in upper Chesapeake Bay: summary of results concerning possible causes. Mar Technol Soc J 17(2):78–89

Lamine EB, Mateos-Molina D, Antonopoulou M, Burt JA, Das HS, Javed S, Muzaffar S, Giakoumi S (2021) Correction to: identifying coastal and marine priority areas for conservation in The United Arab Emirates. Biodivers Conserv 30(7):2277–2277. https://doi.org/10.1007/s10531-021-02181-z

Larkum A, West R (1990) Long-term changes of seagrass meadows in Botany Bay, Australia. Aquat Bot 37(1):55–70

Les DH, Cleland MA, Waycott M (1997) Phylogenetic studies in Alismatidae, II: evolution of marine angiosperms (seagrasses) and hydrophily. Syst Bot 22(3):443–463. https://doi.org/10.2307/2419820

Lidour K, Beech MJ (2020) At the dawn of Arabian fisheries: fishing activities of the inhabitants of the Neolithic tripartite house of Marawah Island, Abu Dhabi Emirate (United Arab Emirates). Arab Archaeol Epigr 31(1):140–150. https://doi.org/10.1111/aae.12134

Lipkin Y, Beer S, Zakai D (2003) The seagrasses of the eastern Mediterranean and the Red Sea. In: Green EP, Short FT, Spalding MD (eds) World atlas of seagrasses. University of California Press, Berkeley, pp 65–73

Marsh H, Channells P, Heinsohn G, Morrissey J (1982) Analysis of stomach contents of dugongs from Queensland. Wildl Res 9(1):55–67. https://doi.org/10.1071/WR9820055

Mateos-Molina D, Antonopoulou M, Baldwin R, Bejarano I, Burt JA, García-Charton JA, Al-Ghais SM, Walgamage J, Taylor OJS (2020) Applying an integrated approach to coastal marine habitat mapping in the North-Western United Arab Emirates. Mar Environ Res 161:105095. https://doi.org/10.1016/j.marenvres.2020.105095

Mateos-Molina D, Ben Lamine E, Antonopoulou M, Burt JA, Das HS, Javed S, Judas J, Khan SB, Muzaffar SB, Pilcher N, Rodriguez-Zarate CJ, Taylor OJS, Giakoumi S (2021) Synthesis and evaluation of coastal and marine biodiversity spatial information in The United Arab Emirates for ecosystem-based management. Mar Pollut Bull 167:112319. https://doi.org/10.1016/j.marpolbul.2021.112319

Mtwana Nordlund L, Koch EW, Barbier EB, Creed JC (2016) Seagrass ecosystem services and their variability across genera and geographical regions. PLoS One 11(10):e0163091. https://doi.org/10.1371/journal.pone.0163091

Neverauskas V (1987) Monitoring seagrass beds around a sewage sludge outfall in South Australia. Mar Pollut Bull 18(4):158–164

Orth RJ, Moore KA (1988) Submerged aquatic vegetation in the Chesapeake Bay: a barometer of bay health. Mar Technol Soc J 22(2):87–99

Orth RJ, Carruthers TJB, Dennison WC, Duarte CM, Fourqurean JW, Heck KL, Hughes AR, Kendrick GA, Kenworthy WJ, Olyarnik S, Short FT, Waycott M, Williams SL (2006a) A global crisis for seagrass ecosystems. Bioscience 56(12):987–996. https://doi.org/10.1641/0006-3568(2006)56[987:Agcfse]2.0.Co;2

Orth RJ, Harwell MC, Inglis GJ (2006b) Ecology of seagrass seeds and seagrass dispersal processes. In: Larkum AWD, Orth RJ, Duarte CM (eds) Seagrasses: biology, ecology and conservation. Springer, Dordrecht, pp 111–133. https://doi.org/10.1007/978-1-4020-2983-7_5

Phillips RC, Loughland R, Youssef A (2002) Seagrasses of Abu Dhabi (UAE). Tribulus 12(1): 20–23

Sheppard C, Al-Husiani M, Al-Jamali F, Al-Yamani F, Baldwin R, Bishop J, Benzoni F, Dutrieux E, Dulvy NK, Durvasula SRV, Jones DA, Loughland R, Medio D, Nithyanandan M, Pilling GM, Polikarpov I, Price ARG, Purkis S, Riegl B et al (2010) The Gulf: a young sea in decline. Mar Pollut Bull 60(1):13–38. https://doi.org/10.1016/j.marpolbul.2009.10.017

Short FT, Wyllie-Echeverria S (1996) Natural and human-induced disturbance of seagrasses. Environ Conserv 23(1):17–27

Short FT, Coles RG, Pergent-Martini C (2001) Global seagrass distribution. Global seagrass research methods. 5:30

Short F, Carruthers T, Dennison W, Waycott M (2007) Global seagrass distribution and diversity: a bioregional model. J Exp Mar Biol Ecol 350(1–2):3–20. https://doi.org/10.1016/j.jembe.2007.06.012

Skaalvik J, Barnes R, Lutz S, Kurvits T (2013) The Abu Dhabi blue carbon demonstration project: blue carbon in Abu Dhabi – protecting our coastal heritage. AGEDI, Arendal. https://url.grida.no/2ZB1qrE. Accessed 30 June 2022

UNEP-WCMC (2021) Global distribution of seagrasses (version 7.1). Seventh update to the data layer used in Green and Short (2003). UN Environment World Conservation Monitoring Centre, Cambridge, UK. https://doi.org/10.34892/x6r3-d211. Accessed 10 June 2022

Walker D, Kendrick G, McComb A (1988) The distribution of seagrass species in Shark Bay, Western Australia, with notes on their ecology. Aquat Bot 30(4):305–317

Waycott M, Duarte CM, Carruthers TJB, Orth RJ, Dennison WC, Olyarnik S, Calladine A, Fourqurean JW, Heck KL, Hughes AR, Kendrick GA, Kenworthy WJ, Short FT, Williams SL (2009) Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc Natl Acad Sci 106(30):12377–12381. https://doi.org/10.1073/pnas.0905620106

Chapter 10
Seaweeds of the Emirates

David M. John

10.1 Seaweed Ecosystems

10.1.1 Introduction to Seaweeds

The relatively low diversity of macroalgae or 'seaweeds' in those emirates bordering the Arabian Gulf reflects the extremely inhospitable nature of the environment within its shallow southern basin where sea surface temperatures (SSTs) now regularly exceed 35 °C in August and salinities are consistently above 44 PSU (see Chap. 4; Foster et al. 2012; Vaughan et al. 2019). The inhospitable environmental conditions encountered within the Arabian Gulf undoubtedly accounts in large part for its low seaweed diversity (<400 spp) (John and Al-Thani 2014). Conditions are particularly harsh in its southern basin and accounts for the relatively low number of seaweeds (about 120 species) recorded so far from those Emirates that border it. Until the end of the twentieth century the seaweed flora of the UAE was virtually unknown, with a catalogue of the benthic marine algae of the Indian Ocean region (Silva et al. 1996) mentioning only a single species along with seven Cyanobacteria from the emirate of Abu Dhabi. Often the seaweeds of the Arabian Gulf are considered as representing a depauperate subset of those in the Indian Ocean due to the environmental extremes.

The most comprehensively studied seaweed flora in the UAE is that of the 700 km long coastline of the emirate of Abu Dhabi where there are many natural rocky areas and lithified 'hardgrounds' along its flanking coast and associated with many barrier islands, shoals and sea mounts. Still little is known of the seaweeds of those other emirates bordering the Arabian Gulf whose coastlines are considerably shorter and possess few hard-bottom seaweed habitats. Very few seaweeds grow on sand and

D. M. John (✉)
Life Sciences Department, Natural History Museum, London, UK
e-mail: D.john@nhm.ac.uk

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_10

fine sediments with information still lacking on the inconspicuous forms usually associated with many coastal developments, including rough stone or concrete block breakwaters, sea walls, piers and revetments surrounding new or enlarged islands. Still scarcely studied are the seaweeds of those eastern emirates lying within the Gulf of Oman, namely Fujairah and Sharjah, where environmental conditions are less extreme and marine biodiversity might be expected to be significantly higher than within the Arabian Gulf.

The seaweeds of Fujairah are mainly confined to the wave-beaten rocky shores lying to the north of the enclave of Khor Fakkan since to the south the wave-exposed coast consists mainly of sand beaches (Chap. 4). Just over 20 seaweeds have so far been reported from Fujairah (John 2023) with even fewer known from the internationally important wetland conservation reserve of Khor Kalba in Sharjah (D. John, unpubl. data). It consists of an extensive system of mangrove-fringed tidal lagoons, where the seaweeds are mostly confined to the rocky channel connecting them to the open sea (see Chap. 8). Also belonging to Sharjah is an island of considerable conservation importance, Sir Bu Nair, within the Arabian Gulf and lying some 65 km from the Dubai-Abu Dhabi border. The conservations importance of the island relates to the unique composition of its corals that until recently remained in a healthy state in contrast to the increasingly degraded inshore reefs (Bejarano et al. 2022). Unfortunately, there is no published information on its seaweed flora, although it is likely that seaweeds will be inconspicuous and few in number because of the complete dominance of table corals (*Acropora*) although the situation might change following a warm water event that took place in summer 2021.

Seaweeds are one of the principal primary producers in the southern basin of the Arabian Gulf along with seagrasses, mangroves, Cyanobacteria, vascular plants in salt marshes, and the symbiotic dinoflagellate associated with corals. Seaweeds are benthic (i.e. bottom-associated) macroalgae, and therefore largely confined to habitats where suitable hard and relatively stable attachment surfaces are present, including rocks, lithified hard grounds, coral skeletons, breathing roots of the grey mangrove *Avicennia marina*, large sponges, man-made surfaces, and the shells of living and dead molluscs. Some smaller seaweeds do commonly grow as so-called epiphytes on some of the larger species. One of the few seaweeds colonising the surface of the soft mud of intertidal flats are the dark-green, felted masses of the coarse, tubular, branching filaments of *Vaucheria piloboloides*, a member of the yellow-green group of seaweeds.

An important group of photosynthetic organisms frequently considered along with seaweeds are the Cyanobacteria, formerly referred to as the blue-green algae (Cyanophyta). It has long been recognised that these organisms are more closely related to bacteria, hence now termed blue-green bacteria or Cyanobacteria. The Cyanobacteria and seaweeds sometimes occur together in fully marine situations although the Cyanobacteria are usually most abundant and conspicuous in some of the most inhospitable environments. In the UAE the Cyanobacteria form very extensive intertidal crusts or mats on sandy or muddy shores, and even above the normal high-tide level within coastal salt marshes or sabkhas where the sediments are often a mixture of sand, silt or clay and are sometimes associated with a crust of salt and other minerals.

Seaweeds are a common feature of natural rocky shores throughout the UAE and often become most evident to the general public along parts of the Abu Dhabi coast in the spring and early summer when masses of dead and decaying seaweeds accumulate in bays and become deposited onto beaches. Otherwise for much of the year seaweeds are not usually very noticeable unless visiting a rocky shore at low tide or venturing below the waves with mask and snorkel.

10.1.2 What Are Seaweeds

Seaweeds or benthic macroalgae are oxygen-producing marine organisms that are usually attached to hard surfaces and all members have somewhat similar ecological requirements. Like seagrasses and other vascular plants, seaweeds all possess chlorophyll *a* and *b*, although the green colour is frequently masked by accessory pigments except in the group commonly known as the green seaweeds (Chlorophyta). As a character colour can be misleading, although it does link to a suite of other characters enabling the recognition of the following major seaweed group: Chlorophyta (green seaweeds), Ochrophyta, Phaeophyceae (brown seaweeds), Rhodophyta (red seaweeds) and Xanthophyta (yellow-green seaweeds) (Box 10.1). The red seaweeds contain the red pigment phycoerythrin and the blue pigment phycocyanin and commonly range in colour from bright red to dark purplish. Sometimes seaweeds belonging to the red group (Rhodophyta) become bleached by bright sunlight and then range from yellow-brown to orange when growing in the intertidal or in shallow water. The brown seaweeds contain the accessory brown pigment fucoxanthin and vary from dark brown to a yellow-brown or straw colour. Besides differences in pigmentation, seaweed groups are separated upon many structural and biochemical features. Some seaweeds exhibit the phenomenon of iridescence and are either completely iridescent, only iridescent at the branch tips or it is in the form of bands and spots.

Seaweeds are an unnatural grouping of organisms, since they fall within different kingdoms on the biological classification system. The green and red seaweeds are in the Kingdom Plantae, whereas the brown and yellow-green seaweeds belong to a separate kingdom, the Chromista. Frequently considered along with the seaweeds are the Cyanobacteria whose cellular and biochemical characteristics are more closely related to the bacteria, hence they are no longer referred to as the blue-green algae. The Cyanobacteria are all microscopic and so only visible when cells, colonies or filaments grow together to form blue-green, black, brownish or red tufts, mats or crusts. Differences in colour relate to the different proportions of a red phycoerythrin and a blue phycocyanin pigment in the cells as well as to a brown scytonemin pigment produced within the sheath of filamentous forms. The Cyanobacteria are placed in the Kingdom Eubacteria and are only briefly considered here since have been scarcely studied in the region, are very difficult to identify and there is much disagreement even amongst specialists concerning their taxonomy and naming of species.

Seaweed show considerably variation in form, size and complexity as well as in the nature of their reproduction. Some consist of simple or branched filaments of one to several rows of cells whereas others have a much greater morphological complexity ranging from cylindrical, compressed or flattened branches through to membrane-like forms. Some seaweeds have a stem-like portion known as a ‘stipe’ and are attached by a disc or a root-like structure, the so-called ‘holdfast’ (none possess true roots or vascular tissues). Some of the membrane-like forms are produced by division of cells in three planes to form what is known as a ‘parenchyma’. The majority have filaments as the basic unit of construction and these sometimes fuse to produce what is known as ‘pseudoparenchyma’. As none of the seaweeds have vascular tissues or roots, all gas and nutrient exchange occurs by diffusion through their tissues from the surrounding water, and hence typically they have thin, laminar surfaces.

Some red seaweeds are impregnated with calcium carbonate, so they are hard, stone-like and are referred to as ‘coralline seaweeds’ or ‘coralline algae’ because of their superficial resemblance to corals. Those calcareous forms having branches of calcified segments separated by darkly coloured uncalcified portions are known as ‘articulated corallines’. Most of the more ecologically important corallines are known as ‘crustose coralline seaweeds’ or ‘crustose coralline algae’ (sometimes abbreviated to CCA). Occasionally the crusts bear surface projects such as nodules or non-articulated branches as is the case in *Lithothophyllum kotschyanum*, the most widely distributed and common crustose form within the Arabian Gulf. These crustose corallines play an important role as ecosystem engineers since involved in the growth and maintenance of coral reefs by stabilising coral rubble and dislodged coral colonies and are known to induce the settlement of the larvae of corals and other benthic animals.

Box 10.1: Seaweed Groups

Green Seaweeds (Phylum Chlorophyta): Characteristically a bright green since no secondary pigments mask the chlorophyll colour. Range from single cells, simple or branched filaments of cells aligned in a single series through to compact spongy forms to flattened membrane-like fronds or tubes. A few are lime-impregnated.

Brown Seaweeds (Ochrophyta, Phaeophyceae): Characteristically range from olive-brown to various shaded of brown due the pigment fucoxanthin masking the green chlorophyll. Varying from filaments of cells in a single series through to strap-like forms or those with leaf-like appendages (foliose forms) and sometimes having a distinct holdfast, stem (stipe) and frond(s).

Red Seaweeds (Rhodophyta): Characteristically red in colour since the green chlorophyll pigment is masked by a combination of the red pigment

(continued)

Box 10.1 (continued)
phycoerythrin and the blue pigment phycocyanin. Often under high light conditions individuals become bleached to a brownish or straw colour. Varying from filaments of a single series of cells through to compact tissues in the form of cylindrical or flattened branches, sometimes membrane-like. Some members are impregnated with lime and are referred to as 'coralline' seaweeds since have been commonly mistaken for hard corals. Reproduction and life history is often very complex and is not considered here in any detail.

Yellow-Green Seaweeds (Ochrophyta, Xanthophyceae): Cells usually yellow-green due to predominance of a secondary pigment diatoxanthin in the chloroplasts (two or more chloroplasts per cell); unicellular, filamentous, colonial or coenocytic and motile forms with two subapical flagella; walls often with overlapping parts; storage material oil, fat or leucosin (never starch)

Blue-Green Bacteria (Cyanobacteria): Single-celled, colonies of large numbers of cells embedded in mucilage or of single filaments or grouped together to sometimes form distinctive filamentous colonies. Filaments are termed 'trichomes' and consist of a single linear row of living cells and these are sometimes enclosed within a sheath, occasionally sheath is lamellated and coloured. Some filamentous forms contain larger colourless cells (known as heterocysts) having one or two refractive polar nodes and are sources of nitrogen fixation in some species. Reproduce by large, thick-walled cells known as akinetes and by fragmentation to produce short lengths of trichome (hormogonia).

Seaweeds have complex life histories, with some species having stages showing so little resemblance to one another as to have once been considered separate species or genera. Some seaweeds reproduce vegetatively by fragmentation, although the majority have asexual reproduction by spores produced by a spore-producing stage known as the sporophyte. The males and female gametes are produced by the sexual stage (gametophyte) and fuse to form a zygote. For a discussion of the details of reproduction and complexity of the different life cycles in the algae, see general works on seaweeds and relevant websites.

10.1.3 Intertidal Habitats

10.1.3.1 Open Rocky Shores

The terminology used to describe biologically defined bands or zones on rocky shores throughout the world by Lewis (1964) and Stephenson and Stephenson (1972) has been applied to shores in the UAE (John and George 2004). According to the universally accepted scheme, the uppermost part of the intertidal (or littoral

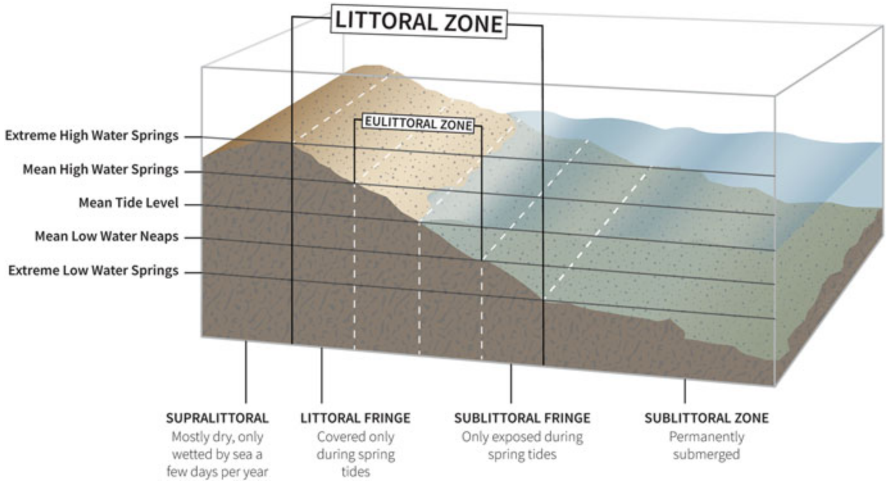


Fig. 10.1 Shore profile showing position of the tides in relation to the terminology used to describe the different zones based upon dominant plants and animal groups. Image credit: Oliver Farrell

zone) is the 'littoral fringe' which lies above the very highest tides (Spring high tides) so is normally only wetted by wave splash and sea spray (Fig. 10.1). This fringe or 'splash-zone' is most conspicuous on wave-beaten rocky shores such as the rocky cliffs and platforms that are especially common to the west of Jebel Dhannah in Abu Dhabi and along much of the northern part of the 70 km long coast of Fujairah. Sometimes the Cyanobacteria form a blackish zone in and just below the littoral fringe and this is especially evident on limestone shores (Fig. 10.2a). There is little information on the composition of the Cyanobacteria within this zone except for the often most common and conspicuous species *Chroococcus varius* (Fig. 10.3c, d), whose colonies swell and become brownish-green when wetted by the incoming tide.

The mid-shore area of the littoral zone is known as the 'eulittoral zone' and immediately below lies the 'sublittoral fringe' which is the zone of the shore only exposed at the very lowest tides (known as 'spring low tides'). A greyish band of barnacles often defines the upper part of the eulittoral zone and these typically occur immediately below or are mixed with the zone dominated by Cyanobacteria. Discovered at this level on rocks and cement blocks associated with an artificial island on Hail Shoal in Abu Dhabi were low growing light brown mats of the filamentous cyanobacterium *Gardnerula fasciculata* (Fig. 10.3b). Below the barnacle zone there is often a noticeable increase in biological diversity with the dominant organisms present often dependent on such factors as wave-exposure, nature of shore, slope and aspect. Sometimes on more steeply sloping rocks in Abu Dhabi were low growing turfs or mats of seaweeds that were frequently accompanied by clusters of calcareous tubes belonging to the serpulid polychaete worm *Pomatoleios kraussii* (Fig. 10.4c). Low growing mats were often particularly noticeable growing over crustose

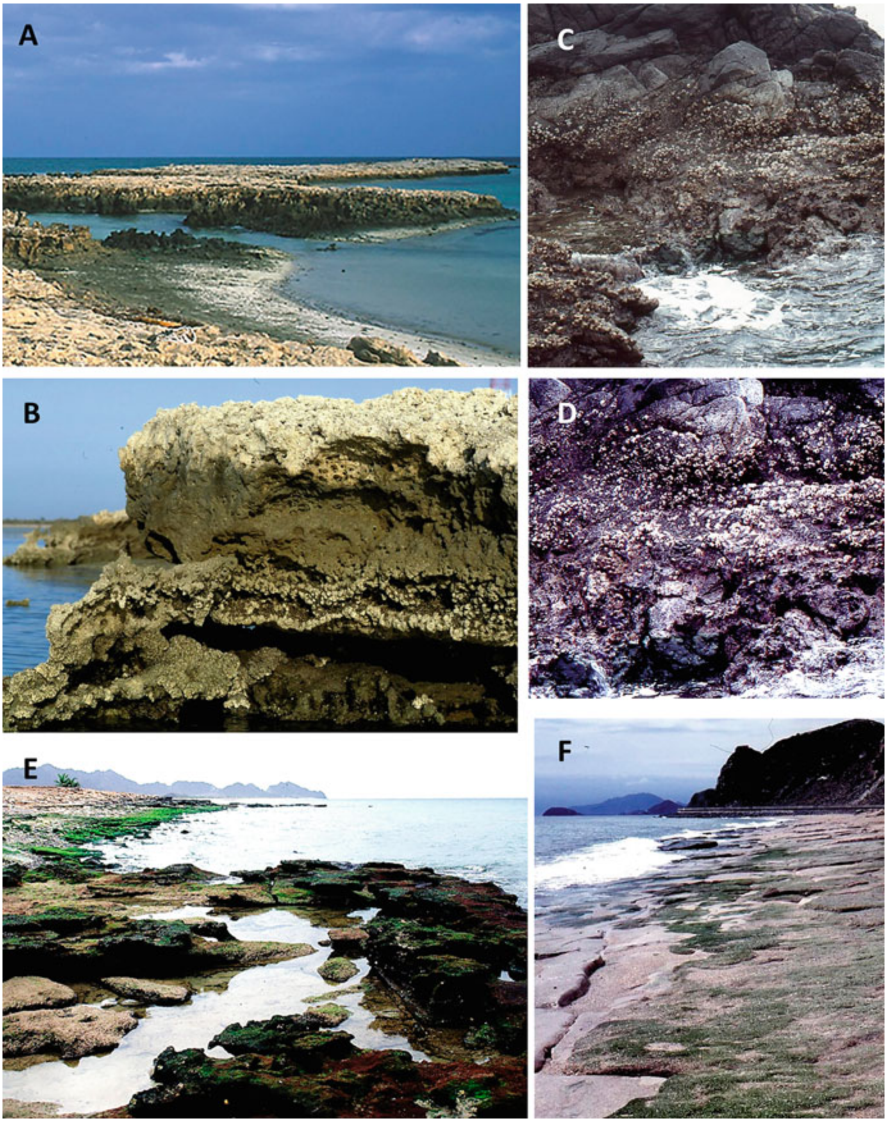


Fig. 10.2 (**a**) Platforms of ancient reef limestone at low tide in western Abu Dhabi with lower parts very irregular due to many surface projections, pits and crevices and, where more steeply sloping, showing an upper dark coloured band of Cyanobacteria, (**b**) view of the zonation pattern on a cliff area in western Abu Dhabi showing a mid-littoral band of barnacles and mussels associated with an upper band of Cyanobacteria, (**c**) cliff area in northern Fujairah showing the upper littoral zone having a light coloured band of barnacles, often associated with darker patches of Cyanobacteria and these extending upwards, below the barnacle the rocks are covered by crustose corallines and dark coloured turf-like seaweed mats (**d**) close view of lower littoral zone showing the continuous crust of corallines and dark-coloured patches of turf-like mats associated with the large barnacle *Tetraclita*, (**e**) Intertidal platform in northern Fujairah revealing tidepools at low water and upper shore rocks covered by a carpet of the green membrane-like *Ulva lacinulata* and below a turf-like mat of red seaweeds, (**f**) Wave-battered littoral zone platform in northern Fujairah covered in lower

corallines on steeply-sloping, wave-battered rocks (Fig. 10.2c) and on the seaward side of rough stone breakwaters subject to an almost constant pounding by the waves.

The lower littoral zone along much of the more sheltered parts of the coastline of Abu Dhabi and emirates to the east is normally characterised by low clumps of *Palisada perforata* (Figs. 10.4c, e and 10.5b), the bottle brush-like *Digenea simplex* (Fig. 10.5b) and the brittle green colonies of *Dictyosphaeria cavernosa* (Fig. 10.4d) whose distinctive polygonal surface cells are visible to the naked eye. These seaweeds persist throughout the year, whereas some of the mat-forming seaweeds are only evident during the winter months; often these seaweeds are most conspicuous along the seaward margin of those rocky platforms constantly wave splashed at low water. During the spring and early summer seasonally present seaweeds disappear, leaving some of the perennial forms mentioned above and these are often accompanied by pinkish or bleached crusts of crustose corallines. Sometimes there develop in early summer dense spongy, cushion-like growths of the green seaweed *Cladophoropsis fasciculata* on rocks in the lower littoral and shallow sublittoral zones (Fig. 10.5a). These have been observed covering extensive areas in the west of Abu Dhabi and sometimes become detached to accumulate in vast quantities in sheltered bays early in summer. This is unusual since nearly all seaweeds are much more conspicuous during the winter months (October-April) when the sea is normally below 25 °C.

The uppermost limit of the infrequently exposed sublittoral fringe is usually defined by organisms normally growing in the shallow sublittoral zone. The black sea-urchin *Echinometra* and the oyster *Pinctada radiata* frequently define the fringe since are commonly present on the seaward margin of intertidal platforms along with mats of filamentous red seaweeds. During the winter months a few larger seaweeds sometimes grow within the fringe along with *Dictyosphaeria cavernosa* (Fig. 10.4d), sometimes this distinctive green seaweed persists throughout the year in the shallow subtidal. Some brown seaweeds similarly occur within the sublittoral fringe but are also more common in the subtidal zone, including the peacock tail weed (*Padina boergesenii*) (Fig. 10.5d), the foliose *Polycladia myrica* and *Sirophysalis trinoidis* and, often in March and April, the distinctive bladder-like *Colpomenia sinuosa* (Fig. 10.5e). The attractive but often bleached filamentous red seaweed *Spyridia filamentosa* (Fig. 10.5f), also occurs in the fringe but is more common in lower shore pools and in the shallow sublittoral zone.

Fig. 10.2 (continued) parts by a carpet-like covering of *Ulva lacinulata*. Photo credits: David George (**a**, **e**, **f**) and David John (**b**, **c**, **d**)

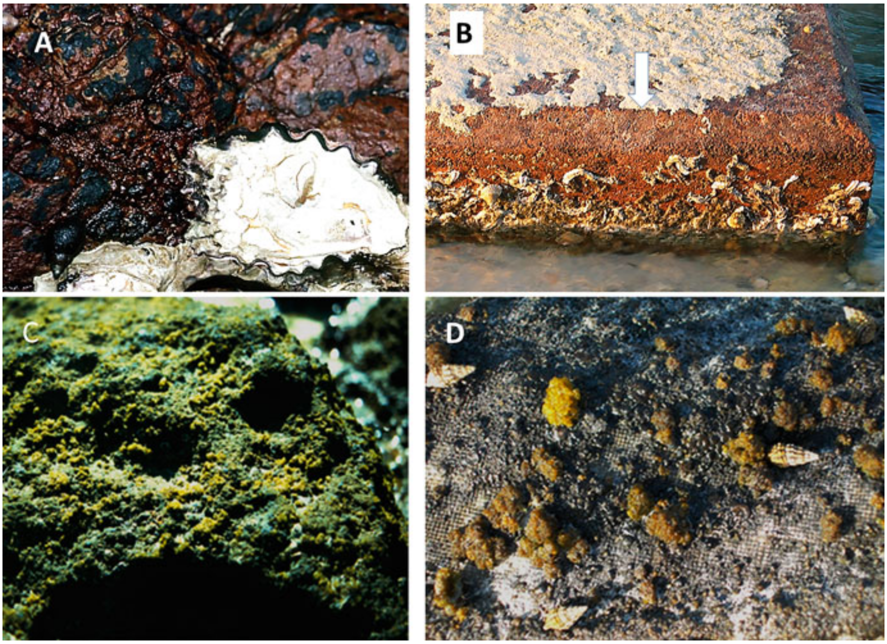


Fig. 10.3 (**a**) Dark crusts or cushions of the cyanobacterium *Kyrtuthrix maculans* (left of oyster) on steeply sloping wave-exposed rocks in Fujairah, (**b**) light brown coloured mat of *Gardnerula fasciculata* (arrowed) growing on intertidal stone block close to an artificial island in Abu Dhabi, (**d**) Upper littoral zone platform showing wetted brownish band of Cyanobacteria, (**c**) upper shore showing light brown colonies of the cyanobacterium *Chroococcus varius* wetted by wave splash, (**d**) close view of the platform showing brownish-yellow polymorphous colonies of *Choococcus varius*, about 5–15 mm across. Photo credits: David George (**a**, **c**) and David John (**b**, **d**)

10.1.3.2 Tidepools

Upper Shore Pools Conditions for marine life are extremely harsh in these rocky pools, with some mostly supplied with water by wave splash and spray. Often Cyanobacteria are the only photosynthesising organisms surviving in such pools that are subject to exceptionally high salinities and water temperatures. These are usually filamentous Cyanobacteria forming brownish mats and are most common in nutrient-enriched pools associated with bird colonies.

Lower Shore Pools During low water some shore platforms are partly covered by wide expanses of shallow water, as is the case at Shuweihat in Abu Dhabi (see Fig. 10.4a), rather than having many small pools. The environmental conditions are much more hospitable within lower shore pools compared to smaller ones at higher shore levels. Sometimes subtidal seaweeds are to be discovered in larger and deeper lower shore pools and frequently grow on the sometimes steeply sloping sides as well as on stones, shells and other debris lying on the bottom of those that are sandy

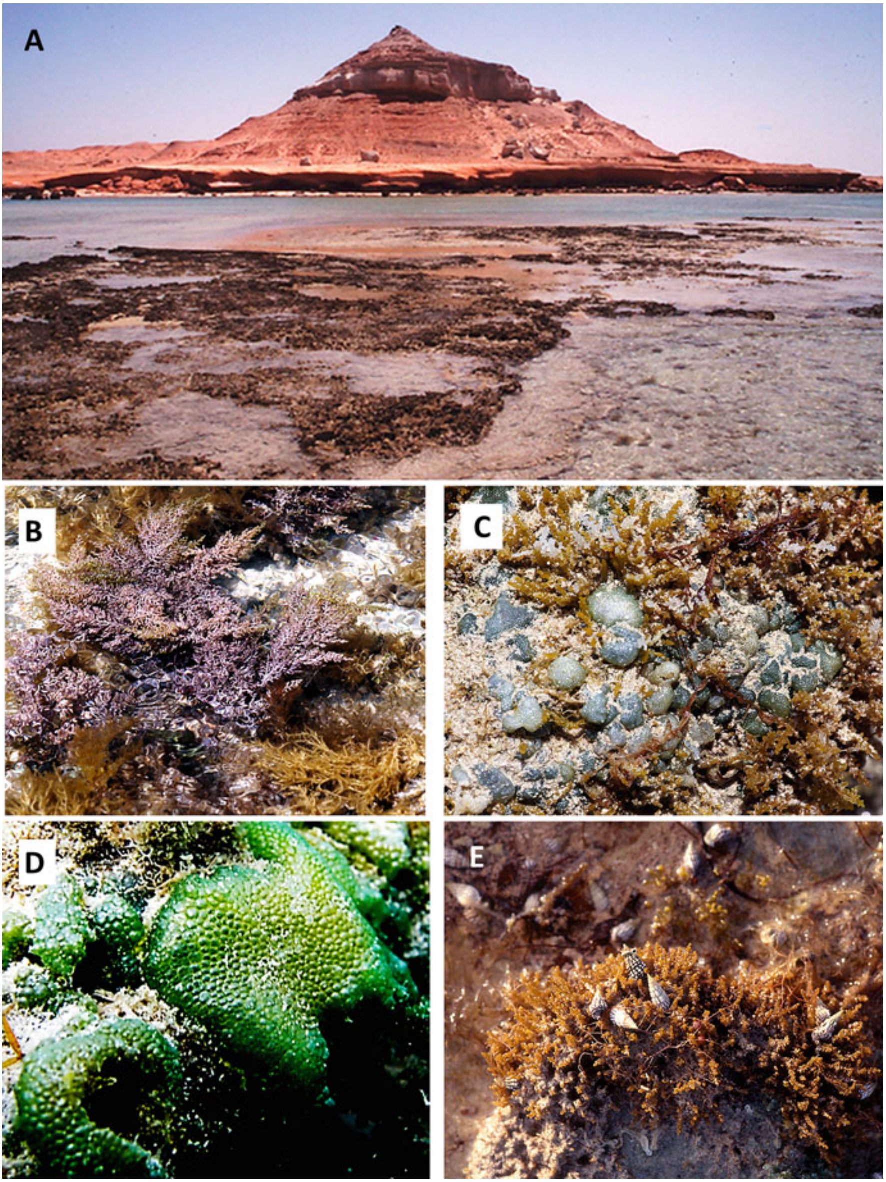


Fig. 10.4 (**a**) View from edge of a wide intertidal platform revealing seaweed covered rocks and extensive shallow tidepools left as the tide drops at Shuweihat in Abu Dhabi, (**b**) shallow tidepool in 'winter' showing *Polycladia myrica* with its somewhat triangular outline and covered by the pinkish crusts of the coralline seaweed *Hydrolithon*, (**c**) lower littoral zone covered by colonies of green seaweed and brownish clumps of the common shore seaweed *Palisada perforata*, (**d**) close view of clumps of the green seaweed *Dictyosphaeria cavernosa* with its distinctive polygonal surface cells, (**e**) close view of the brownish branches of a clump of *Palisada perforata*, like many members of the red seaweed group it is brownish or straw-coloured when growing on the shore under stressful conditions. Photo credits: David George (**a**, **b**) and David John (**c**, **d**, **e**)

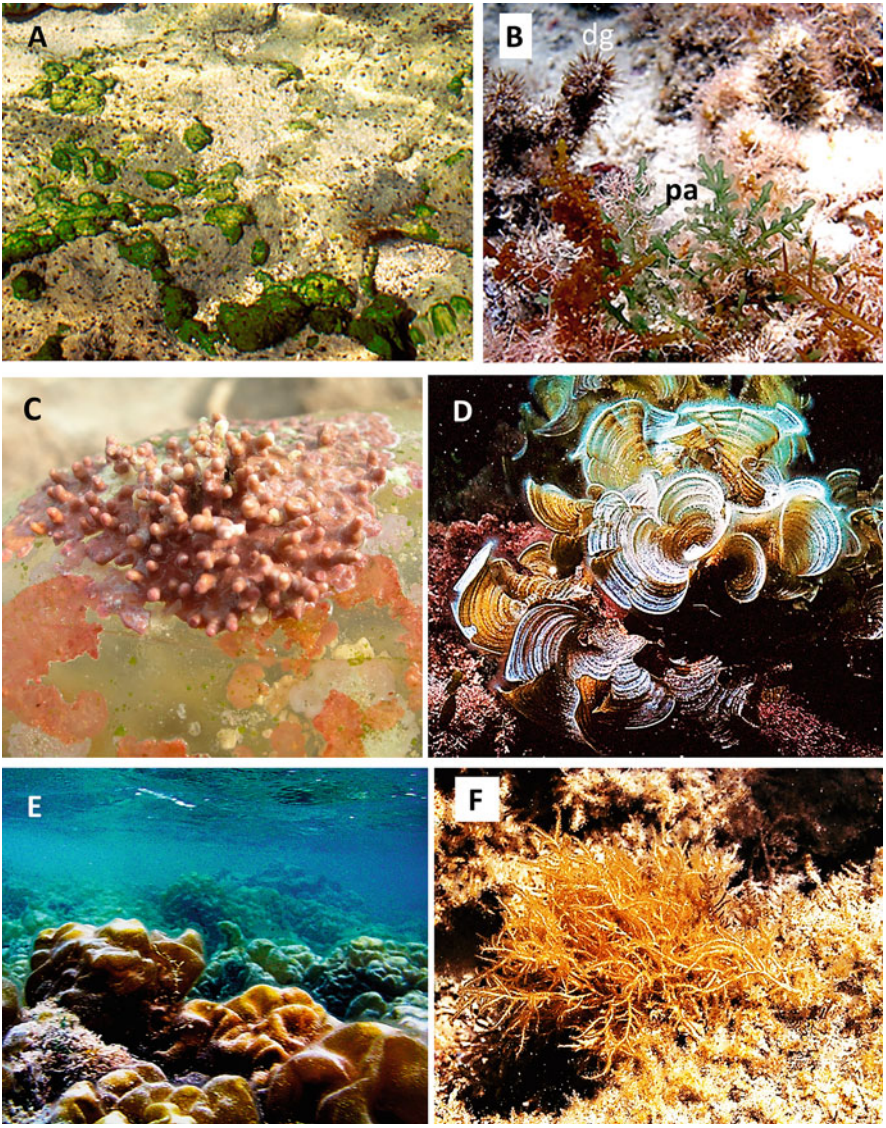


Fig. 10.5 (**a**) Green clumps and mats of *Cladophoropsis fasciculata* growing in a sheltered rocky area, (**b**) close view of lower shore community in Abu Dhabi including *Digenea simplex* (Dg) and *Palisada perforata* (Pa), (**c**) the crustose coralline *Lithophyllum kotschyanum* showing the crust bearing nodules and cylindrical or flattened erect branches, (**d**) clump of the peacock tail brown seaweed *Padina boergesenii* showing the distinctive concentric zones of hairs on the fronds, (**e**) shallow water population of the inflated bladder-like brown seaweed *Colpomenia sinuosa*, (**f**) bleached clump of the fine red seaweed *Spyridia filamentosa* growing in the shallow sublittoral zone. Photo credits: David John (**a**–**c**), Chris Teasdale (**d**, **e**), and David George (**f**)

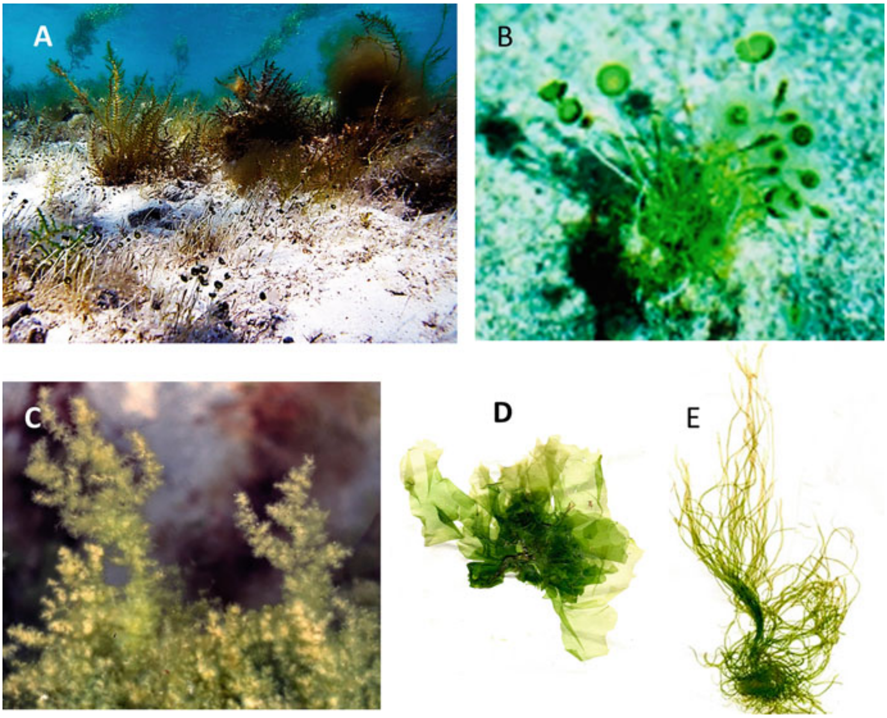


Fig. 10.6 (**a**) Many umbrella-like individuals of *Acetabularia calcyculus* growing through sand in the fore and middle ground and a community in background dominated by clumps of brown and red seaweeds, (**b**) Close view of colonies of *Acetabularia calcyculus* bearing one or a series of the characteristic whorled fertile branchlets, often terminate in a cap, (**c**) soft, bushy clumps of *Cladophora nitellopsis* consisting of fine, clusters of densely branched filaments, (**d**) membrane-like fronds of *Ulva lacinulata*, (**e**) clumps of *Ulva flexuosa* with its tubular branches. Photo credits: Chris Teasdale (**a**, **b**) and David John (**c**–**e**)

floored. Some of those growing on the steep sides of pools are perennial forms that also occur on adjacent rock. Many seaweeds become bleached straw-coloured or brownish and this applies to *Polyides myrica,* a rhodiophyte that is sometimes heavily epiphytised by the small crustose coralline *Hydrolithon* (Fig. 10.4b). If sand is absent then lower shore rock pools might become lined by the pinkish crusts of coralline seaweeds, most commonly *Lithophyllum kotschyanum* (Fig. 10.5c). In Fujairah very small pools or depressions in the sublittoral fringe are typically lined by such crustose corallines and these are often occupied by the black sea urchin *Echinometra.* Easily overlooked is the beautiful umbrella-shaped green seaweed *Acetabularia calyculus* (Fig. 10.6b) that grows on partially sand or sediment-covered rocks and shells in lower shore pools and in the shallow subtidal.

10.1.3.3 Sedimentary Shores

10.1.3.3.1 Sandy Beaches

Sandy beaches range from steep, wave-exposed beaches of coarse sand through to those that are low to moderately wave-exposed, gently sloping and of fine-grained sand. Seaweeds are normally absent from such beaches unless sufficiently sheltered to enable hard sand-embedded sediments to be stable enough to allow colonisation by often fast-growing seaweeds. If partially sand-buried rocks, coral fragments, shells, cables or other artificial surfaces are present then these may be colonised by various seaweeds over the winter months. Most common are green seaweeds such as the much branched filamentous *Cladophora nitellopsis* (Fig. 10.6c), the fine tubular branches of *Ulva flexuosa* (Fig. 10.6e) and the membrane-like fronds of *Ulva lacinulata* (Fig. 10.6d). The latter commonly forms a low carpet-like mat on wave-exposed rocky platforms along the northern coast of Fujairah (Fig. 10.2e, f).

10.1.3.3.2 Mangrove Areas

The grey mangrove *Avicennia marina* is the only true mangrove tree to survive the temperature and salinity extremes encountered within the Arabian Gulf (see Chap. 7). The trees often form well-developed stands on the compacted muddy shores of creeks, channels, lagoon systems (Fig. 10.7a, b) and also along more wave-sheltered sandy shores on the mainland coast and offshore islands. Dark-coloured cyanobacterial mats commonly cover the frequently compacted mud associated with the trees. Also associated with the mangroves are some of the same seaweeds growing on partially buried hard surfaces on sandy shores. Occasionally the unbranched threads of the green seaweed *Chaetomorpha linum* become entangled with the breathing roots (pneumatophores) of the mangroves to form a curtain-like shroud (Fig. 10.7b, c). Sometimes associated with the mangroves are bushy clumps of the filamentous green seaweed *Cladophora nitellopsis* (Fig. 10.6c) and dense mats of the inflated, tubular branches of *Ulva intestinalis* (Farzanah et al. 2022). Sometimes such green seaweeds as *Ulva* are commonly association with dredged navigation channels close to industrial areas. Unsurprisingly the seaweeds on the uppermost margins of the calcareous limestone platforms through which these channels are cut are similar to those growing around and below the sublittoral fringe.

10.1.3.3.3 Mud Flats

Fine sediments and decomposing organic material tend to accumulate in inner harbour basins, sheltered embayments, quiet areas of lagoons and on the lee side of islands. These areas of very soft, muddy deposits are high in organic matter and often black and anoxic just a few millimetres beneath the surface. Sometimes the

Fig. 10.7 (**a**) The mangrove *Avicennia marina* fringing a creek, with breathing roots (pneumatophores) in the foreground and cyanobacterial mats on the muddy foreshore, (**b**) pneumatophores of *Avicennia* at low water and draped by the green filaments of *Chaetomorpha linum*, (**c**) close view of the unbranched thread-like filaments of *Chaetomorpha linum*. Photo credits: David George (**a**, **b**) and David John (**c**)

mud surface on the lower shore is covered by a dark green, felty mat consisting of the finely branched filaments of *Vaucheria piloboloides*, the only yellow-green seaweed so far reported from the UAE (Fig. 10.8a, b).

10.1.3.3.4 Lagoons and Coastal Sabkha

Where lagoons have no through-flow or only flood during the highest tides (spring tides) conditions are hypersaline, especially in their innermost reaches (see Chap. 8). Commonly on the sand or muddy shores of such lagoons there are cyanobacterial crusts or mats (Box 10.2), often referred to as 'algal mats'. These are usually most extensive along the seaward margins of low-lying areas of the coastal plain that only flood during very high spring tides and periods of strong onshore wind. The seaward

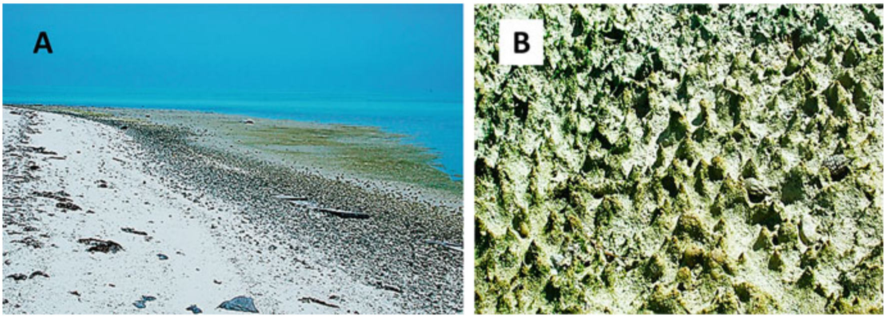


Fig. 10.8 (**a**) Sheltered lee side of an artificial island on Hail Shoal, Abu Dhabi showing the darker coloured zone of *Vaucheria piloboloides* close to the level of the low tide, (**b**) close view of mat showing the somewhat pyramidal clumps of *Vaucheria* filaments. Photo credits: David John (**a**) and David George (**b**)

margins of these coastal plains are subjected to very high rates of evaporation and are often referred to as evaporative coastal salt flats, called sabkha (pl. sabkhat) in Arabic. The sabkha plain extends well beyond the cyanobacterial mats and is influenced by changes in the groundwater level and the sediments are associated with surface deposits of gypsum and anhydrite (see Chap. 2).

Box 10.2: Cyanobacterial Mat Types and Composition

Cyanobacterial mats have distinctive surface features relating to a number of factors, including frequency of immersion by the tides, seawater salinity, drainage, water flow and what species of cyanobacteria are present (Golubic and Abed 2010). Two of the main mat-forming cyanobacteria, *Microcoleus chthonoplastes* and species of *Schizothrix* (principally *S. splendida*), consist of microscopically twisted bundles of very narrow filaments (known as trichomes) confined within simple or branched sheaths. *Schizothriz splendida* is common along the banks of creeks and the sandy floors of well-drained lagoons where it forms pinnacle-shaped mounds (Fig. 10.9b). The *Microcoleus* frequently forms flat mats in ponds and variously sized waterlogged depressions and is sometimes accompanied in the middle and upper shore by *Lyngbya aestuarii,* another filamentous cyanobacterium. In the mid-tidal zone the Cyanobacteria are rearranged at a finer scale in response to changes in the length of time surfaces are exposure to air and therefore to water loss.

According to Golubic and Abed (2010), the non-filamentous cyanobacterium *Entophysalis major* assists in stabilizing sediments by producing copious amounts of hydrated extracellular polymers and this accounts for much of the appearance of what they term the ‘cinder’ zone. This zone extends from about the lower to mid-shore level and is so-called because the surface is covered by

(continued)

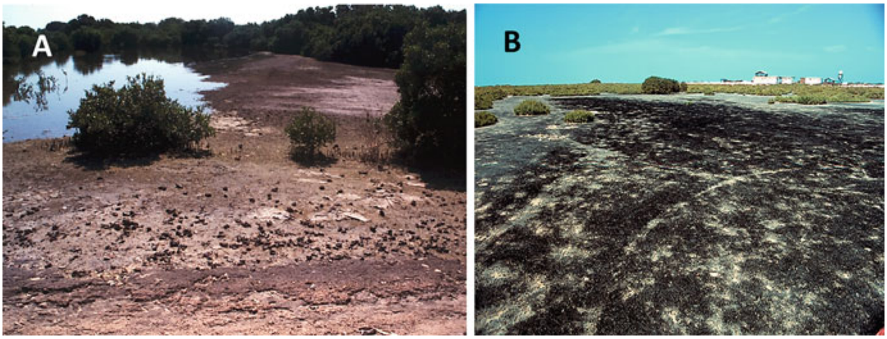


Fig. 10.9 (**a**) Lagoon fringed by the grey mangrove *Avicennia marina* with mud in foreground covered by a cyanobacterial mat, (**b**) wave-sheltered sandy lagoon showing a well-drained tidal area with the lower littoral zone covered by the pinnacle-shaped mounds of the cyanobacterium *Schizothrix splendida*. Photo credits: David John (**a**) and David George (**b**)

Box 10.2 (continued)
minute blisters (pustular) or nipple-like projections (see Abed et al. 2010). Immediately above this zone lies a so-called polygonal zone where desiccation results in the surface mat cracking into polygons whose upturned edges enclose dark green, leathery, layers of cyanobacteria. These polygons tend to form in shallow pools and channels, especially those frequently flooded by the sea, with cracking of the surface resulting in the formation of different microhabitats. Different Cyanobacteria are dominant in the water-retaining depressed centre of the polygons compared to the upturned margins and cracks. In the littoral fringe there is often a thin, crinkled, crenulated or convoluted, leathery, blackened cyanobacterial mat that often dries out and crumbles. Usually very flat is the landscape in areas dominated by cyanobacterial mats and crusts due to sediment accumulation and poor drainage, with the mats developing initially on what becomes soft, swampy ground when flooded by the tide. The sabkha plain extends well beyond these mats and is influenced by changes in the groundwater level and associated with the sediments are surface deposits of gypsum and anhydrite.

Golubic and Abed (2010, p. 241, Fig. 1) include a montage of photomicrographs of the more common Cyanobacteria forming Abu Dhabi's microbial mats.

10.1.4 Subtidal Habitats

10.1.4.1 Rock Surfaces of Low Relief

Many shallow water platforms have low physical relief and are partially sand-buried, often much fissured and have creviced hard surfaces. Periodic sand-burial of hard surfaces is especially common in shoal areas where there are strong tidal streams as well as considerable wave action. There is a diverse faunal assemblage associated with these surfaces, including the pearl oyster *Pinctida radiata*, the mussel *Brachydontes variabilis*, and the snail *Cerithium scabridium* to name a few. Also present are many annual and perennial seaweeds that are frequently attached to surfaces that are sometimes buried beneath a thin layer of sediment or sand. Often in winter this shallow water community is spatially dominated by foliose brown seaweeds and these extend into deeper water where growing on loose lying rocks and dead sand-embedded coral fragments that are sometimes on the bed of dredged channels. The most conspicuous brown seaweeds present are the distinctively flattened branches of *Sargassopsis decurrens* (Figs. 10.10c and 10.13a), the much-branched *Sirophysalis trinodis* (Fig. 10.12e), *Hormophysa cuneiformis* (Fig. 10.10b) and the rather rigid *Polycladia myrica* (Fig. 10.4b).

On occasion orange-coloured clumps of *Chondria dasyphyllum*, with its irregularly divided and distinctively club-shaped laterals, form extensive beds on low sand-embedded rocks and lithified hard-grounds (Fig. 10.11a, b). It is often accompanied by other bleached red seaweeds such as *Laurencia obtusa* (Fig. 10.15d), A*canthophora spicifera* (Fig. 10.10e) and *Spyridia filamentosa* (Fig. 10.5f) that are also attached to partially sand-buried hard surfaces including the shells of living or dead bivalve molluscs.

Sand movement is a significant factor influencing the composition, abundance, distribution and biodiversity of organisms on low platforms or lithified ‘hard-grounds’ (Fig. 10.11). The mosaic of seaweed communities reflects the instability of these hard surfaces that are available for colonisation for varying lengths of time and at different times during the year.

10.1.4.2 Rock Surfaces of High Physical Relief

The diversity and abundance of UAE’s seaweed flora goes largely unnoticed since hidden beneath the waves. Of the submarine seaweed communities, the most diverse and complex is the forest-like one in which brown foliose seaweeds are the canopy dominants (Fig. 10.12a–c). These submarine forest usually occur on gently seaward sloping rocky platforms that fringe the mainland coast of Abu Dhabi as well as some of its offshore barrier islands and shoals. Many of these fringing slopes in the central and eastern region of this Emirate, somewhat sheltered from the north-westerly shamal winds, were probably once spatially dominated from about 1 to 4 m depth

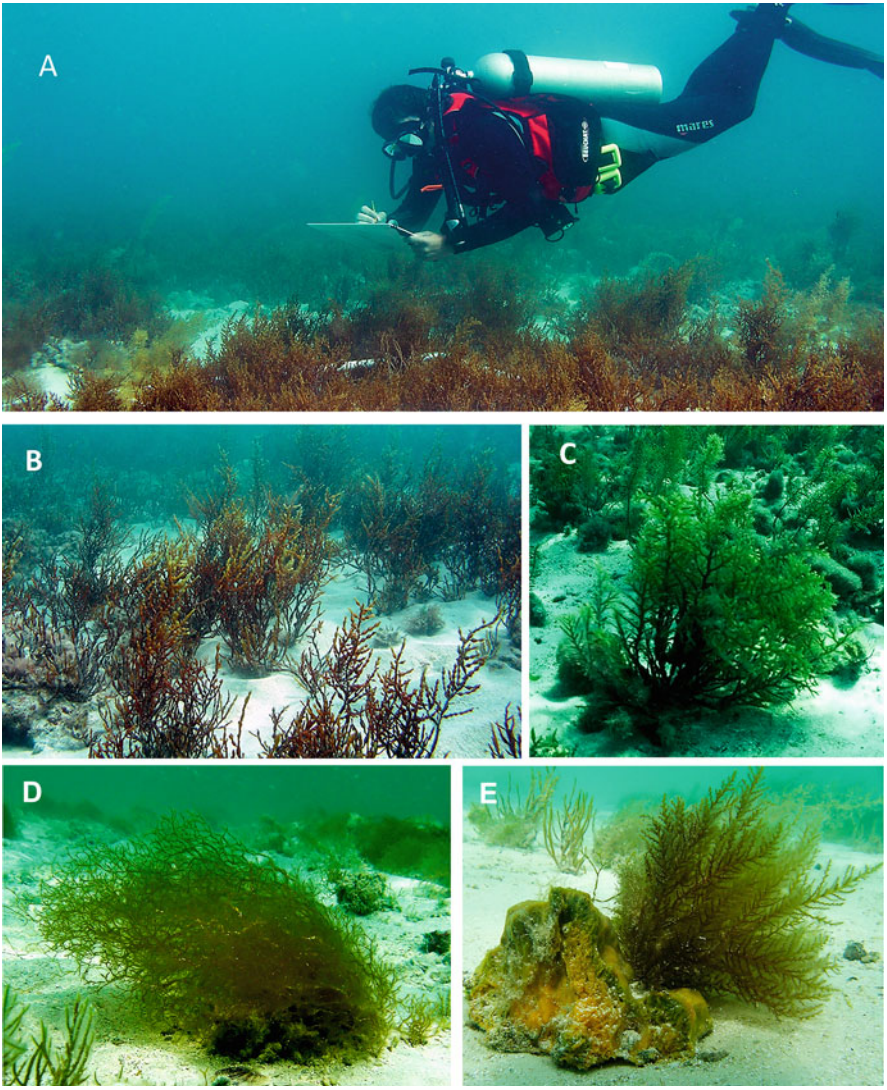


Fig. 10.10 (**a**) General view of a shallow water community dominated by various foliose brown seaweeds, (**b**) The wedge-shaped chainweed *Hormophya cuneiformis* growing on sand-buried hard surfaces, (**c**) a clump of *Sargassopsis decurrens* on a sand-embedded hard surface and consisting of compressed, distinctively alternate and pinnately divided secondary branches, (**d**) clump of the flattened and regularly forked branches of the brown seaweed *Canistrocarpus cervicornis* on relatively stable rock fragments, (**e**) brownish clump of the bleached red seaweed *Acanthophora spicifera* growing on a large detached sponge and showing its somewhat spiny lateral branches. Photo credits: David George (**a**–**d**) and Chris Teasdale (**e**)

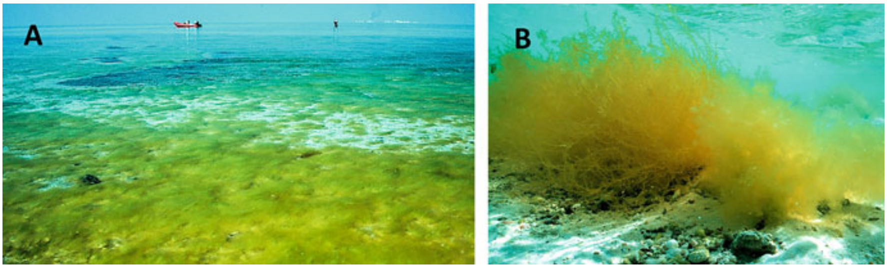


Fig. 10.11 (**a**) Shallow seabed with foreground showing clumps of *Chondria dasyphyllum* growing close to the natural island on Hail Shoal, Abu Dhabi, (**b**) large clump of *Chondria dasyphyllum* growing on a partially sand-covered area of lithified 'hard ground' and on small stones. Photo credits: David John (**a**) and David George (**b**)

by table corals (*Acropora*) along with an understorey of mound and brain corals such as *Porites, Platygyra* and many other smaller merulinids (George and John 2004).

Over the past two decades there appears to have been what has been termed a 'phase' or 'regime' shift as seaweeds replace corals in some shallow rocky areas following bleaching and death of many stony corals as a consequence of episodes of warmer sea temperature. The first of such warm water episode was in the summer of 1996 and its impact was particularly severe on shallow water stands of *Acropora* table corals. A second and even more severe episode took place 2 years later and this now impacted many of other shallow water corals, especially the frame-building mound and pillar coral (*Porites*) colonies together with various corals that historically flourished in the understorey of the shallower *Acropora* (George and John 1999, 2000, 2001; Riegl 1999). Since the 1990s there have been further warm water episodes, with these becoming more frequent and sometimes more intense. It has been estimated by Burt et al. (2021) that coral cover has decline by 20% per decade and Riegl et al. (2018) mentions that *Acropora* table corals have all but disappeared from the UAE's Gulf coast reefs (Sir Bu Nair island the one exception), now leaving only more temperature-tolerant species. The recent 2017 bleaching event was one of the most severe on record, with nearly three-quarters (73%) of corals lost across Abu Dhabi within a year of that event (Burt et al. 2019); as such events increase in frequency, the shift from coral to algal dominance is expected to continue.

The dense 'forest-like' seaweed community finds its maximum expression during the 'winter' months (about November-April) and during that time the principal canopy forming brown seaweeds are *Sargassum's* (principally *S. latifolium*, Fig. 10.12d) with their leaf-like fronds, *Sirophysalis trinodis* (Fig. 10.12e) and the wedge-shaped chainweed *Hormophysa cuneiformis* (Fig. 10.10b), the latter so named because of its characteristically shaped branches. Smaller brown seaweeds commonly form an understorey and include the somewhat rigid and distinctively shaped *Polycladia myrica* (Fig. 10.4b), the peacock tail weed (*Padina boergesenii*) (Fig. 10.5d) and *Canistrocarpus cervicornis* with its regularly forked, flattened branches (Fig. 10.10d). Often seen between about March and April are the

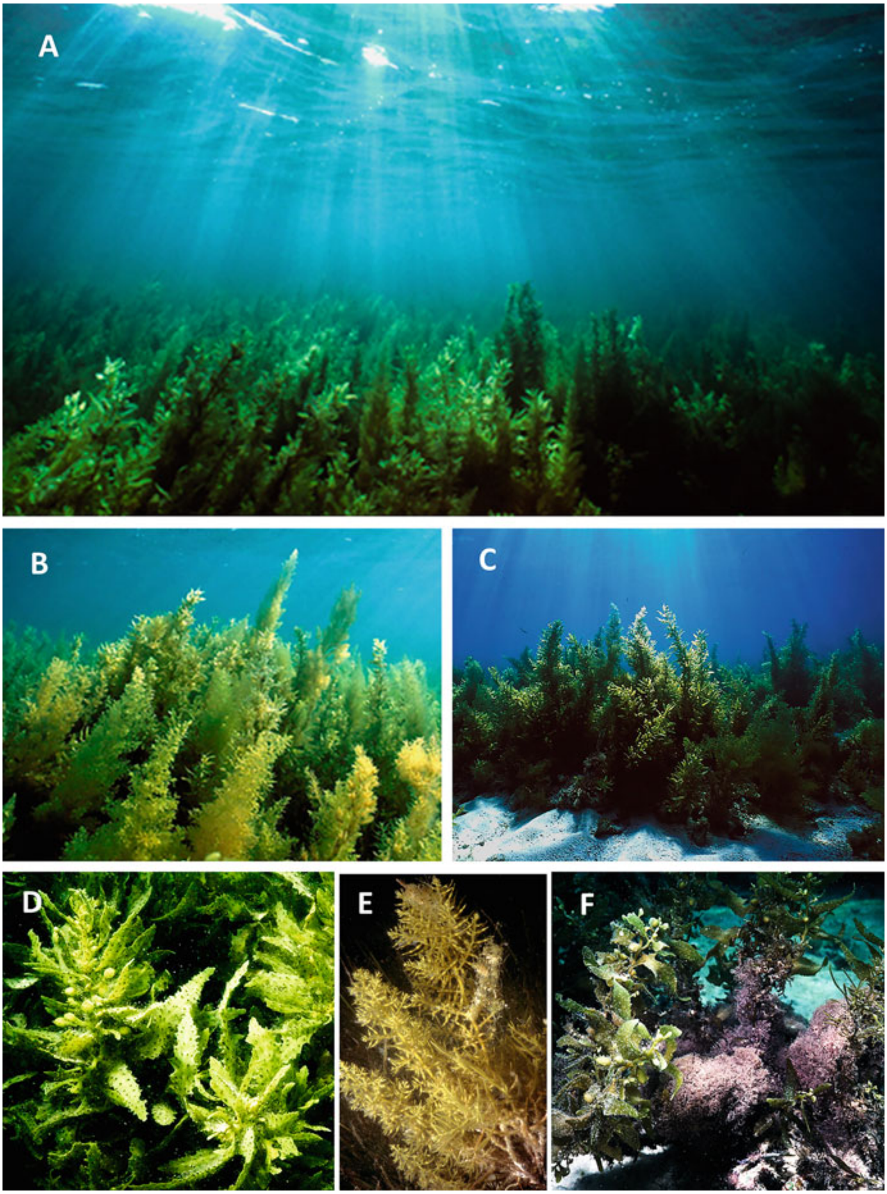


Fig. 10.12 Sublittoral zone seaweed-dominated communities: (**a**) dense community ('forest') spatially dominated by foliose brown seaweeds in March ('winter') and growing on a rocky platform fringing an offshore shoal, (**b**) closer view showing some of the brown seaweeds forming the canopy of the submarine forest, (**c**) diverse brown seaweed dominated community growing where a rocky platform abuts sand, (**d**) bushy clump of the very common *Sargassum latifolium* showing its conspicuous hair pits on the leaf-like appendages and subspherical to spindle-shaped bladders, (**e**) habit of the common brown seaweed *Sirophysalis trinoidis* with its branches terminating in three bladder like nodes, (**f**) the almost spherical, pom-pom like, often bleached clumps of the articulated coralline *Jania rubens* growing on a *Sargassum*. Photo credits: David George (**a**–**e**) and Chris Teasdale (**f**)

distinctive, spherical or somewhat convoluted bladders of the brown seaweed *Colpomenia sinuosa* (Fig. 10.5c), especially when washed up on beaches.

Many of the canopy-dominant brown seaweeds begin to die-off and decay as the temperature begins to rapidly rise in April/May and these often become heavily overgrown by other seaweeds (Fig. 10.13a), including the minute filamentous brown seaweed *Sphacelaria rigidula* (Fig. 10.13b), the pinkish spots of the crustose coralline *Hydrolithon* and the pinkish pom-pom like tufts of the articulate coralline *Jania rubens* (Fig. 10.12f). The on-going decay of the canopy dominant seaweeds leads to the eventual loss of the *Jania* which sometimes washes ashore in vast numbers along parts of the coast of Abu Dhabi as whitish balls. Occasionally large accumulations of these balls have been observed lying on the seabed in the shallows and remain pinkish in colour and seem still to be growing.

Many of the canopy-dominant brown seaweeds begin to die-off and decay as the temperature begins to rapidly rise in April/May and these often become heavily overgrown by other seaweeds (Fig. 10.13a), including the minute filamentous brown seaweeds *Sphacelaria rigidula* (Fig. 10.13b), the pinkish spots of the crustose coralline *Hydrolithon* and the pinkish pom-pom like tufts of the articulate coralline *Jania rubens* (Fig. 10.12f). The on-going decay of the canopy dominants seaweeds leads to the eventual loss of the *Jania* which sometimes washes ashore in vast numbers along parts of the coast of Abu Dhabi and appear as whitish balls. Occasionally large accumulations of these balls have been observed lying on the seabed in the shallows and remain pinkish in colour and seem still to be growing.

Some of the canopy dominants survive into the following growing season despite losing many of their side branches and become reduced in summer to sometimes a perennial holdfast bearing a few almost naked main axes. The greatly reduced cover of these canopy-dominants during summer results in the submarine seascape becoming transformed, since now the most conspicuous seaweeds present are those forming turf-like mats, crustose corallines and various sessile animals (Fig. 10.13c). One of the more common of these low growing forms is *Gelidium pusillum* (Fig. 10.13e) whose creeping prostrate branches give rise to flattened, simple or divided erect branches. Also evident during summer are semi-erect fronds of the brown seaweed *Lobophora variegata* (Fig. 10.13d), reddish-purple crusts of *Peyssonnelia simulans* (Fig. 10.13f) and crustose corallines including *Lithophyllum kotschyanum* (Fig. 10.13c); the latter varies morphologically from crusts bearing simple, cylindrical branches through to clumps of somewhat flattened, fan-shaped and interweaving branches.

10.1.4.3 Coral Carpets

It has been suggested that the coral reefs of the southern basin of the Arabian Gulf are best described as 'coral carpets' since the colonies form but a single layer growing directly on rock surfaces (Sheppard et al. 1992). Seaweeds were always an inconspicuous component of healthy coral carpets, but are now becoming increasingly significant due to the demise of the corals caused by recurrent episodes

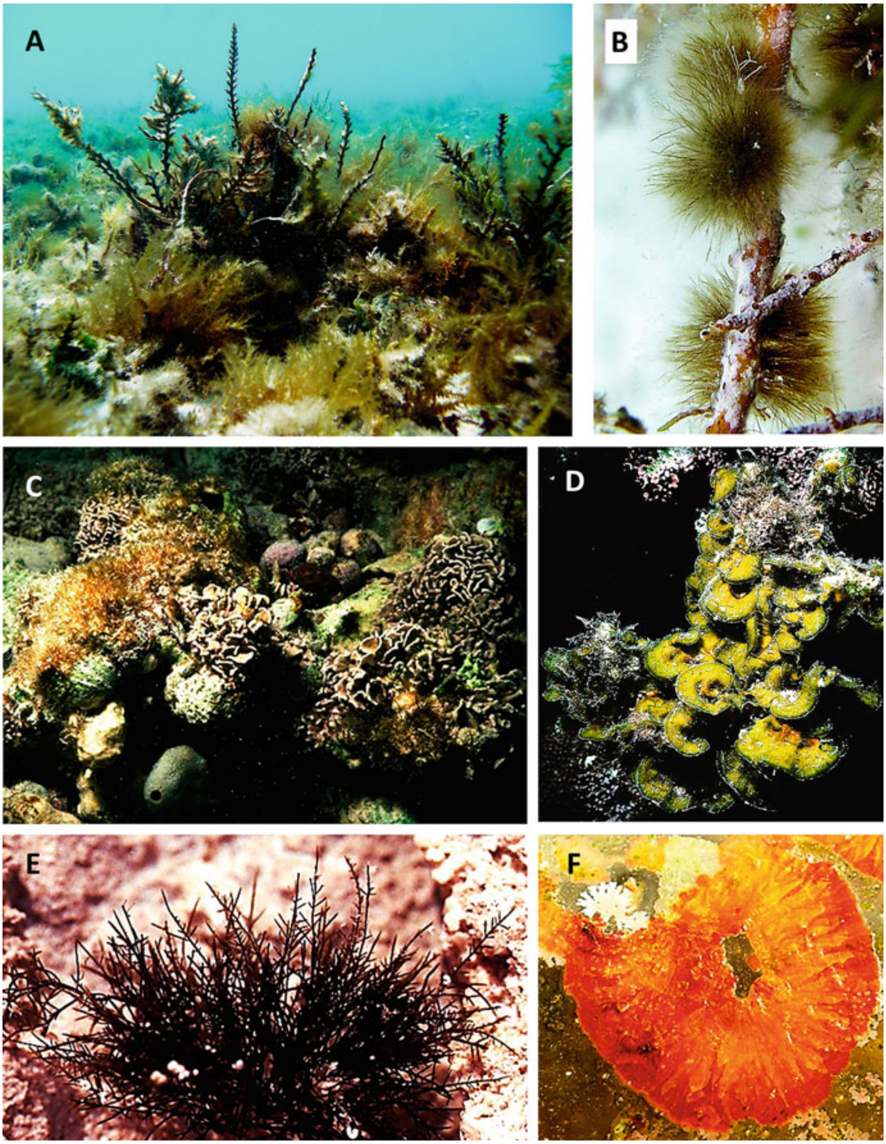


Fig. 10.13 (**a**) A moribund *Sargassopsis decurrens* heavily epiphytised by smaller seaweeds, (**b**) somewhat rigid tufts of the filamentous brown seaweed *Sphacelaria rigidula* growing as an epiphyte, (**c**) clump of a form of *Lithophyllum kotschyanum* with flattened fan-shaped branches and accompanied by mats of filamentous red seaweeds, (**d**) the semi-erect or prostrate flattened fronds of the brown seaweed *Lobophora variegata*, (**f**) this distinctive uncalcified crustose red seaweed *Peyssonnelia simulans* varies from red to purplish-red, (**e**) showing the creeping and prostrate branches of *Gelidium pusillum*, one of the more common turf-forming red seaweeds. Photo credits: David George (**a**, **c**, **d**) and David John (**b**, **e**, **f**)

of their bleaching and death. The first such incidence in the UAE took place in 1996 (George and John 1999, 2000, 2001; Riegl 1999) and only became apparent when the coral

skeletons were covered by a layer of fine silt and were colonised by the minute filaments of fast-growing seaweeds, principally the brown seaweed *Feldmannia mitchelliae* (Fig. 10.17e, f). Subsequently Cyanobacteria have been reported in Chap. 11 to be another group quickly colonising lesions on dead corals. By the spring of 1997 there was a succession of seaweeds on the still intact skeletons of the tabular coral *Acropora* with the crustose coralline the spatially dominant group (Fig. 10.14b). There was a large reduction in physical complexity as the framework of *Acropora* skeletons began to collapse, leaving many shallow rocky platforms in Abu Dhabi covered by mounds of coral rubble (Fig. 10.14a).

The island of Sir Bu Nair remains the only place of those emirates within the Arabian Gulf where relatively healthy stands of the tabular coral *Acropora* still exist, although even these have been damaged by recent severe warm water episodes (Bejarano et al. 2022; Burt et al. 2021). Seaweeds are more commonly associated with rocky areas where the corals have become degraded and coral communities are becoming dominated by more stress-tolerant brain and mound corals (Burt and Bauman 2019). One seaweed particularly associated with dead and living corals is *Lobophora variegata* (Fig. 10.13d) whose flattened, brown fronds are most frequent towards the base of living corals where sometimes also present are the reddish crusts of *Peyssonnelia simulans* (Fig. 10.13f). Otherwise, turf-like mats are typically confined to dead or damaged areas on coral where they are occasionally accompanied by the green filamentous seaweeds *Cladophora* and *Cladophoropsis*. Most commonly associated with corals are crustose coralline seaweeds, with *Lithophyllum kotschyanum* the most conspicuous and varies from a crust bearing nodules and simple or divided, cylindrical branches (Fig. 10.5e) through to one having flattened, often somewhat convoluted, interweaving, fan-shaped branches (Fig. 10.13c). Often

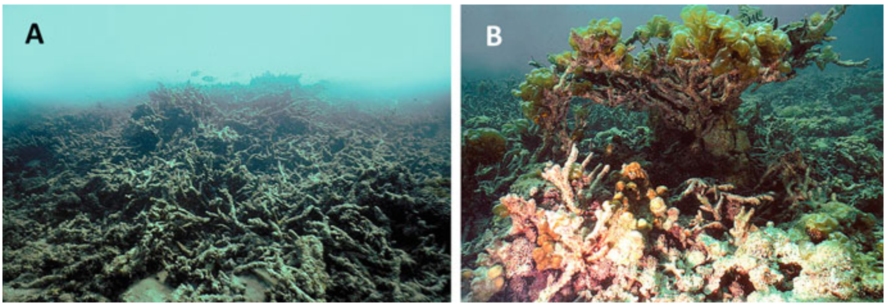


Fig. 10.14 (**a**) The piles of rubble left following the collapse of the skeletons of the tabular coral *Acropora* at Al Dhabiya (now Al Nouf) in Abu Dhabi at about 6 months after the bleaching event of summer 1996, (**b**) the inflated bladder-like brown seaweed *Colpomenia sinuosa* growing on the upper dead branches of the coral *Acropora* and below are overgrown mainly by crustose coralline seaweeds; photographed near Marawah Island, Abu Dhabi in March 1997. Photo credit: David George

crustose corallines develop on the steep sides of rock ledges and coral skeletons (Fig. 10.14b) and are occasionally accompanied by reddish or purplish tufts or mats of filamentous Cyanobacteria.

10.1.4.4 Seagrass Beds

There are vast seagrass beds or meadows covering comparatively shallow (<10 m) sand-covered inshore areas in those emirates bordering the southern basin of the Arabian Gulf, particularly Abu Dhabi (see Chap. 9). By far the most abundant seagrass is the narrow leaved *Halodule uninervis* and is accompanied in places by the two broader leaved species belonging to the genus *Halopila*, namely *H. ovalis* and *H. stipulacea* (Fig. 10.15a, b). Sometimes there is a mosaic of seagrass (vascular flowering plants) and seaweed communities where the sea bed is of sand and also contains surfaces suitable for seaweed attachment. The only seaweeds growing directly on sand in the UAE are *Caulerpa sertulariodes*, *Caulerpa racemosa* and

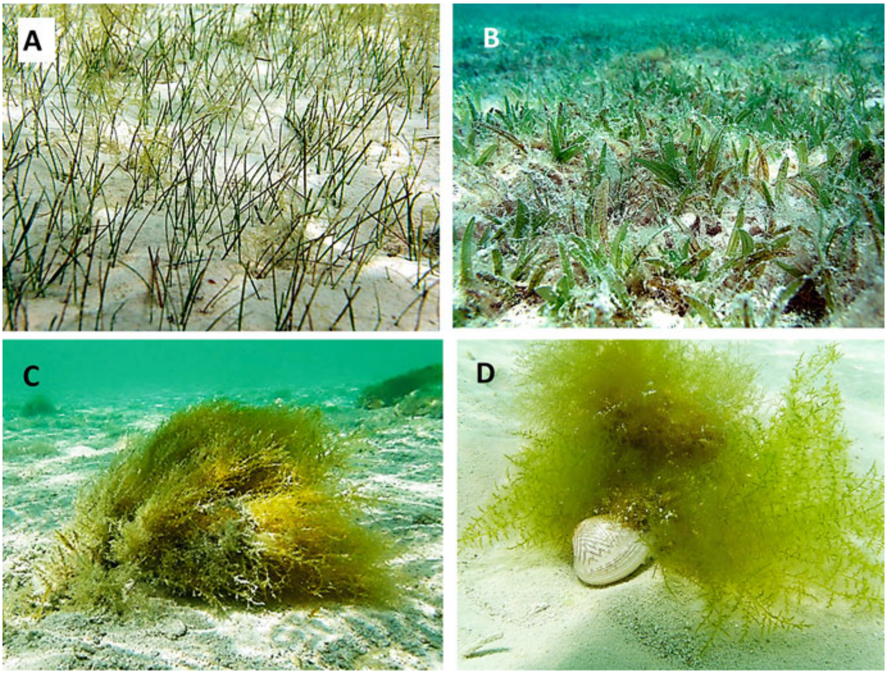


Fig. 10.15 (**a**) Shallow seagrass meadow dominated by the broader leaved *Halophila stipulacea* and occasionally with small seaweed on sand-embedded hard surfaces, (**b**) close view of narrow leaves of *Halodule uninervis*, oval leaves of the seagrass *Halophila ovalis* and *Halophila stipulacea*, (**c**) clump of the bleached, filamentous red seaweed *Polysiphonia kampsaxii*, about 8 cm high, (**d**) bleached clump of the red seaweed *Laurencia obtusa* growing attached to a bivalve shell. Photo credits: David George (**a**–**c**) and Chris Teasdale (**d**)

Avrainvillea amadelpha. The most common *Caulerpa* is *Caulerpa sertularioides* form *farlowii* (Fig. 10.16a, b) and this occurs within seagrass beds as well as on the sides of floating pontoons (Fig. 10.17a). *Avrainvillea amadelpha* is mostly encountered in very shallow sandy areas where its large holdfasts produce solitary or clusters of branches that often terminate in flattened blades (Fig. 10.16c, d).

The seaweeds accompanying seagrasses usually grow on a variety of partially sand-buried surfaces, including low lying rocky areas, lithified 'hard grounds', large sponges, coral fragments, stones and living or dead bivalve mollusc shells. Common on these hard surfaces are a mix of filamentous green seaweeds, such as *Cladophora nitellopsis* (Fig. 10.6c) and *Chaetomorpha linum* (Fig. 10.7c), accompanied by various red seaweeds that include *Spyridia filamentosa* (Fig. 10.5f), *Acanthophora spicifera* (Fig. 10.10e), and clumps of the fine filaments of *Polysiphonia kampsaxii* (Fig. 10.15c). Some seaweeds and the surfaces to which they are attached occasionally become dislodged by strong tidal streams and sometimes leave a distinctive trail when dragged across the sandy seabed (Fig. 10.15d). Smaller seaweeds grow epiphytically on the blades of the seagrass *Halodule uninervis*, including the crustose coralline *Hydrolithon* that often appears as small pink spots.

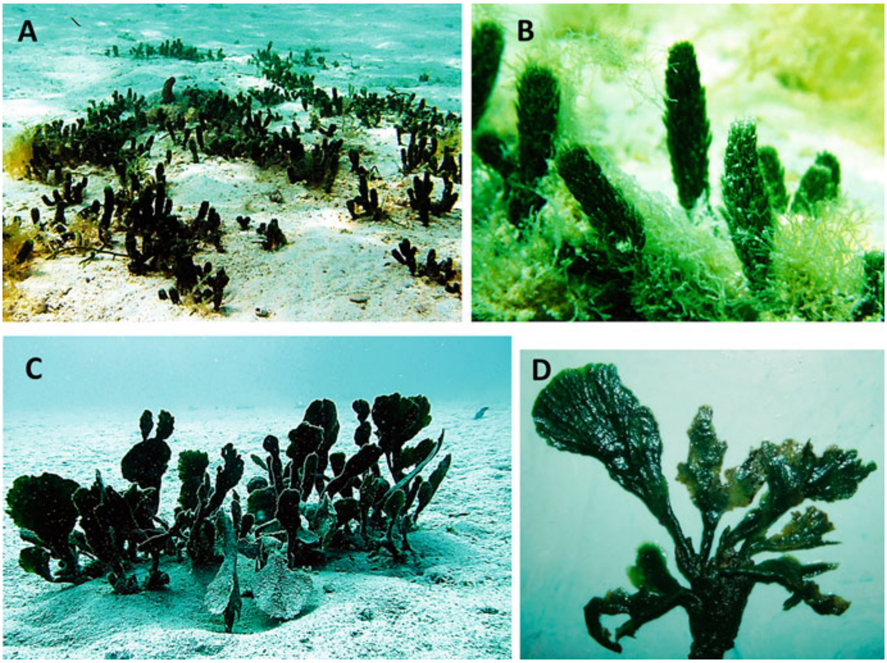


Fig. 10.16 (**a**) *Caulerpa sertularioides* form *farlowii* growing in a shallow sandy area of Hail Shoal in Abu Dhabi, (**b**) close view of the form showing its dense, bottle-brush, erect branches of compactly arranged pinnules arising at intervals from creeping stolon-like branches, (**c**) clumps of the dark green seaweed *Avrainvillea amadelpha* showing its long stipes bearing anvil- or fan-shaped terminal blades (about 20 cm high), (**d**) closer view of flattened fan-shaped terminal blades. Photo credits: Chris Teasdale (**a**–**c**) and David John (**d**)

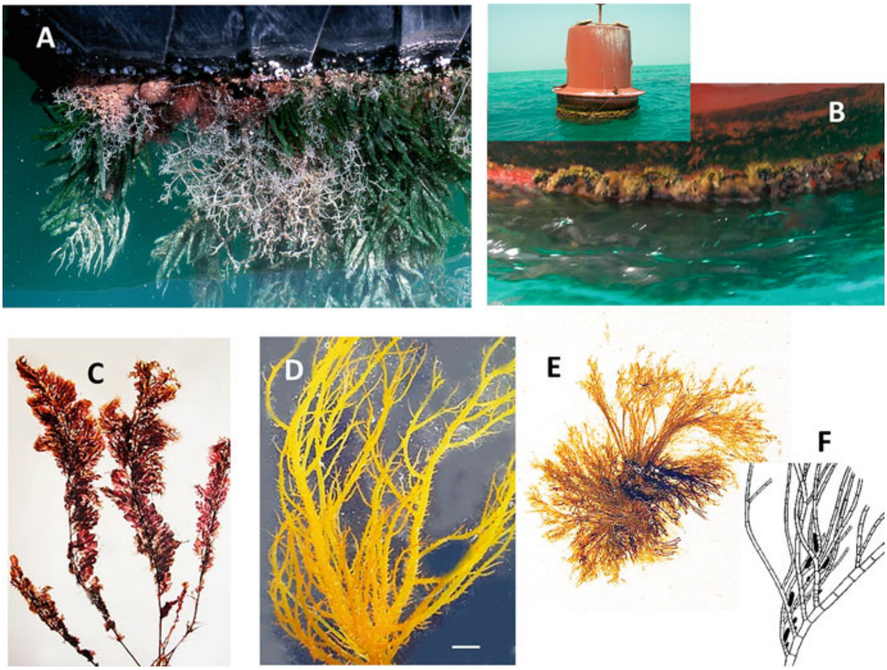


Fig. 10.17 (**a**) Floating pontoon with the submerged sides colonized by a diverse assemblage of organisms, including branched bryozoan colonies and the green seaweed *Caulerpa sertularioides* form *farlowii*, (**b**) insert of floating buoy and closer view showing dense cover of fouling organisms around and just below the water surface, (**c**) the bushy, somewhat plumose branches of the sexual life-history stage of *Asparagopsis taxifolia* (asexual stage forms delicate pinkish red tufts), (**d**) the bushy, straw coloured *Hypnea cornuta* with its upwardly curved branchlets, often these bear anvil-shaped propagules, (**e**) brown tuft of the filamentous seaweed *Feldmannia mitchelliae*, (**f**) line drawing of microscopic filaments of *Feldmannia mitchelliae* showing its characteristically shaped organs of reproduction (plurilocular gametangia). Photo credits: David George (**a**) and David John (**b**–**e**); image (**f**) from Borgesen (1939)

10.1.5 Man-Made Habitats

10.1.5.1 Fixed Structures

Suitable seaweed habitats continue to be created as the coastal zone of the UAE is increasingly modified by the construction of new breakwaters, stone jetties, metal piers, floating marinas, harbours, channels, landfill, rock armoured islands and peninsulas (e.g., Dubai's 'Palm Islands'). Many islands and breakwaters have revetments of natural stone blocks (usually of limestone) or, less commonly, of concrete tetrapods or metal piles. Most of these surfaces become quickly colonised by fouling animals along with fast-growing seaweeds and sometimes are in areas where no such hard-bottom had existed previously. Suspension-feeding invertebrates frequently foul pier piles and floating pontoons whereas hard corals are recorded on the sediment-free seaward side of rough stone breakwaters and are accompanied by red seaweeds, such as the bushy seaweed *Asparagopsis taxifolia* (Fig. 10.17c), various brown seaweeds and the ubiquitous crustose corallines. Breakwaters and other shoreline developments might be thought of as large-scale artificial reefs capable of supporting abundant and diverse marine communities. Consideration has therefore been given to applying ecological engineering principles to such shoreline developments in order to enhance biodiversity, with the first step been to determine those best suited to enhance recruitment of desirable organisms (Burt and Bartholomew 2019; Burt et al. 2009).

10.1.5.2 Floating Structures

Channel marker buoys and pontoons are frequently festooned by a diverse assemblage of seaweeds during the winter months, together with many invertebrates. Immediately at or just below the water surface (Fig. 10.17a, b) there is often a dense seaweed mat that sometimes includes the articulated coralline *Jania rubens* (Fig. 10.12f), *Acanthophora musciformis* (Fig. 10.10e), the creeping green *Caulerpa sertularioides* form *farlowii* (Figs. 10.16b and 10.17a), the peacock/turkey tail brown seaweed (*Padina boergesenii*) (Fig. 10.5d), the often straw-coloured *Hypnea cornuta* (Fig. 10.17d) and the inflated colonies of *Colpomenia sinuosa* (Fig. 10.5c) that are usually present in the spring. Occasionally present are clumps of the form of the crustose coralline *Lithophyllum kostchyanum* whose branches are flattened (Fig. 10.13c). These man-made structures are periodically cleaned to remove fouling organisms so a stable animal-dominated assemblage is probably never attained. Small buoys in sheltered marinas and the hulls of small boats frequently have a covering of the green filaments of *Cladophora nitellopsis* (Fig. 10.6c) and sometimes mats or tufts of the filamentous brown seaweed *Feldmannia mitchelliae* (Fig. 10.17e, f); these fast-growing seaweeds are usually the first conspicuous colonizers of newly available surfaces.

10.2 Ecological Interactions

A feature of many rocky areas and lithified 'hard grounds' is the complexity of biological interactions taking place, including competition for space, avoidance of predation and herbivory through structural or chemical adaptations, and temporal escape through rapid growth and regeneration. The ability of some seaweeds to quickly colonise and become establish might impact on the successful colonization and re-establishment of corals following episodes of bleaching and death. It is known that turf-like mats very soon colonize coral skeletons following bleaching and yet Birrell et al. (2005) was able to show experimentally that turf-like seaweed mats only have a negative impact upon coral recruitments if containing trapped sediment.

Some seaweeds are adapted to survive the ravages of herbivorous fish and sea urchin grazing through morphological and chemical defence mechanisms (Duffy and Hay 1990; Hay and Fenical 1992). The heavy calcification of crustose corallines means they are not normally grazed by fish other than parrotfish and are well adapted to survive chronic grazing or scraping by sea urchins. These forms also survive in habitats where there is violent wave action hence are conspicuous on very wave-battered and often steeply sloping shores, including the seaward side of breakwaters. For example, the crustose corallines form a very distinctive band in the lowermost zone on rocky headlands along the northern coastline of Fujairah (see Fig. 10.2c, d). The success of crustose corallines is not only due to their hardness but also their ability to continuously replace those surface cell layers lost through grazing, heavy wave-action and sand abrasion.

Some of the larger seaweeds, such as the foliose browns, are known to be an important food source in the UAE for animals including green turtles and dugongs. It has been suggested by Fulton et al. (2020) that in diverse tropical seascapes, what they term macroalgal meadows (p. 3), '. . .could provide stepping-stones or refuge habitats for fishes occupying a diverse tropical seascape subject to disturbance events. Depending on the trophic diversity of these macroalgal-associated fishes, such overlaps in habitat occupation could help stabilise ecosystem structure and function in the face of disturbances affecting a particular habitat type (e.g., mass-bleaching of corals)'. Much of the large biomass of decaying seaweed often seen floating in the sea along parts of the western coast of Abu Dhabi in spring and early summer becomes deposited on beaches and probably contributes significantly to detrital food webs as well as to the microbial loop.

Small turf-like mats of seaweeds are typically formed of short, tightly packed, highly branched filaments and consist of erect branches arising from a system of creeping or prostrate branches. Such growth forms are common and survive loss or damage to the apices of the erect portion by fish browing, desiccation, wave action and sand abrasion by having basally positioned growing points or meristems. These mats are conspicuous in the lower littoral zone of rocky shores or breakwaters including those subject to considerable heavy wave action. Such mats are also commonly associated with shallow rocky areas and 'hard grounds' (0.5–5 m), especially where there is much physical relief and are sometimes associated with large populations of herbivorous fish. Still to be investigated in the UAE are such plant-animal interactions, including the impact of herbivory on the distribution and composition of the seaweeds in the littoral and shallow subtidal zone.

10.3 Seaweed Seasonality

The maximum summer sea temperature and seasonal temperature range in the southern basin of the Arabian Gulf is the greatest worldwide. Temperatures range from 19 to 36 °C with the lowest ones are from February to April (winter-spring period) and the highest from about August to October (summer-autumn) (see Chap. 4). The annual temperature regime accounts for the pronounced seasonal changes in the distribution, abundance and composition of the UAE's seaweeds flora (John and George 2003). The temperature changes are not as extreme outside the Arabian Gulf, and therefore seaweeds in the eastern emirates are unlikely to display anything like the same very pronounced seasonality, although such information is lacking since they have been little studied in Fujairah or Sharjah's coastal waters.

Observations on seasonal changes to the seaweed flora have been confined to Abu Dhabi, where seaweeds undergo a dramatic transformation as the sea temperature rapidly rises in spring and early summer (April-May). Many seaweeds begin to undergo decay and are lost during this period, and large floating masses have been observed in the western region of Abu Dhabi which frequently accumulate in sheltered bays before washing ashore (Fig. 10.18a, b).

Most seaweeds appear to be moribund or dormant over the summer when sea conditions tend to be very calm and most submarine surfaces become coated in what is believed to be a film of sediment mixed with microalgae.

A further transformation of the seascape takes place from about November onwards and corresponds to the sea temperate dropping below about 25 °C, when many seaweeds begin to reappear and the larger brown seaweeds once more spatially dominate many shallow rocky areas. Recovery of these seaweeds often takes the form of new branches from often persistent basal portions and of small juveniles arising from resting spores and microscopic life history stage. The winter period is the most appropriate time for studying this important group, since this is at the time when seaweeds are most abundant and diverse.

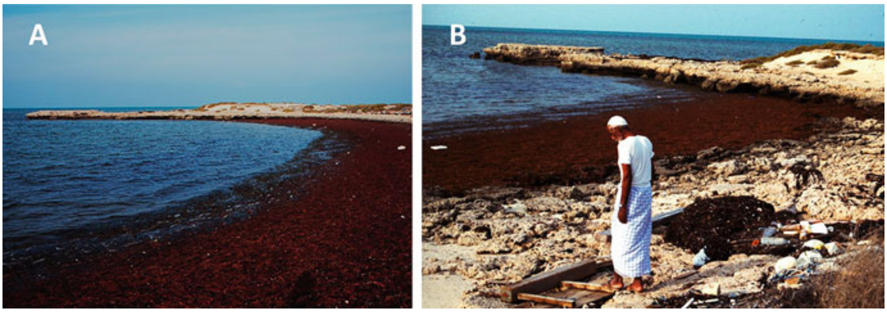


Fig. 10.18 (**a**, **b**) Rocky bay in the west of Abu Dhabi showing the mass of seaweeds washed ashore in spring and early summer following the seasonal die-back of offshore seaweed communities. Photo credits: David George

10.4 Invasive Seaweeds

The only seaweed believed to have been introduction in recent times is *Caulerpa racemosa* form *requienii* (Fig. 10.19). This green seaweed was first discovered in September 2010 in Palm Jebel Ali (Dubai) where it formed dense and extensive beds over the sandy and muddy seabed at depths ranging from 3 to 5 m (Venneyre et al. 2014). It consists of creeping stoloniferous branches attached by clusters of rhizoids and giving rise at intervals to cylindrical or slightly compressed, regularly forked branches. The only other site from which it is reported is a sheltered muddy area lying about 700 m off Ras Ghantoot and close to a what at the time was a causeway connecting the mainland to the Dubai 'Waterfront Islands Development'; a site just a few kilometers from the Abu Dhabi border.

One possible vector responsible for its introduction are the suction dredgers employed for the construction of Palm Jebel Ali and the Dubai waterfront. These dredgers use sand as ballast in their hoppers and, just prior to travelling to Dubai, had been deployed extracting and transporting sand from near Jakarta in Indonesia for the construction of a harbour in Singapore. To determine whether this is the source of the introduction it will be necessary to carry out a genomic investigation to compare the Dubai population with that from Indonesia.

This introduced species is a potential invasive species, since other members of the genus have become widely distributed and have brought about disastrous changes in shallow water environments in different parts of the world, especially in the

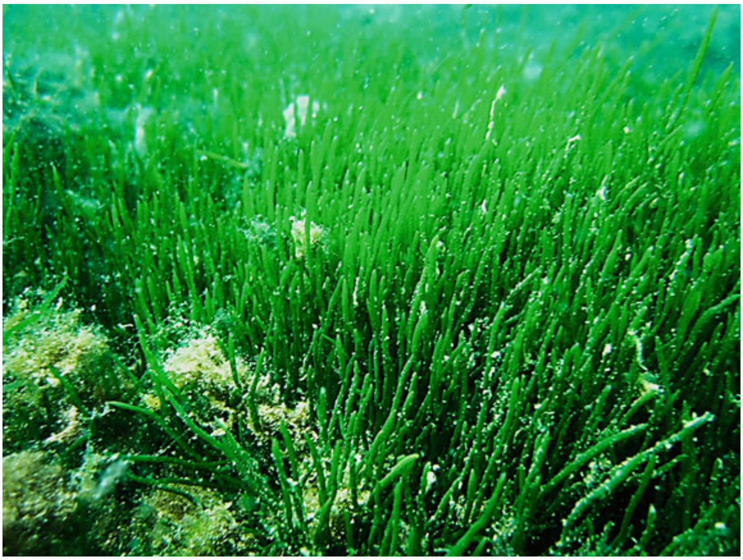


Fig. 10.19 Dense bed showing the cylindrical or slightly compressed erect branches of *Caulerpa racemosa* form *requienii* growing on the sandy floor of Palm Jebel Ali in Dubai. Image credit: Laurence Vanneyre

Mediterranean. There is no recent information on these seaweeds within the Arabian Gulf so its current status is unknown.

10.5 Importance of Seaweeds

Seaweeds, along with seagrasses, are the key primary producers lying at the base of inshore food webs within the southern basin of the Arabian Gulf. The larger brown seaweeds are key primary producers involved in nutrient cycling and the seasonally developed, complex three-dimensional subtidal 'forests' in which they are the canopy dominants are important spawning and nursery habitats for many fish, as well as foraging areas for adult shrimps. Some seaweeds are a direct food source for fish, invertebrates, as well as turtles and dugongs, but much seaweed biomass enters the food web as detritus. They are therefore seasonally important to suspension and detrital feeders alike and, through decomposition, make a significant contribution to the microbial loop.

Detrital feeders are important general consumers of organic material and along with microalgae probably account for the importance of inshore mud flats and offshore shoals and islands as feeding grounds for millions of migratory and resident water fowl (see Chap. 15). The spring and the early summer are when a large quantity of decaying seaweeds and seagrasses are cast up on some beaches with brown seaweeds and contributing to much of this biomass (Fig. 10.18a, b), principally species of *Sargassum*, *Hormophysa cuneiformis* and *Sarcothalia trinodis* whose floatation is aided by air-filled vesicles or bladders. Decaying seaweeds deposited on beaches (i.e. beach wrack) are consumed by animals living in the strandline and, therefore, make an important contribution to terrestrial food webs. This justifies leaving them in situ rather than removing them simply because they are considered unsightly when on leisure beaches.

The increase in abundance in rocky subtidal areas of crustose coralline seaweed following the mass bleaching and death of corals was first observed in Abu Dhabi in the late 1990s (George and John 1999, 2000, 2002). The increased importance of crustose corallines has been confirmed by a study of colonisation of tile surfaces in which these seaweeds were a major component of the settlement community and this led Bento et al. (2017) to conclude that in the southern Gulf 'the CCA [crustose coralline algae] appear to be a persistent, long-term characteristic of this highly disturbed extreme environment'. In the same study it was discovered that 'turf algae' were more important than crustose corallines in the Sea of Oman (including Fujairah) with sea squirts (ascidians) and moss animals (bryozoans) dominating the settlement community in what was considered to be a more benign region.

The crustose corallines play an important role in coral-dominated areas by reinforcing dead coral skeletons. They stabilise surfaces by 'cementing' coral debris and dislodged blocks of living coral and reduce erosion. Seaweeds are known to induce the settlement of coral larvae (Ritson-Williams et al. 2014; Tebben et al. 2015) so the presence of crustose corallines should favour coral colonisation

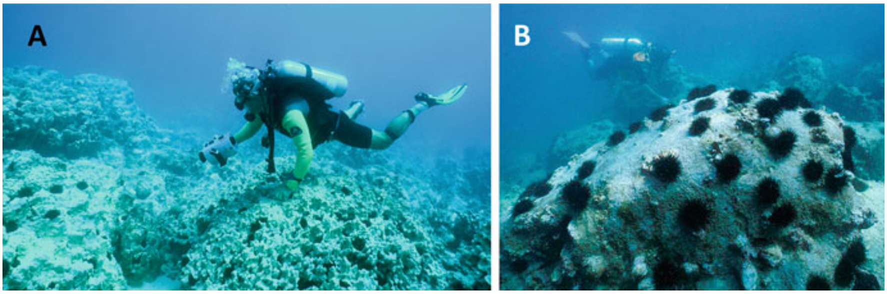


Fig. 10.20 (**a**) Submarine rocky reef at Hail Shoal in Abu Dhabi chronically grazed by large populations of the sea urchin *Echinometra* and showing its much-eroded surface, (**b**) closer view of chronically sea urchin grazed rocky area now spatially dominated by crustose coralline algae (CCA). Photo credits: David George

following disturbance. This has important implications given the increasingly degraded nature of coral reefs around the UAE since such beneficial coral-algal interactions might aid their recovery.

Crustose corallines are able to survive where wave-exposure is extreme, hence are conspicuous on wave-beaten shores such as the rocky headlands along the northern coast of Fujairah (John 2023). These are predominant and sometimes the only conspicuous seaweeds to survive in submarine rocky areas where there is chronic grazing by large aggregations of the black sea urchin *Echinometra* (Fig. 10.20a, b). Crustose seaweeds persist because they have a subsurface growth or meristematic layer that continually replenishes the outer surface cells removed by the scraping or rasping of urchins. One of the only threats to crustose corallines comes from parrotfish that feed by removing entire portions of crust along with any branches or surface nodules, although parrotfishes are relatively rare along the southern Gulf coast of the UAE (Hoey et al. 2016).

So far 16 species of crustose coralline seaweeds have been recorded in the UAE (John and Al-Thani 2014) of which three are only known from Fujairah. All these corallines were originally described in three unpublished reports written in the late 1990s by Dr Yvonne Chamberlain, a specialist in crustose corallines, and reproduced in a report prepared for what was then the Abu Dhabi Company for Onshore Oil Operations (John and George 2001).

There is an urgent need for a taxonomic revision of this increasingly important, and yet much neglected group of seaweeds, ideally involving combining the more traditional approach based on morpho-anatomical characters with modern DNA sequence analysis.

10.6 Seaweeds as a Resource

There have been several studies in the southern Gulf focusing on chemical elements extracted from local seaweeds, and Al-Adilah et al. (2021) have reported on the nutritionally important polysaturated fatty acids and suggested local seaweeds to be a possible commercial source of such compounds. Less convincing is the suggestion by Farzanah et al. (2021) that UAE seaweeds might be a feasible source of biomass for refining and producing fuel for jet aircraft and as high value chemicals. All such studies have focused on a few of the more readily recognised and relatively common seaweeds, including the green seaweed *Ulva.* A species of *Ulva*, referred to as *Ulva intestinalis*, has been discovered to have high concentrations of essential minerals such as potassium, magnesium, iron and zinc, so making it a promising novel food source in the UAE according to Farzanah et al. (2022). Other seaweeds investigated elsewhere in the southern Gulf include the seasonally common inflated brown seaweed *Colpomenia sinuosa*, the so-called peacock tail weed *Padina boergesenii,* various species of *Sargassum* and *Sarcothalium trinodis.* These studies all fail to address the problem of having a constantly available and reliable source of supply since most species are only present in any quantity during the months of cooler sea temperature ('winter'). That is not to say a small scale or 'cottage' industry approach might not be adopted if it were acceptable for harvesting to cover a very short period when seaweeds are locally available in quantity.

10.7 Conclusions

The submarine seascape of the shallow inshore environment of the emirates bordering the Arabian Gulf and Gulf of Oman has undergone a dramatic transformation or 'phase' or 'regime' shift over the past two decades. The degradation and decline in coral cover over the last two decades has been very significant and has resulted in new opportunities for seaweeds to colonise and replace them as the spatial dominants in some shallow rocky areas (Fig. 10.20). All indications are that environmental stressors such sea temperature will continue to favour seaweeds that are likely to continue to become an ever more significant component of benthic marine communities.

Differences in the composition and abundance of seaweeds between the emirates reflects the availability of suitable substrates for seaweeds, extent of these hard substrates and the amount of collecting effort. Abu Dhabi has received, by far, the greatest amount of attention, in part due to many nearshore and offshore habitats suitable for the development of seaweeds and the presence of extensive rocky areas once completely dominated stony corals (see Grizzle et al. 2016). Surveys are needed of the seaweeds of those emirates lying to the west of Abu Dhabi since few, if any, records exist for most of these areas (see John and Al-Thani 2014).

The seaweed flora has been scarcely studied in the emirates bordering the Gulf of Oman (Fujairah, Sharjah), unlike in the neighbouring sultanate of Oman where they have been well researched and for which over 400 species have been recorded (see Wynne 2018). The exceptional high seaweed diversity in Oman compared to Fujairah and Sharjah is not just a reflection of greater research effort but, rather, the exceptional development of seaweeds that takes place where there is upwelling of colder, nutrient-rich water along its southern coast during the seasonal monsoon (Savidge et al. 1990). The rockier parts of the coastline of Fujairah are more comparable to northernmost parts of the Omani coast where seaweed diversity is low due to high air temperatures, desiccation and low nutrient levels (B. Jupp, pers. comm.).

Since the 1990s new coastal and offshore developments in the UAE will have benefitted seaweeds by providing hard surfaces suitable for colonisation, sometimes where none existed before. Although there is no evidence that increasing summer sea temperatures has had an adverse impacted upon the seaweed flora, it is impossible to know whether this will continue to be the case as the environment becomes more stressful. There are a multitude of environmental factors that impact seaweeds, corals and other marine organisms besides sea temperature, including sea water acidity that is increasing in the Arabian Gulf (see Uddin et al. 2012) as well as seas and oceans worldwide. The decline in pH and carbonate levels combined with rising CO_2 and bicarbonate levels will be a threat to crustose coralline seaweeds, corals as well as marine invertebrates having shells of calcium carbonate. Acidification might not only affect the organisms themselves, but results in softening of the lithified sediments and debris (‘hardgrounds’) which are often crucially important surfaces for seaweeds and other benthic organisms (Purkis et al. 2011). Uncertain surrounds the threat from acidification because the seawater in the Arabian Gulf is supersaturated with aragonite as a result of regional environmental conditions.

One of the groups most likely to benefit from some of the predicted longer-term changes in the marine environment will probably be the Cyanobacteria. The most significant cyanobacterial communities, often referred to as ‘algal mats’, principally develop on low lying and flat or gently sloping sedimentary shores (e.g., coastal sabkha, intertidal mudflats). These mats will be at risk from storm surges predicted to increase linked in response to rising temperatures in the region. Other risks include inundation resulting from land subsidence linked to oil and groundwater extraction and sea-level rise due to thermal expansion and melting of land-based ice elsewhere on the globe (Melville-Rea et al. 2021).

Seaweeds and Cyanobacteria remain some of the least-researched primary producers in the UAE, with very few genomic studies yet undertaken using DNA sequence data to identify seaweed floras. There are some questionable new records from the southern region since these are not supported by informative illustrations/photographs and no attempt has been made to fully described the specimens upon which they are based or confirm by DNA sequence analysis. It is of crucial importance to ensure material is correctly identified and representative specimens suitably stored in national institutions (e.g., herbaria, museums, universities) for future reference and further study by taxonomic specialists. Representatives of all the species reported from the UAE are housed in the herbarium at the Natural History Museum in London (BM).

10.8 Recommended Readings

For further information on the seaweeds of the Emirates, the following sources are recommended as accessible readings: Al Abdessalaam (2007), John (2005, 2012), John and George (2004, 2005), George and John (2005).

Acknowledgements Thanks go to the Abu Dhabi Company for Onshore Oil Operations (now ADNOC Onshore) for providing grant funding to the Natural History Museum in London in order to carry out the marine environmental survey of Abu Dhabi upon which much of this chapter is based, and to the following: the late Peter Hellyer for much invaluable advice and support over many years, Veryan Pappin and Richard Hornby of Nautica Environmental Associates (Abu Dhabi) who were involved in all phases of my research, Gareth John, Graham Hornby and Chris Teasdale of Nautica Environmental Associates who accompanied me on fieldwork, very special thanks go to David George for his scholarly advice, friendship and providing many of the photos in this chapter. Finally, thanks to the Natural History Museum in London for providing facilities to enable me to undertake the research necessary to complete this chapter.

References

Abed RMM, Kohls K, Palinska KA, Golubic S (2010) Diversity and role of Cyanobacteria and aerobic heterotrophic microorganisms in carbon cycling in arid cyanobacterial mats. In: Seckbachm J, Oren A (eds) Microbial mats: modern and ancient microorganisms in stratified systems, cellular origin, life in extreme habitats and astrobiology. Springer, Dordrecht, pp 253–273. https://doi.org/10.1007/978-90-481-3799-2_13

Al Abdessalaam TZ (2007) Coastal and Marine Habitats. In: Al Abdessalaam TZ (ed) Marine environment and resources in Abu Dhabi. Motivate, Dubai, pp 55–91

Al-Adilah H, Al-Sharrah TK, Al-Bader D, Rainer Ebel R, Küpper FC, Kumari P (2021) Assessment of Arabian Gulf seaweeds from Kuwait as sources of nutritionally important polyunsaturated fatty acids (PUFAs). Foods 10(10):2442. https://doi.org/10.3390/foods10102442

Bejarano I, Orenes-Salazar V, Bento R, Garcia-Charton A, Mateos-Molina D (2022) Coral reefs at Sir Bu Nair Island: an offshore refuge of *Acropora* in the southern Arabian Gulf. Mar Pollut Bull 178:1561–1569. https://doi.org/10.1016/j.marpolbul.2022.113570

Bento R, Feary DA, Hoey AS, Burt JA (2017) Settlement patterns of corals and other benthos on reefs with divergent environments and disturbances histories around the Northeastern Arabian Peninsula. Front Mar Sci 4:1–12. https://doi.org/10.3389/fmars.2017.00305

Birrell C, McCook L, Willis B (2005) Effects of algal turfs and sediment on coral settlement. Mar Pollut Bull 51(1–2):408–414. https://doi.org/10.1016/j.marpolbul.2004.10.022

Borgesen F (1939) Marine algae from the Iranian Gulf especially from the innermost part near bushire and Island Kharg. In: Jesse K, Spark R (eds) Danish scientific investigations in Iran part 1. Munksgaard, Copenhagen, pp 42–141

Burt JA, Bartholomew A (2019) Towards more sustainable coastal development in the Arabian Gulf: Opportunities for ecological engineering in an urbanized seascape. Mar Pollut Bull 142:93–102. https://doi.org/10.1016/j.marpolbul.2019.03.024

Burt JA, Bauman AG (2019) Suppressed coral settlement following mass bleaching in the southern Persian/Arabian Gulf. Aquat Ecosyst Health Manag 23(2):1–9. https://doi.org/10.1080/14634988.2019.1676024

Burt J, Bartholomew A, Bauman A, Saif A, Sale P (2009) Coral recruitment and early benthic community development on several materials used in the construction of artificial reefs and breakwaters. J Exp Mar Biol Ecol 373:72–78. https://doi.org/10.1016/j.jembe.2009.03.009

Burt J, Paparella F, Al-Mansoori N, Al-Mansoori A, Al-Jailani H (2019) Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. Coral Reefs 38:567–589. https://doi.org/10.1007/s00338-019-01767-y

Burt J, Range P, Claereboudt M, Al-Mealla R, Salimi P, Salimi M, Ben-Hamadou R, Bolouki M, Bouwmeester J, Taylor O, Wilson S (2021) Chapter 4. Status and trends of coral reefs of the ROPME Sea Area. In: Souter D, Planes S, Wicquart J, Logan M, Obura D, Staub F (eds) Status of coral reefs of the world: 2020. GCRMN, Lausanne, pp 1–13

Duffy JE, Hay ME (1990) Adaptation to herbivory. Chem, struct and morphological defences are often adjusted to spatial or temporal pattern of attack. Bioscience 40(5):360–375. https://doi.org/10.2307/1311214

Farzanah R, Danosh C, Augousti A, Wang J (2021) A review of the UAE native seaweeds as potential bio-refinery feedstock for jet-fuel and high value chemicals. Adv Environ Waste Manag Res 3(1):1–6

Farzanah R, Clausen MP, Arnspang EC, Schmidt JE, Bastidas-Oyanedel J-R (2022) Feasibility of United Arab Emirates native seaweed Ulva intestinalis as a food source: study of nutritional and mineral compositions. Phycology 2(1):120–113. https://doi.org/10.3390/phycology2010008

Foster K, Foster G, Al-Cibahy A, Al-Harthi S, Purkis SJ, Riegl B (2012) Environmental setting and temporal trends in southeastern Gulf coral communities. In: Riegl B, Purkis S (eds) Coral reefs of the Gulf: adaptation to climatic extremes. Springer, Dordrecht, pp 51–70. https://doi.org/10.1007/978-94-007-3008-3_10

Fulton CJ, Berkström C, Wilson SK et al (2020) Macroalgal meadow habitats support fish and fisheries in diverse tropical seascapes. Fish Fish 21:700–717. https://doi.org/10.1111/faf.12455

George JD, John DM (1999) High sea temperatures along the coast of Abu Dhabi (UAE), Arabian Gulf—their impact upon corals and macroalgae. Reef Encount 25:21–23

George JD, John DM (2000) The effects of the recent prolonged high seawater temperatures on the coral reefs of Abu Dhabi (UAE). In: Anon (ed) Proceedings of the international symposium on the extent and impact of coral bleaching in the Arabian region. NCWCD, Riyadh, pp 28–29

George JD, John DM (2001) The status of coral reefs and associated macroalgae in Abu Dhabi (UAE) after recent coral bleaching events. In: Abuzinada AH, Joubert E, Krupp F (eds) The extent and impact of coral bleaching in the Arabian region. NCWCD, Riyadh, pp 184–200

George JD, John D (2002) Is it curtains for coral reefs in the southern Arabian Gulf. In: Anon (ed) Abstract volume. Proceedings of the International Society for Reef Studies (ISRS) European meeting, 4–7 Sept 2002, Cambridge, p 37

George JD, John DM (2004) The coral reefs of Abu Dhabi (UAE): past, present and future. Marine Atlas Abu Dhabi. Emirates Heritage Club, Abu Dhabi, UAE, pp 140–157

George JD, John DM (2005) The marine environment. In: Hellyer P, Aspinall S (eds) The Emirates: a natural history. Trident, London, pp 111–122

Golubic S, Abed RMM (2010) *Entophysalis* mats as environmental regulators. In: Seckbach J, Oren A (eds) Microbial mats: modern and ancient microorganisms in stratified systems, cellular origin, life in extreme habitats and astrobiology 14. Springer, Dordrecht, pp 237–251. https://doi.org/10.1007/978-90-481-3799-2_12

Grizzle RE, Ward KM, AlShihi RMS, Burt JA (2016) Current status of coral reefs in the United Arab Emirates: Distribution, extent, and community structure with implications for management. Mar Pollut Bull 105:515–523. https://doi.org/10.1016/j.marpolbul.2015.10.005

Hay ME, Fenical W (1992) Chemical mediation of seaweed-herbivore interactions. In: John DM, Hawkins SS, Price JH (eds) Plant-animal interactions in the marine benthos. Systematics Association Special Volume. Clarendon, Oxford, pp 319–337

Hoey AS, Feary DA, Burt JA, Vaughan G, Pratchett MS, Berumen ML (2016) Regional variation in the structure and function of parrotfishes on Arabian reefs. Mar Pollut Bull 105:524–531. https://doi.org/10.1016/j.marpolbul.2015.11.035

John DM (2005) Marine plants. In: Hellyer P, Aspinall S (eds) The Emirates: a natural history. Trident, London, pp 161–167

John DM (2012) Marine algae (seaweeds) associated with coral reefs in the Gulf. In: Riegl BM, Purkis SJ (eds) Coral reefs of the gulf: adaptation to climatic extremes. Coral reefs of the world 3. Springer, Dordrecht, pp 308–335. https://doi.org/10.1007/978-94-007-3008-3

John DM (2023) Seaweeds and microalgae. In: Hellyer P, Ziolowski M (eds) The natural history and heritage of Fujairah. Motivate, Dubai, pp 297–311

John DM, Al-Thani RF (2014) Benthic marine algae of the Arabian Gulf: a critical review and analysis of distribution and diversity patterns. Nova Hedwigia 98(3–4):341–392. https://doi.org/10.1127/0029-5035/2014/0156

John DM, George JD (2001) The marine life of the emirate of Abu Dhabi. A report for the Abu Dhabi Company for Onshore Oil Operations. Nat Hist Museum, London, 219 pp

John DM, George JD (2003) Coral death and seasonal seawater temperature regime: their influence on the marine algae of Abu Dhabi (UAE) in the Arabian Gulf. In: Chapman ARO, Anderson RJ, Vreeland VJ, Davison IR (eds) Proceedings of the international seaweed symposium 17. Oxford University Press, Oxfordshire, pp 341–348

John DM, George JD (2004) Intertidal and subtidal benthic communities in Abu Dhabi Emirate. In: Anon (eds) Marine Atlas of Abu Dhabi. Emirates Heritage Club, Abu Dhabi, pp 95–123

John DM, George JD (2005) The shore & shallow seas. In: Hellyer P, Aspinall S (eds) The Emirates: A natural history. Trident, London, pp 123–131

Lewis JR (1964) British rocky shores: the ecology of rocky shores. English Universities Press, London

Melville-Rea H, Eayrs C, Anwahi N, Burt JA, Holland D, Samara F, Paparella F, Al Murshidi AH, Al-Shehhi MR, Holland DM (2021) A roadmap for policy-relevant sea-level rise research in the United Arab Emirates. Front Mar Sci 8. https://doi.org/10.3389/fmars.2021.670089

Purkis SJ, Renegar DA, Riegl BM (2011) The most temperature-adapted corals have an Achilles' Heel. Mar Pollut Bull 62(2):246–250. https://doi.org/10.1016/j.marpolbul.2010.11.005

Riegl BM (1999) Corals in a non-reef setting in the southern Arabian Gulf (Dubai, UAE): fauna and community structure in response to recurring mass mortality. Coral Reefs 18(1):63–73. https://doi.org/10.1007/s003380050156

Riegl B, Johnston M, Purkis S, Howells E, Burt J, Steiner SCC, Sheppard CRC, Bauman A (2018) Population collapse dynamics in Acropora downingi an Arabian/Persian Gulf ecosystem-engineering coral linked to rising temperature. Glob Chang Biol 24(6):2447–2462. https://doi.org/10.1111/gcb.14114. 10.1111/gcb.2018.24.issue-6

Ritson-Williams R, Arnold SN, Paul VJ, Steneck RS (2014) Larval settlement preferences of *Acropora palmata* and *Montastraea faveolata* in response to diverse red algae. Coral Reefs 33:59–66. https://doi.org/10.1007/s00338-013-1113-2

Savidge G, Lennon J, Matthews AJ (1990) A shore-based survey of upwelling along the coast of Dhofar region, southern Oman. Cont Shelf Res 10:259–275. https://doi.org/10.1016/0278-4343(90)90022-E

Sheppard C, Price A, Roberts C (1992) Marine ecology of the Arabian region: patterns and processes in extreme tropical environments. Academic, Toronto

Silva PC, Basson PW, Moe RL (1996) Catalogue of the benthic marine algae of the Indian ocean. Univ Calif Publ Bot 79:1–1259

Stephenson TA, Stephenson A (1972) Life between tide-marks on rocky shores. Freeman WH, New York

Tebben J, Motti CA, Siboni N et al (2015) Chemical mediation of coral larval settlement by crustose coralline algae. Sci Rep 5:10803. https://doi.org/10.1038/srep10803

Uddin S, Gevao B, Al-Ghadban AN, Nithyanandan M, Al-Shamroukh D (2012) Acidification in Arabian Gulf—insights from pH and temperature measurements. J Environ Monit 14:1479–1482. https://doi.org/10.1039/c2em10867d

Vaughan GO, Al-Mansoori N, Burt JA (2019) The Arabian Gulf. In: Sheppard C (ed) World seas: an environmental evaluation, vol. 2: The Indian Ocean to the Pacific, 2nd edn. Academic, Cambridge, pp 1–23. https://doi.org/10.1016/B978-0-08-100853-9.00001-4

Venneyre L, Wilson S, John DM (2014) Note on *Caulerpa racemose* var. *lamourouxii* f. *requienii*: the first record of a potentially invasive non-native green seaweed from the Arabian Gulf. Phycologist 86(spring):15–18

Wynne MJ (2018) A checklist of the benthic marine algae of the Northern Arabian Sea coast of the Sultanate of Oman. Bot Mar 61:481–498. https://doi.org/10.1515/bot-2018-0035

Chapter 11
Coral Reefs of the Emirates

John A. Burt

11.1 UAE Coral Reefs in a Global and Regional Context

Coral reefs extend across the tropics from the Tropic of Cancer to the Tropic of Capricorn (30 °N to 30 °S), mainly in shallow coastal areas. They are among the most diverse ecosystems on earth, covering less than 0.1% of the ocean yet containing over a quarter of all marine species—a level of diversity comparable to tropical rainforests (Hoegh-Guldberg et al. 2017). They are also important for humanity, providing coastal protection, food, and livelihoods to over 850 million people, nearly a tenth of the global population (Burke et al. 2011). They are also economically important and are classified as the most valuable ecosystem on earth on a per unit area basis (over US \$35 million/km^2/year), each year providing over US \$9 trillion in goods and services globally, equating to nearly 8% of annual global GDP (de Groot et al. 2012; 2007 dollars; Costanza et al. 2014).

Over 6% of the world's coral reefs (15,000 km^2) occur in the Arabian region, largely made up by the extensive reef systems of the Red Sea and Gulf of Aden (Souter et al. 2021). Northeastern Arabia is broken into two marine biogeographic provinces with very distinct environmental conditions: the Sea of Oman and the Arabian Gulf (see Chap. 4; Sheppard et al. 1992; Briggs and Bowen 2012). While environmental conditions in the Sea of Oman are more benign and therefore more suitable for coral growth, the sharp increase in depth near the coast and the generally sandy sea-bottom make much of the Sea of Oman coastline unsuitable for coral growth (Burt et al. 2016). As a result, while the environment supports high coral diversity (ca. 120 species), only a modest area (196 km^2) is occupied by coral reefs across the Sea of Oman's entire coast (Claereboudt 2019; Burt et al. 2021b). In

J. A. Burt (✉)
Arabian Center for Climate and Environmental Sciences (ACCESS) and Center for Genomics and Systems Biology (CGSB), New York University Abu Dhabi, Abu Dhabi, UAE
e-mail: John.Burt@nyu.edu

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_11

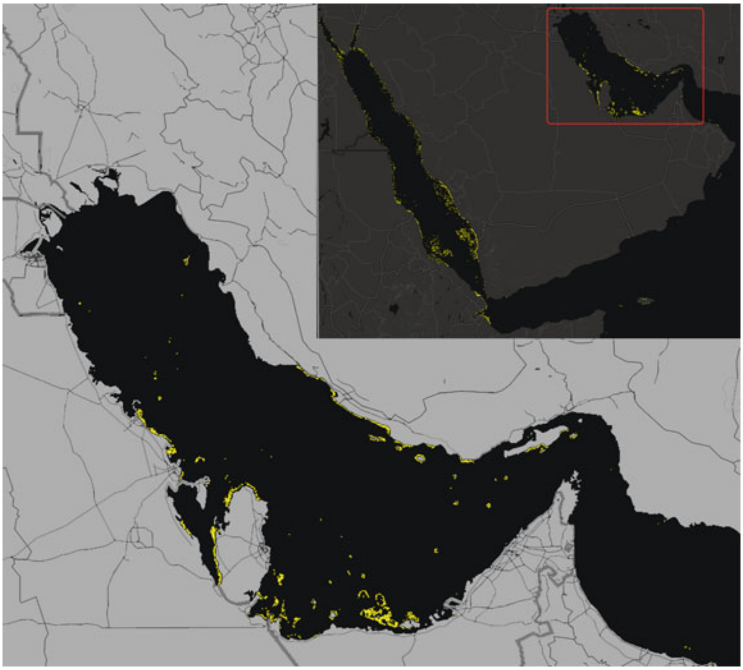


Fig. 11.1 Map illustrating the location of mapped coral reefs across the Arabian region, including the Arabian Gulf. In total, 6% of the world's coral reefs occur in Arabia, and corals occur in all eight nations bordering the Arabian Gulf. Map source: Modified from Allen Coral Atlas (2022) and shared under Creative Commons license (CC BY 4.0)

contrast, coral reefs have far greater area of coverage in the Arabian Gulf, where shallow water (mean depth <30 m) and widespread availability of hard-bottom support 1482 km^2 of reef habitat (Fig. 11.1) (Vaughan et al. 2019; Burt et al. 2021b). However, the shallow, semi-enclosed nature of the Gulf results in a marine environment that is characterized by extremes in salinity and temperature, particularly towards the southwest (see Chap. 4; Vaughan et al. 2019). As a result, while reefs are widespread, the diversity and complexity of reefs drops markedly with distance from the entrance of the Gulf. Approximately 70 coral species occur at the Strait of Hormuz (a third lower than in the wider Sea of Oman), dropping to around 50 species in the northwestern Gulf near Kuwait and Saudi Arabia, with the lowest diversity occurring in the southern basin along the coast of the United Arab Emirates (UAE) where 34 species have been reported (Sheppard and Sheppard 1991; Riegl et al. 2012; Bouwmeester et al. 2022). As a result of its young age, small size, high latitude (27–30 °N) and extreme environmental conditions, the Gulf contains only about a tenth of the coral diversity occurring in the wider Indo-Pacific, with only two regionally endemic coral species (*Acropora downingi* and *Porites harrisoni*) (Coles 2003). Reef complexity also varies with environmental conditions. True reefs, where corals grow on top of skeletal remains of older corals, only occur around the entrance of the Gulf at the Strait of Hormuz and around the offshore islands of Kuwait and Saudi Arabia, while reefs of the southern Gulf near the UAE are best described as 'coral carpets', where individual coral colonies grow as a single layer directly on rocky substrates (Sheppard and Sheppard 1991; Carpenter 1997; Riegl et al. 2012).

11.2 Coral Distribution and Diversity in the Emirates

Corals reefs in the Emirates fall into several distinct assemblage types that are largely structured by the prevailing environmental conditions in the local marine systems. Each of these are discussed separately below.

11.2.1 East Coast Reefs

In the UAE corals only occur where rocky habitats emerge from the sands that dominate the sea-bottom on both coasts. On the Sea of Oman coast, these occur mainly as headlands and nearshore islands that push out past the gravel plains at the base of the Hajar mountains (Fig. 11.2). Areas with the most extensive coral growth occur at rocky promontories around Dibba, Al Aqah, Mirbah, and Khor Fakkan; no reefs occur south of Khor Fakkan due to the absence of rocky substrate on this sandy coast. Virtually all corals on the East Coast occur in a narrow band of just a few tens of meters from the shoreline due to the steep slope, with corals largely restricted to <15 m depth. The relatively benign environmental conditions here are more typical of the Indian Ocean and support the highest diversity of corals in the UAE, estimated at approximately 60 species, although this is likely an underestimate as

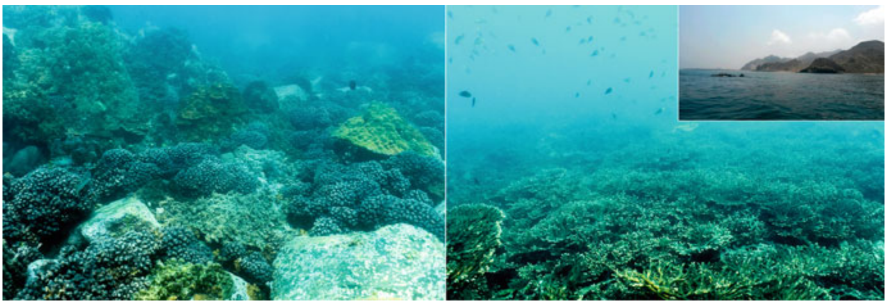


Fig. 11.2 Diverse coral reefs occur on the UAE's east coast wherever the Hajar Mountain headlands extend into the Sea of Oman (right inset), providing rocky bottom that supports coral growth. A mixed coral assemblage at Martini Wall (left) is mainly made up of mound corals (*Porites*, background) and cauliflower coral (*Pocillopora*, foreground), while table corals (*Acropora*) dominate Shark Island (right), both in Khor Fakkan. Photographer: John Burt

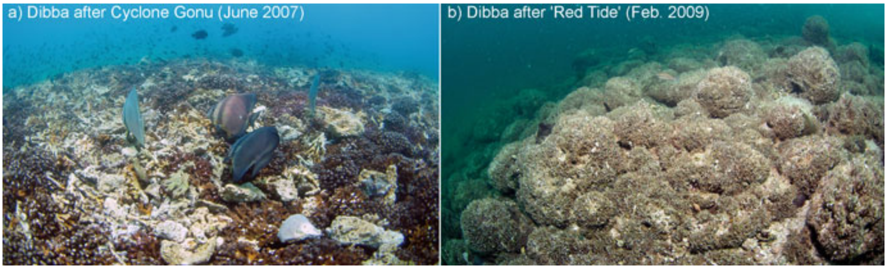


Fig. 11.3 A dense stand of cauliflower coral (*Pocillopora damicornis*) at Dibba Rock was impacted by (**a**) wave action during supercyclone Gonu in 2007 and by (**b**) low oxygen during a harmful algal bloom (HAB) in 2008/9, after which the corals were colonized by algae. Such impacts extended across most UAE east coast reefs. Images: Maral Chreiki (**a**) and Rita Bento (**b**)

comprehensive surveys (particularly of the large corals stands around Khor Fakkan) have not yet been published.

Coral reefs on the UAE's east coast have largely escaped the impacts of coastal development that have affected many nearshore reefs on the Arabian Gulf coast (see below), and the deeper adjacent waters have historically buffered corals against marine heat waves. However, two major back-to-back disturbances in the late 2000s resulted in the first record of wide-scale coral loss in this area.

In 2007 Supercyclone Gonu struck reefs across the Sea of Oman with sustained winds of over 270 km/h and waves reaching 5 m height (Fritz et al. 2010). The resulting storm surge heavily impacted the UAE's east coast, causing the loss of over half of coral from many reefs, with breakage and dislodgement particularly acute for the fragile branching corals (e.g. *Acropora* table corals and *Pocillopora* cauliflower corals) that had dominated these reefs (Fig. 11.3a) (Foster et al. 2008, 2011). Unfortunately, this was followed the next year by a severe harmful algal bloom (HAB) which caused oxygen-deprivation in waters across the northern portion of the UAE's east coast (Dibba to Mirbah) that persisted for several months (Bauman et al. 2010). This long-term exposure to hypoxia caused mortality of >80% of corals in many areas (Fig. 11.3b), and the local extirpation of particularly sensitive coral species (Bauman et al. 2010; Foster et al. 2011).

Despite the dramatic impacts to the UAE's northern east coast reefs in the late 2000s, recovery was underway within several years. Although there was only modest improvement in the total amount of coral on Sea of Oman reefs between 2009 and 2011 (Bento et al. 2016), juvenile colonies of table corals (*Acropora*), cauliflower corals (*Pocillopora*) and smooth cauliflower corals (*Stylophora*)—groups that had been particularly heavily impacted by earlier events—were observed in reef surveys performed in 2012 (Pratchett et al. 2017), indicating that recovery was underway. It generally takes 10–15 years for coral reefs to recover from a severe disturbance (Burt et al. 2008; Gilmour et al. 2013), suggesting that follow-up surveys of the coral reefs at these sites are warranted to determine the extent of recovery.

Fig. 11.4 Soft corals such as this colorful *Dendronephytha* sp. are common on the east coast (here, Khor Fakkan), but are absent on the UAE's Arabian Gulf coastal reefs south of Ras Al Khaimah, presumably due to environmental differences. They can be observed on far offshore islands in the Gulf, such as Sir Bu Nair, where conditions are more less extreme due to deeper water, but are uncommon. Photographer: John Burt

While the extensive coral reefs of Khor Fakkan, further to the south, were also impacted by Cyclone Gonu, they escaped most of the impact of the HAB event that afflicted reefs to the north near Dibba and Mirbah. Although Cyclone Gonu did cause breakage and fragmentation of much of the complex table corals (*Acropora*) that dominated these reefs down to ~7 m depth (Maghsoudlou et al. 2008), this did not lead to local extirpation. Because each fragment is capable of adhering to the bottom and growing into a new individual, within several years many of the fragments had grown into new colonies. Given the rapid growth rates (10–15 cm/year) of table corals, anecdotal observations suggested that much of the table coral community had recovered across Khor Fakkan within several years.

More delicate soft corals such as *Sinularia* and *Sarcophyton* generally only occur on the UAE's coast (Fig. 11.4), mainly around Khor Fakkan, and are largely absent on the UAE's Arabian Gulf nearshore reefs, presumably due to the more severe environment there. Soft corals were also heavily impacted by Cyclone Gonu, with large areas heavily denuded by the storm surge. However, recovery of soft corals was rapid, with significant regrowth observed within 6 months (Maghsoudlou et al. 2008). Unfortunately, there has been no comprehensive monitoring program for Khor Fakkan's reefs in the past, and quantitative data on trends in reef health are unavailable for these important reefs; development of such a program is highly warranted.

11.2.2 Reefs of the Gulf's Northern Emirates

The distribution of corals along the UAE's Arabian Gulf coast varies as a function of depth and availability of rocky bottom. Corals here are typically restricted to <10 m depth as a result of light limitation from the moderate turbidity of Gulf waters (Fig. 11.5) (Chap. 4; Grizzle et al. 2016). Where the sea-bottom slope is steep, as in Ras Al Khaimah, this restricts coral growth to the immediate coastline in areas where hard-bottom occurs (e.g. Ghalilah), although occasional coral colonies can be found on rocky outcrops offshore at depths exceeding 40 m (so-called mesophotic coral reefs (Fig. 11.6), about which little is known in the Gulf; Pyle and Copus 2019).

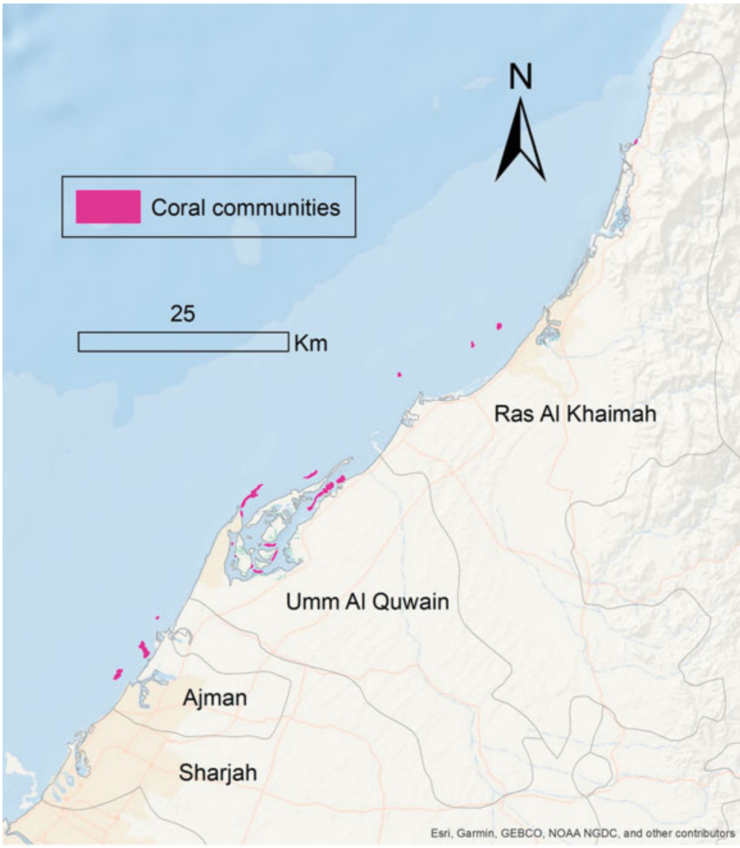


Fig. 11.5 Although often underappreciated by the general public, coral reefs do occur in nearshore areas and in lagoons across the northern Emirates, some quite extensive in area (e.g. around Umm Al Quwain). Not shown are unique 'mesophotic' offshore reefs that occur at >40 m depth and remain largely unmapped and unstudied. Modified from Fig. 4 in Mateos-Molina et al. (2020), reprinted under Elsevier license 5514050185453

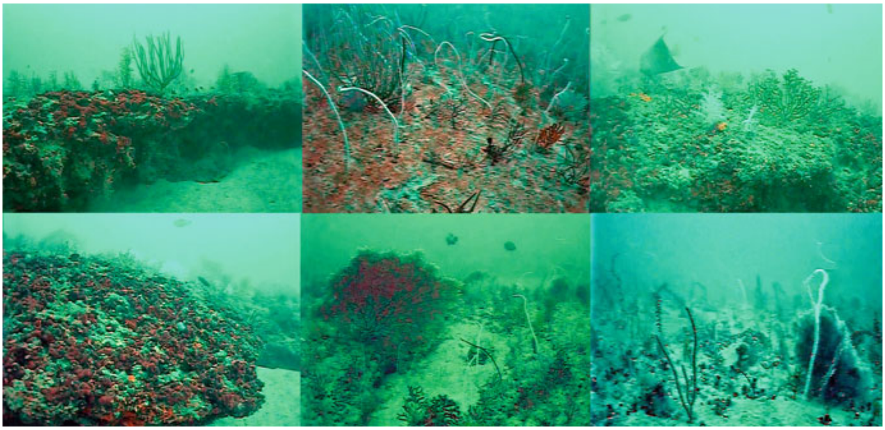


Fig. 11.6 A variety of fan corals, whip corals, and other soft and hard corals occur on a rocky outcrop that makes up the Sheikh Salim reef, a deep (ca. 40 m) mesophotic (low light) reef that occurs approximately 37 km offshore from Ras Al Khaimah, occupying an area of over 3 km^2. Image credit: Samantha Allyson

Fig. 11.7 Corals are a major building material of the >500 buildings that make up the historic village of Jezirat Al Hamra, Ras Al Khaimah, as well as various other historic buildings across the Emirates. The local coral construction trade seems to have peaked in the 1800s before being supplanted by concrete in the 1920s. Members of the Emirates Natural History Group have catalogued the diversity and abundance of these corals (right). Photographer: John Burt

Coral reefs had previously occurred in a discontinuous narrow band approximately 500–1000 m from shore in each of the Gulf Emirates, and new reefs are still occasionally being documented today (e.g. a recently described nearshore reef in Umm Al Quwain; Grizzle et al. 2016). Historically, corals from these reefs had served as a major source of building materials in a unique trade industry that originated in the 1400s and continued through the early twentieth century before being supplanted by concrete (King 1997; Hawker 2006; Petersen 2012). Historic sites such as the Qasr Al Hosn in Abu Dhabi, the Al Hisn fort in Sharjah, and the >500 buildings that made up the village of Jezirat Al Hamra in Ras Al Khaimah (Fig. 11.7) all incorporated corals into their walls (Lorimer 1908; Fox et al. 2006;

Petersen 2012), an ingenious solution to the lack of stone along the sandy coast of the early Emirates. Together, an estimated 45 km^2 of reef was historically estimated to have occurred in this nearshore strip from Dubai through the northern Emirates (Grizzle et al. 2016).

Unfortunately, coastal dredging and reclamation since the 1980s have decimated the once extensive reefs in Dubai and the Northern Emirates, and the large reefs once documented adjacent to Jebel Ali, the Sharjah corniche and Jezirat Al Hamra have all been lost (Riegl 1999; Goudie et al. 2000; Burt et al. 2008; Sheppard et al. 2010). Any remaining reefs in the northern Emirates should be recognized as vestiges of what were much more widespread ecosystems just 50 years ago (Fig. 11.8).

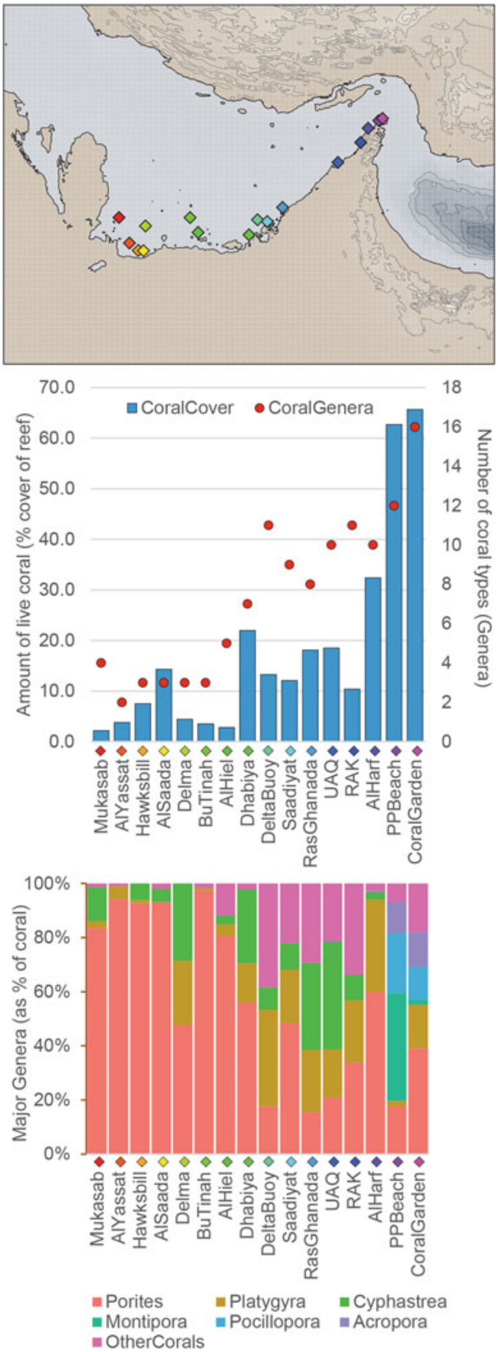
11.2.3 Corals of the Capital and Western Region

Nearshore coral reefs were quite extensive in the capital area and western region up until the 1970s (Fig. 11.9), and even today the most extensive reef areas in the UAE occur across Abu Dhabi (79.5 km^2, representing 60% of all coral reefs in the UAE) (Grizzle et al. 2016). Geologists supporting the nascent petroleum industry during the 1970s ‘oil boom’ have provided vivid descriptions and detailed aerial photographs of extensive coral reefs dominating the nearshore areas and tidal channels next to many of the familiar barrier islands surrounding the capital, including Saadiyat, Halat Al Bahraini, Dhabiya, Abu Al Abyad islands and in front of Abu Dhabi city itself (Evans et al. 1964; Kinsman 1964b; Kendall and Skipwith 1969; Murray 1970; Purser and Evans 1973). Descriptions of complex and extensive table coral reefs are common in the 1960s literature, with Kinsman (1964a) stating that, “. . .Trucial Coast reefs are composed dominantly of *Acropora* [table corals], even in very shoal areas which suffer maximum temperature changes”, while Evans et al. (1964) writes of the capital area that “. . .directly fronting the islands are coral reefs, predominantly of *Acropora* [table corals] with subordinate *Platygyra* [brain corals] and other massive corals. . . . The coral here is diffuse and occurs in patches, whereas on the steep walls of the ebb [tidal] channels the growth of the dominant coral, *Acropora*, is extremely prolific”.

Unfortunately, many of these once extensive reefs have been lost or heavily degraded as a result of channel dredging and land reclamation to support the early oil and port industries in the 1970s (Murray 1970; Carp 1976; Crisp 1976). Today the large nearshore reef that provided food to local communities on Abu Dhabi island for millennia sits under the footprint of the man-made Lulu Island and Mina Zayed, while navigation channel dredging led to complete loss of the table-coral (*Acropora*) dominated reefs that had fringed the shallow tidal areas around Reem and Mariyah Islands (Murray 1970).

Today, coral reefs do continue to exist in some nearshore locations in the Abu Dhabi emirate, with large reefs still occurring in front of Ras Ghanada, Saadiyat and Dhabiya (Burt et al. 2011; Grizzle et al. 2016), but the current coral communities are degraded relative to historic descriptions (e.g. the virtual extirpation of the *Acropora*

Fig. 11.8 Changes in coral communities across the Arabian Gulf coast of the UAE and Oman as a result of a gradient of environmental conditions. (**a**) Map of survey sites. (**b**) Coral abundance (bars) and diversity (dots) are highest near the entrance of the Gulf and decline towards the west. (**c**) Broad shifts in coral composition from west (where *Porites* dominates) to east (where a number of other groups are common, including *Acropora* and other sensitive groups not seen at western sites). Data are from 2019 surveys; all site names are color-coded under charts. Source: John Burt, unpubl. data



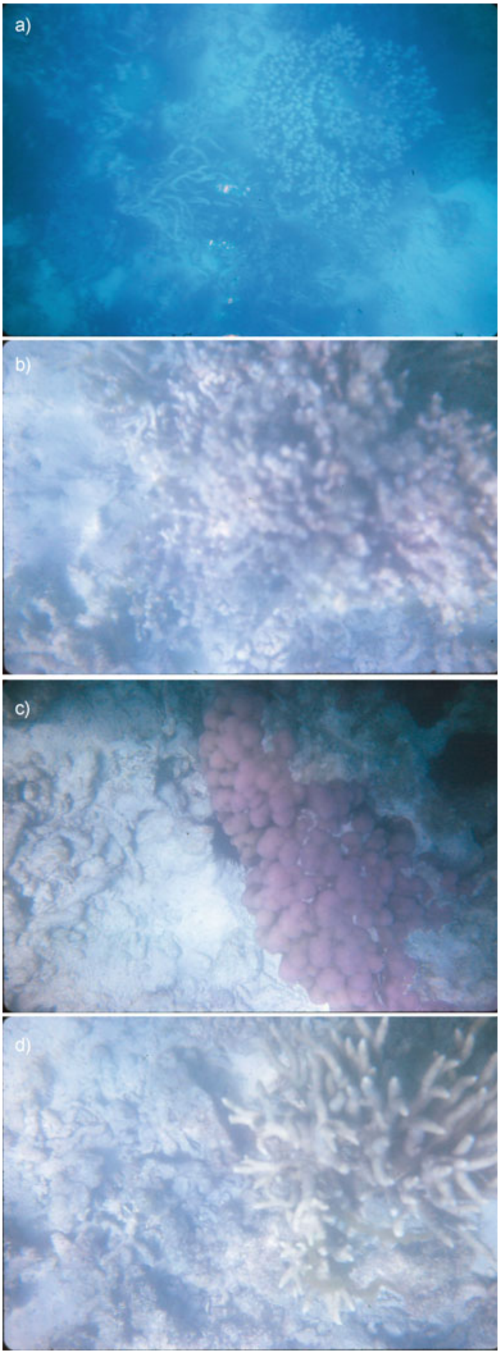


Fig. 11.9 Corals photographed over a half-century ago in 1965 in Abu Dhabi. (**a**) Table coral (*Acropora*) and finger coral (*Porites harrisoni*) in the Abu Dhabi lagoon, (**b**) dead coral (*P. harrisoni*) encrusted with turf algae and (**c**) live *Porites* mound coral (likely *P. lobata*) in the Abu Dhabi lagoon, and (**d**) live table coral (*Acropora*) on the reef in front of Abu Dhabi city. Photographer: John Murray

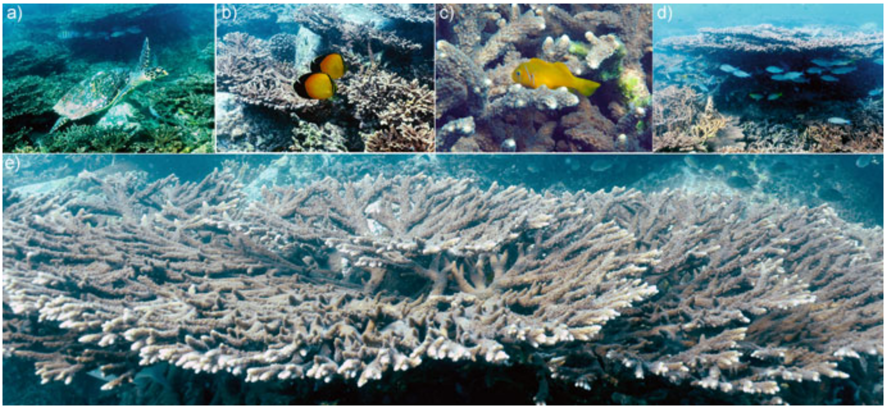


Fig. 11.10 Table corals (*Acropora* spp.) have historically dominated reefs across the UAE. They are an important reef building coral that provides (**a**) foraging habitat for the critically endangered hawksbill turtle (*Eretmochelys imbricate*), (**b**) a food source for coral-feeding fish such as the Arabian butterflyfish (*Chaetodon melapterus*), (**c**) obligate habitat for table coral-dwelling organisms such as the lemon goby (*Gobiodon citrinus*), and (**d**) shelter from predators for many other species. (**e**) Table corals such as the regional endemic *Acropora downingi* are common to the East Coast of the UAE and offshore islands such as Sir Bu Nair, but have largely been lost on coastal reefs along the Arabian Gulf coast of the Emirates due to marine heat waves. Photographer: John Burt

table corals that had once been common (see Box 11.1) (Burt et al. 2011). Continuing pressure from coastal urbanization and industrialization represent a threat to their long-term persistence (Burt 2014).

Box 11.1 Table Corals (*Acropora*) as Bellwethers of Environmental Change

When the general public sees videos or photographs of coral reefs anywhere in the world, they are most likely looking at images of a shoal of bright and colorful reef fishes surrounding a stand of table corals—a group of corals belonging to the genus *Acropora* (Fig. 11.10). At least 12 species of table corals have been described for the UAE, although taxonomic uncertainty remains (Riegl et al. 2012), which includes the regionally endemic species *Acropora downingi* that once dominated reefs across the southern Gulf (Evans et al. 1964). Table corals represent one of the primary reef-building corals in the Emirates, with their long horizontal branches fusing into 'tables' that can reach over 3 m in diameter, with the fastest growth rates of any corals in the Emirates, estimated at 10 cm per year (Riegl 2002).

Table corals provide considerable three-dimensional complexity that support a diverse array of fishes using the colonies as shelter from predators, or even as a home (e.g. the coral-dwelling citron goby); they also provide shade

(continued)

Box 11.1 (continued)
to an understory of sub-dominant species such as brain and mound corals that are typically found in deeper low-light environments (Riegl 1999,2002).

Unfortunately table corals are highly sensitive to environmental stress, and are widely known to be among the first corals to suffer under pressures such as sedimentation, extreme temperatures and disease, which can decimate local populations (Loya et al. 2001; Dana and Margaret 2005; Burt et al. 2011; Clark et al. 2017; Riegl et al. 2018). If conditions remain benign for a period of 10–15 years after a mass die-off, their rapid growth rates can provide a capacity to recover (Burt et al. 2008; Gilmour et al. 2013). However, if recovery is 'reset' by more frequent disturbances, for example by recurrent bleaching events associated with marine heat waves that are becoming all-too-common under climate change, then the stock of remaining adults on reefs can crash or be so physiologically impaired that it affects reproductive output, resulting in loss of larvae to help replenish these reefs (Howells et al. 2016a; Burt and Bauman 2019). If this happens at regional scales, as it has in the Gulf in recent decades (Bauman et al. 2014; Bento et al. 2017; Pratchett et al. 2017), then this can result in a region-wide collapse of these species, with little hope for their return without active restoration interventions.

11.2.4 Offshore Reefs of the Southern Gulf

The southern basin of the Gulf is the only area of the UAE where substantial offshore coral reefs occur. These reefs mainly surround islands and shoals in Abu Dhabi waters, although the most diverse and extensive reefs occur at Sir Bu Nair island, which is governed by Sharjah but geographically sits 70 km offshore from the Abu Dhabi-Dubai border towards the center of the Gulf. The prevalence of offshore reefs in the southern basin is due to the shallow, low sloping bathymetry in the area which keeps much of the bottom in the well-lit photic zone, as well as the presence of large hard-bottomed shoals and offshore islands that occur where salt domes push up rocky substrate through the largely sand bottom (Riegl and Purkis 2012). This combination of features provides corals with hard substrate suitable for growth at a depth where sunlight can readily penetrate, and the offshore nature of these locations protects these reefs from the influence of urban-related pressures that typically affect nearshore areas (e.g. dredging, nutrient pollution; Riegl and Purkis 2012; Aeby et al. 2020). The presence of deeper waters surrounding many of the offshore islands has also been suggested to buffer these reefs during summer, as tidal currents push cool, deeper waters up into the shallows where corals occur, providing temporary respite from summer heat (Cavalcante et al. 2020; Bento et al. 2021).

Extensive fringing reefs occur adjacent to islands such as Sir Bu Nair, Delma and Arzanah (Burt et al. 2011; Riegl and Purkis 2012; Bento et al. 2021), and were known to have occurred at Sir Bani Yas island prior to widespread dredging and

Fig. 11.11 The most diverse coral reefs on the UAE's Arabian Gulf coast occur at Sir Bu Nair, an island situated ca. 70 km offshore from the mainland. The deeper surrounding water is thought to buffer coral communities from the prolonged extreme temperatures that affect inshore reefs, allowing existence of sprawling stands of table corals (*Acropora downingi*, left) and environmentally sensitive species such as the smooth cauliflower coral (*Stylophora pistillata*, right), corals that are now functionally extinct on nearshore reefs. Photographer: John Burt

reclamation in the 1980s (Purser and Evans 1973). Sharjah's Sir Bu Nair island, lying farthest out from land and surrounded by deep (>30 m) waters, today represents the best developed and most extensive coral reef ecosystem in the UAE's Arabian Gulf waters (Fig. 11.11), in part because of its isolation but also because of its strictly enforced 'no go' protected area supported by the presence of military infrastructure on the island. Reefs here are dominated by table corals (*Acropora*) which makes up over half of all coral, with large stands typically occurring in shallow (<6 m) depths to the northwest and south of the island; with increasing depth these shallow-water specialists become less common and the community grades to one dominated by brain corals and mound corals (Merulinids and Poritids) that are more resilient to lower light (Bejarano et al. 2022). The coral reefs of Sir Bu Nair are considered to be extremely important as one of the only remaining source of table coral (*Acropora*) larvae that have potential to colonize and replenish the nearshore reefs along the Gulf coast of the UAE and, as such, their continued conservation is considered a high priority for the nation (Cavalcante et al. 2016; Riegl et al. 2018; Bento et al. 2021).

11.3 UAE Coral Reefs: A Globally Important Scientific Asset

Coral reefs are the most biodiverse ecosystem in the Emirates, and are also highly economically valuable, supporting fisheries productivity that is comparable to the most productive coral reefs on earth (Grandcourt et al. 2011). In addition to these local benefits, coral reefs of the UAE are also increasingly regarded as an important asset for global science, particularly around the implications of future climate change across the tropics (Burt et al. 2014, 2020).

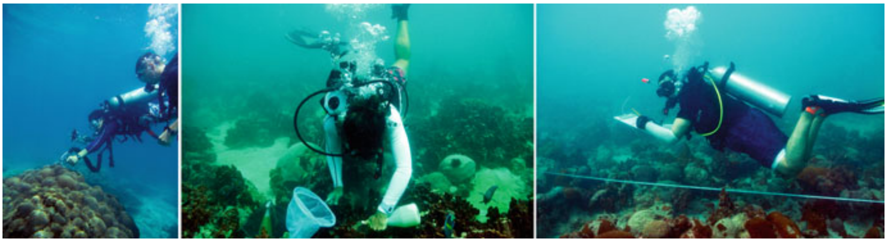


Fig. 11.12 Research on the Emirates' coral reefs has grown dramatically in the past decade as scientists are increasingly using reefs in the Arabian Gulf—the world's hottest sea—to understand how corals and other organisms cope with and respond to extreme temperatures. Photographer: John Burt

Each summer the Arabian Gulf becomes the world's hottest sea, and this is particularly true of the southern Gulf basin along the UAE's Abu Dhabi coast where sea temperatures regularly exceed 36 °C (Coles 2003; Riegl and Purkis 2012). Such temperatures are upwards of 5 °C warmer than temperatures that would be lethal to corals in tropical regions such as the Caribbean and the Great Barrier Reef (Riegl et al. 2011), and represent conditions that are predicted to occur across much of the tropics by the end of the century as a result of climate change (Burt et al. 2020). As such, there has been dramatic growth of research on the UAE's coral reefs in the past decade as scientists race to understand how local corals are able to cope with such extreme temperatures, and what the implications of these responses are for corals elsewhere in the world (Fig. 11.12) (Burt 2013; Vaughan and Burt 2016).

While the extreme summer temperatures in the southern Gulf have drawn the most attention, reefs here are also exposed to extreme cold in winter (<18 °C), high salinity (>44 PSU), high turbidity, and recurrent low oxygen exposure, each of which represent major stressors for coral (Coles 2003; Bauman et al. 2012; de Verneil et al. 2021). These extreme conditions do have costs for corals, as only a hardy subset of regional species is capable of surviving in the southern Gulf, where coral diversity is approximately half of that occurring in the Gulf of Oman and <10% of the diversity of the wider Indo-Pacific (Coles 2003; Bauman et al. 2012; Bento et al. 2016; Claereboudt 2019; Bouwmeester et al. 2021). Yet those species that are able to survive can be highly abundant in the southern Gulf, with dense coral communities often having coverage of live coral that rivals reefs of the east coast (Sheppard et al. 2000; Bento et al. 2016; Grizzle et al. 2016; Riegl et al. 2018).

Recent research has shown that a number of different mechanisms permit coral survival under the extreme environmental stress of the southern Gulf. Population genetics analyses on a locally abundant brain coral (*Platygyra daedalea*) has shown that corals rapidly colonized the Gulf following the flooding of the basin after the last glacial period, and in the final stages corals had colonized the modern UAE's Gulf coast approximately 8000–6000 years ago (Smith et al. 2022). In the intervening millennia, the environment has acted a 'filter' for natural selection, resulting a preponderance of genes related to temperature and stress tolerance being fixed in the genome of local populations, such that they are now genetically distinct from populations outside of the Gulf (Smith et al. 2022). In addition to the coral animal itself, the UAE's Gulf corals also host a unique species of thermally tolerant symbiotic algae (*Cladocopium thermophilum*) that dominates virtually all corals in the southern Gulf and is functionally absent in corals east of Ras Al Khaimah where conditions are less extreme (Hume et al. 2013, 2016, 2018). This coral-algae association is even retained across extreme seasonal cycles of temperature and through severe bleaching events, suggesting that this symbiosis is critical for coral survival in the southern Gulf (Hume et al. 2015; Smith et al. 2017; Howells et al. 2020). Together, the unique genetic adaptations of Gulf corals and their symbionts support the highest thermal tolerance and bleaching thresholds known anywhere on earth (Riegl et al. 2011; Howells et al. 2016b).

11.4 Climate Change and the Future of Coral Reefs in the Emirates

Paradoxically, while the UAE is home to some of the most heat tolerant corals on earth, it may be one of the first nations to experience the functional loss of coral reefs as a result of climate change. This is because while these corals do have adaptations allowing them to exist in the most extreme temperatures known on earth, they already live very close to their physiological limits and, as a result, can be easily pushed across this threshold during bleaching events in unusually warm summers (Fig. 11.13) (Lincoln et al. 2021).

As a whole, the Gulf is warming at over twice the rate of the global oceans, and this is leading to the occurrence of more frequent and severe marine heat waves (Riegl et al. 2018; Lachkar et al. 2021). Historically, coral bleaching events were first reported for the UAE's Gulf reefs in the early 1980s, followed by severe back-to-back events in 1996 and 1998 which resulted in the loss of over 90% of corals from reefs in Abu Dhabi and Dubai (Fig. 11.14) (Riegl 1999, 2002). This was followed by more than a decade of benign temperatures, which allowed corals to recolonize degraded areas and coral coverage to return to mid-1990s levels in many locations by the late 2000s (Sheppard and Loughland 2002; Burt et al. 2008). Recurrent marine heat waves occurred again in 2010, 2011 and 2012, though temperatures were not as extreme as earlier and only a fifth of corals were estimated to have been lost following these three events (Riegl and Purkis 2015). Unfortunately, one of the most severe marine heat waves ever recorded in the Gulf occurred in 2017, when nearly three-quarters (73%) of corals were killed across the southern Gulf (Burt et al. 2019), with the summers of 2020 and 2021 also characterized by unusually extreme periods of elevated temperatures (data on coral losses during this period are still being developed). As a result, coral reefs of the UAE's Gulf coast are now heavily degraded both in terms of the amount of live coral, as well as in terms of the overall

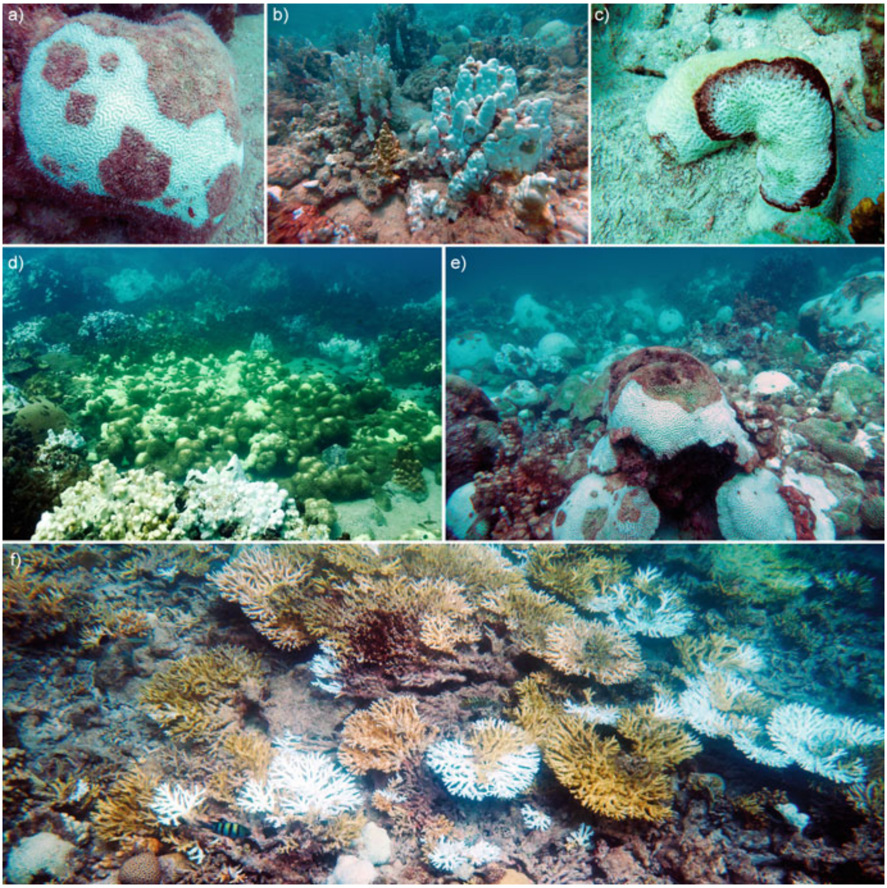


Fig. 11.13 Temperature-induced coral bleaching is occurring with increasing frequency as a result of climate change and has caused considerable loss of corals from UAE reefs in recent years. While colonies may survive bleaching for several days, partial colony mortality will start to occur after several days (**a**, **c**, **e**) with whole colonies dying off within a period of a week or 2 (**e**, top) unless temperatures abate. Bleached colonies of (**a**) *Platygyra daedalea* showing partial colony mortality, (**b**) *Porites* spp., fully bleached, and (**c**) *Coscinaraea monile* showing partial mortality with cyanobacterial overgrowth on the lesion edge, all from Dhabiya, August 2017. (**d**) A bleached cluster of *Goniopora* (center) surrounded by *Porites* at Martini Wall, Khor Fakkan, September 2021. (**e**) Saadiyat reef during mass bleaching in August 2017, which led to the loss of over 70% of corals from Abu Dhabi. (**f**) The large *Acropora* stands at Sir Bu Nair island had escaped the impacts of earlier bleaching events, but heavily bleached in summer 2021 due to a marine heat wave. Photographer: John Burt

community structure, with formerly-dominant table corals (*Acropora*) now largely extirpated from coastal reefs.

The coral reefs of the UAE's east coast and those offshore in the Gulf, such as Sir Bu Nair island, have historically managed to escape the impacts of earlier bleaching events, largely due to the presence of deep, cool water in the surrounding

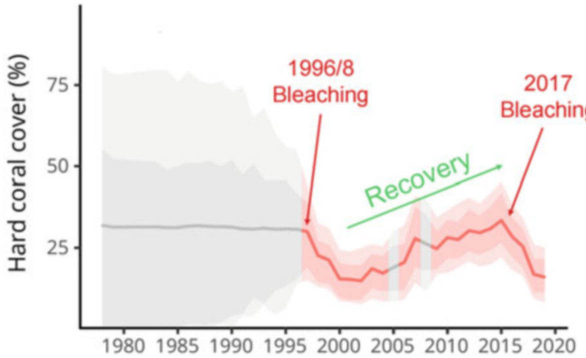


Fig. 11.14 Changes in the amount of live coral over time across the Arabian Gulf based on reef monitoring surveys. Lighter shades represent uncertainty (greater in the past when fewer surveys were performed) while the dark line represents the average; UAE reef surveys make up the majority of this dataset. Between 1995 and 2000 there was a loss of ca. 40% of coral as a result of the back-to-back severe bleaching events in 1996 and 1998. This was followed by 15 years of recovery where the amount of coral returned to pre-1996 levels. However, a severe bleaching event in 2017 again caused substantial coral loss. Whether reefs can again recover will be dependent on the frequency and magnitude of future bleaching events (modified from Burt et al. 2021b)

Fig. 11.15 Algae-covered dead coral framework shortly after bleaching-induced mortality. Although the corals in these images may appear intact, there is virtually no live coral in any of these photos. Instead, algae is overgrowing dead coral skeleton; in the coming year or two this framework will slowly break down (left to right: Martini Wall, Khor Fakkan, 2021; Saadiyat Reef, Abu Dhabi, 2018; Dhabiya Reef, Abu Dhabi, 2019). Photographer: John Burt

environment that buffered these reefs from extreme temperatures. This came to an end in the summer of 2021 when an extended period of low winds resulted in elevated temperatures, particularly at shallow depths. Surveys conducted at Shark Island in Khor Fakkan in early September 2021 showed near complete mortality of table corals down to ca. 6.5 m depth and severe bleaching of most coral species occurring at Martini Wall (Fig. 11.13d); surveys at Sir Bu Nair island several weeks later showed widespread bleaching of this last remaining stand of table corals for the UAE's Gulf waters, although mortality appeared to be less extreme than in Khor Fakkan (Fig. 11.13f). Analyses are currently underway to determine the extent of coral loss and shifts in species that may have occurred as a result of this event, but algal overgrowth has become much more common than in the past (Fig. 11.15).

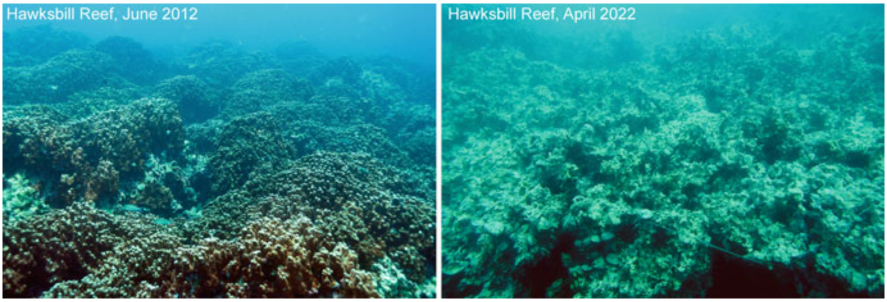


Fig. 11.16 A decade of change at Hawksbill Reef (western Abu Dhabi) between 2012 and 2022. This reef had among the highest abundance of coral in all of Abu Dhabi in 2010 surveys (60% coverage, mainly the finger coral *Porites harrisoni*) (Burt et al. 2011), but is now largely dead (<5% live coral coverage) as a result of recurrent bleaching events due to marine heat waves. Photographer: John Burt

The occurrence of these recent bleaching events across the Emirates represents a profound existential threat to the continued persistence of coral reef ecosystems for the nation (Fig. 11.16). The total amount of coral on most reefs in the UAE has declined by at least half and often over three-quarters since the late 2000s (Bento et al. 2016; Burt et al. 2019).

Recovery of the UAE's coral reefs will be contingent on two processes: vegetative growth and settlement of sexually produced larvae. While vegetative growth from surviving adults is possible, most coral species in the UAE are extremely slow growing (<1 cm/year), meaning that regrowth of pre-2010 coral coverage would take several decades without disturbance—an unlikely scenario given the frequency of recent marine heat waves (Howells et al. 2018; Burt et al. 2019). In addition, several sensitive groups such as table corals (*Acropora*) have been largely extirpated from most reefs (Riegl et al. 2018), meaning vegetative regrowth from surviving colonies will not be possible for these taxa. The news is not much better for the potential of sexually produced larvae to aid the recovery of the UAE's increasingly degraded reefs (Fig. 11.17). The substantial declines in coral abundance in recent years means that the standing stock of adults with reproductive potential has declined considerably and bleaching-induced stress has likely impaired fecundity for at least some species, reducing reef-level reproductive output (Howells et al. 2016a; Burt et al. 2019). Reefs further offshore or in surrounding nations have also been heavily impacted by bleaching events since 2017, suggesting that rescue from larvae produced further afield is also unlikely (Burt et al. 2021b). Recent surveys for recently-settled coral spat and juveniles bear this out, with studies reporting suppressed larval coral settlement after bleaching events (Burt and Bauman 2019), with extremely low levels of juvenile settlement overall compared with reefs in other regions (Bauman et al. 2014; Bento et al. 2017). Worryingly, formerly common coastal species such as table corals (*Acropora*) have all but disappeared from the juvenile communities on the Arabian Gulf coast of the UAE (Bauman et al. 2014; Burt and Bauman 2019), although they have continued to be observed on reefs in

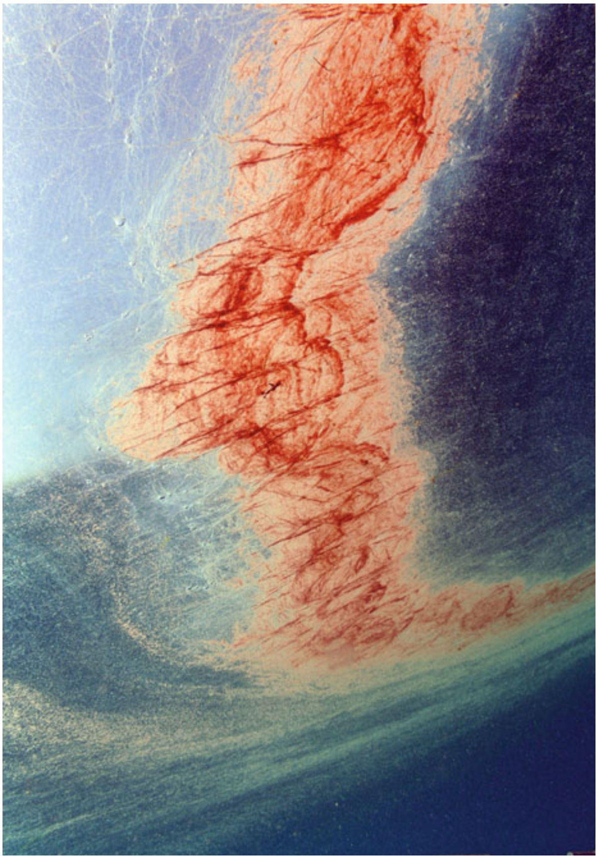


Fig. 11.17 A coral spawn slick floating above Ras Ghanada reef on 20 April, 2011, photographed from below by a diver. The production and dispersal of viable eggs is necessary to ensure the continued persistence of coral reefs in the UAE, but recent studies have demonstrated that egg production is impaired for several common coral species and settlement of new larvae is extremely impaired as a result of recurrent bleaching. Such observations cast doubts on the ability of these reefs to naturally recover from recent marine heat waves, suggesting that more active management intervention approaches are needed. Photographer: John Burt

Fujairah as well as the offshore island of Sir Bu Nair in the Gulf (Pratchett et al. 2017; Bento et al. 2021). Overall, these results suggest that we are witnessing a major transition of coral reef ecosystems in the UAE, particularly on nearshore reefs in the Gulf, where coral communities are characterized by much lower abundance and diversity of corals than in history, with limited capacity for successful natural recovery.

11.5 Improving the Future Trajectory of UAE Reefs

While recent bleaching-induced impacts suggest that the important coral reef ecosystems that line the Emirates' coast are in a vulnerable state, there are actions that can be taken to reverse this trajectory and enhance their recovery going forward.

The UAE has taken increasing steps to conserve various marine ecosystems, including reefs, through the establishment of Marine Protected Areas (MPAs), with

MPAs now covering 12% of the nation's coastal and marine zones (5 in the Sea of Oman and 10 on the Arabian Gulf coast) and two-thirds of this area established in the short period since 2010 (IUCN 2022). In addition, the establishment of new MPAs is being supported by an evolving understanding of the location and nature of marine ecosystems through recent marine habitat mapping efforts (Grizzle et al. 2016; Lamine et al. 2020; Mateos-Molina et al. 2020), allowing identification of gaps in current protection so that future MPAs could prioritize conservation of key reefs (Mateos-Molina et al. 2021). These efforts are laudable and should continue, but should also be enhanced through the development of a national coral reef monitoring program to support such initiatives. While a well-established long-term reef monitoring program exists in Abu Dhabi (e.g. Burt et al. 2011, 2019), only periodic 'snapshot' surveys have occurred in other emirates (e.g. Bento et al. 2016; Grizzle et al. 2016). It is impossible to manage a system which is not understood, nor is it possible to assess the efficacy of any management efforts (e.g. MPA establishment) without detailed monitoring programs. This clearly represents a 'low hanging fruit' that would aid understanding of trends in coral community health, the impact of any intervention measures, and the identification of which areas are most essential for management and conservation efforts (be it based on biodiversity, vulnerability or other factors) at national scales. Such a monitoring program would strongly aid the development of ecosystem-based management and marine spatial planning approaches that are increasingly being promoted in the Emirates and surrounding nations (Fanning et al. 2021; Burt et al. 2017; Ben-Romdhane et al. 2020; Mateos-Molina et al. 2021), and should be considered a priority for adoption.

Reef management and conservation interventions must also be accompanied by active reef restoration efforts. Given the worrying state of larval settlement and the degraded state of many reefs in the Emirates, natural recovery is unlikely to occur in the near-term (Burt et al. 2019). Reef restoration sciences have improved markedly in the past two decades (Bayraktarov et al. 2019; Boström-Einarsson et al. 2020), and development of new approaches such as aquaculture-based nurseries, selection and propagation of thermally-tolerant genotypes, and implementation of techniques to utilize sexually-produced larval out-plants (as opposed to fragments derived from vulnerable and scarce wild colonies) all offer novel approaches that could showcase the UAE as a leader in the reef restoration field on a global stage. The above approaches will not be able to ameliorate the temperature trends resulting from climate change, but they will allow a program to focus on those species and individual genotypes with the highest likelihood of success, particularly when combined with a monitoring program that helps identify those areas where such restoration efforts are likely to have the most success. It should be noted that artificial reefs are not surrogates for natural reefs and often serve to exacerbate the issues they are often designed to resolve (Bartholomew et al. 2022; Burt et al. 2021a), and therefore should not serve as part of the reef management toolkit for the Emirates.

In addition to having local value, the coral reefs of the UAE also represent an important asset for coral reefs on a global stage (Burt et al. 2014, 2020). The local prevalence of corals pre-adapted to temperatures anticipated to occur across most of the tropics by the end of the century cannot be overstated. Currently researchers across the globe are racing to enhance the thermal tolerance of corals through 'assisted evolution' approaches, where several generations of corals are subject to experimentally induced temperature stress with the goal of enhancing the thermal tolerance of later offspring (van Oppen et al. 2015; Anthony et al. 2017). An alternative approach that side-steps the need for time consuming multi-generational experiments would be through the adoption of cross-breeding approaches that utilize the standing genetic stock of coral populations already adapted to extreme thermal stress such as those in the UAE. Recent work in the Emirates has shown that cross-breeding of heat-tolerant Gulf corals with thermally naïve coral populations in the Indian Ocean resulted in the cross-bred offspring having survival at extreme temperatures that was comparable to pure-bred Gulf corals and that was up to 84% higher than pure-bred offspring from thermally-naïve populations (Howells et al. 2021). These findings highlight the tremendous importance of UAE reefs as a scientific asset and as a resource that could help mitigate against climate change in other regions. The conservation of this unique natural asset should be given high priority.

11.6 Conclusions

Coral reefs represent one of the most important natural assets of the United Arab Emirates, from the perspective of biological diversity, economic value and for their value to global scientific research. While coral reefs are a relatively young ecosystem to a large part of the nation along the Arabian Gulf coast, these corals have experienced a 'trial by fire' that has winnowed out weaker species and individuals, leaving a remarkably robust and thermally tolerance assemblage lining the shores. While the reefs of the east coast and offshore in the Gulf may not exhibit the remarkable stress tolerance of those along the western shores, they contain some of the most diverse and relatively pristine coral communities in the nation. Despite their importance, coral reefs across the Emirates have undergone substantial decline in recent decades, and the reefs today represent just a vestige of what occurred in recent memory. Whether these amazing ecosystems continue on the path they are currently on, or take a new trajectory to recovery towards their former grandeur will largely be depending on UAE government institutions taking bold steps to restore and conserve these ecosystems for the benefit of its future citizenry.

11.7 Recommended Readings

Additional information on the coral reefs of the UAE may be found in Vaughan et al. (2019), Burt et al. (2014) and Riegl and Purkis (2012).

References

Aeby GS, Howells E, Work T, Abrego D, Williams GJ, Wedding LM, Caldwell JM, Moritsch M, Burt JA (2020) Localized outbreaks of coral disease on Arabian reefs are linked to extreme temperatures and environmental stressors. Coral Reefs 39:829–846. https://doi.org/10.1007/s00338-020-01928-4

Allen Coral Atlas (2022) Imagery, maps and monitoring of the world's tropical coral reefs. https://doi.org/10.5281/zenodo.3833242

Anthony K, Bay LK, Costanza R, Firn J, Gunn J, Harrison P, Heyward A, Lundgren P, Mead D, Moore T, Mumby PJ, van Oppen MJH, Robertson J, Runge MC, Suggett DJ, Schaffelke B, Wachenfeld D, Walshe T (2017) New interventions are needed to save coral reefs. Nat Ecol Evol 1:1420–1422. https://doi.org/10.1038/s41559-017-0313-5

Bartholomew A, Burt JA, Firth LB (2022) Artificial reefs in the Arabian Gulf: benefits, challenges and recommendations for policy-makers. Reg Stud Mar Sci:1–23. https://doi.org/10.1016/j.rsma.2022.102723

Bauman AG, Burt JA, Feary DA, Marquis E, Usseglio P (2010) Tropical harmful algal blooms: an emerging threat to coral reef communities? Mar Pollut Bull 60:2117–2122

Bauman A, Feary D, Heron S, Pratchett MS, Burt J (2012) Multiple environmental factors influence the spatial distribution and structure of reef communities in the northeastern Arabian Peninsula. Mar Pollut Bull 72:302–312

Bauman A, Baird A, Burt J, Pratchett MS, Feary D (2014) Patterns of coral recruitment in an extreme environment: the southern Persian Gulf (Dubai, United Arab Emirates). Mar Ecol Prog Ser 499:115–126

Bayraktarov E, Stewart-Sinclair PJ, Brisbane S, Boström-Einarsson L, Saunders MI, Lovelock CE, Possingham HP, Mumby PJ, Wilson KA (2019) Motivations, success, and cost of coral reef restoration. Restor Ecol 27:981–991. https://doi.org/10.1111/rec.12977

Bejarano I, Orenes-Salazar V, Bento R, García-Charton JA, Mateos-Molina D (2022) Coral reefs at Sir Bu Nair Island: An offshore refuge of Acropora in the southern Arabian Gulf. Mar Pollut Bull 178:113570. https://doi.org/10.1016/j.marpolbul.2022.113570

Ben-Romdhane H, Jabado RW, Grandcourt EM, Perry RJO, Al Blooshi AY, Marpu PR, Ouarda TBMJ, Ghedira H (2020) Coral reefs of Abu Dhabi, United Arab Emirates: analysis of management approaches in light of international best practices and a changing climate. Front Mar Sci 7. https://doi.org/10.3389/fmars.2020.00541

Bento R, Hoey AS, Bauman AG, Feary DA, Burt JA (2016) The implications of recurrent disturbances within the world's hottest coral reef. Mar Pollut Bull 105:466–472. https://doi.org/10.1016/j.marpolbul.2015.10.006

Bento R, Feary DA, Hoey AS, Burt JA (2017) Settlement patterns of corals and other benthos on reefs with divergent environments and disturbances histories around the northeastern Arabian peninsula. Front Mar Sci 4:1–12. https://doi.org/10.3389/fmars.2017.00305

Bento R, Cavalcante G, Mateos-Molina D, Riegl B, Bejarano I (2021) Recruitment and larval connectivity of a remnant Acropora community in the Arabian Gulf, United Arab Emirates. Coral Reefs. https://doi.org/10.1007/s00338-021-02187-7

Boström-Einarsson L, Babcock RC, Bayraktarov E, Ceccarelli D, Cook N, Ferse SCA, Hancock B, Harrison P, Hein M, Shaver E, Smith A, Suggett D, Stewart-Sinclair PJ, Vardi T, McLeod IM (2020) Coral restoration—a systematic review of current methods, successes, failures and future directions. PLoS One 15:e0226631. https://doi.org/10.1371/journal.pone.0226631

Bouwmeester J, Riera R, Range P, Ben-Hamadou R, Samimi-Namin K, Burt JA (2021) Coral and reef fish communities in the thermally extreme Persian/Arabian Gulf: insights into potential climate change effects. In: Rossi S, Bramanti L (eds) Perspectives on the marine animal forests of the world. Springer International Publishing, Cham, pp 63–86. https://doi.org/10.1007/978-3-030-57054-5_3

Bouwmeester J, Ben-Hamadou R, Range P, Al Jamali F, Burt JA (2022) Spatial patterns of reef fishes and corals in the thermally extreme waters of Qatar. Front Mar Sci 9. https://doi.org/10.3389/fmars.2022.989841

Briggs JC, Bowen BW (2012) A realignment of marine biogeographic provinces with particular reference to fish distributions. J Biogeogr 39:12–30. https://doi.org/10.1111/j.1365-2699.2011.02613.x

Burke L, Reytar K, Spalding M, Perry A (2011) Reefs at risk revisited. World Resources Institute, Washington, DC

Burt J (2013) The growth of coral reef science in the Gulf: A historical perspective. Mar Pollut Bull 72:289–301

Burt J (2014) The environmental costs of coastal urbanization in the Arabian Gulf. City Anal Urban Trends Cult Theory Policy Action 18:760–770. https://doi.org/10.1080/13604813.2014.962889

Burt JA, Bauman AG (2019) Suppressed coral settlement following mass bleaching in the southern Persian/Arabian Gulf. Aquat Ecosyst Health Manag 23(2):166–175. https://doi.org/10.1080/14634988.2019.1676024

Burt J, Bartholomew A, Usseglio P (2008) Recovery of corals a decade after bleaching in Dubai, United Arab Emirates. Mar Biol 154:27–36

Burt J, Al-Harthi S, Al-Cibahy A (2011) Long-term impacts of bleaching events on the world's warmest reefs. Mar Environ Res 72:225–229

Burt J, van Lavieren H, Feary D (2014) Persian Gulf reefs: an important asset for climate science in urgent need of protection. Ocean Challenge 20:49–56

Burt J, Coles S, van Lavieren H, Taylor O, Looker E, Samimi-Namin K (2016) Oman's coral reefs: A unique ecosystem challenged by natural and man-related stresses and in need of conservation. Mar Pollut Bull 105:498–506. https://doi.org/10.1016/j.marpolbul.2015.11.010

Burt JA, Ben-Hamadou R, Abdel-Moati MAR, Fanning L, Kaitibie S, Al-Jamali F, Range P, Saeed S, Warren CS (2017) Improving management of future coastal development in Qatar through ecosystem-based management approaches. Ocean Coast Manag 148:171–181. https://doi.org/10.1016/j.ocecoaman.2017.08.006

Burt J, Paparella F, Al-Mansoori N, Al-Mansoori A, Al-Jailani H (2019) Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. Coral Reefs 38:567–589. https://doi.org/10.1007/s00338-019-01767-y

Burt J, Camp E, Enochs IC, Johansen JL, Morgan KM, Riegl B, Hoey AS (2020) Insights from extreme coral reefs in a changing world. Coral Reefs 39:495–507. https://doi.org/10.1007/s00338-020-01966-y

Burt J, Bartholomew A, Firth L (2021a) Policy and management considerations for artificial reefs in the Arabian Gulf. Sheikh Saud bin Saqr Al Qasimi Found Policy Res Policy Pap 51:1–31. https://doi.org/10.13140/RG.2.2.25898.49605

Burt J, Range P, Claereboudt M, Al-Mealla R, Salimi P, Salimi M, Ben-Hamadou R, Bolouki M, Bouwmeester J, Taylor O, Wilson S (2021b) Chapter 4. Status and trends of coral reefs of the ROPME Sea Area. In: Souter D, Planes S, Wicquart J, Logan M, Obura D, Staub F (eds) Status of coral reefs of the world: 2020. ICRI-GCRMN, Lausanne, pp 1–13

Carp E (1976) United Arab Emirates: report of a survey of marine habitats carried out during 3–-15 February 1975 promotion of the establishment of marine parks and reserves in the Northern Indian Ocean, including the Red Sea and Persian Gulf: papers and proceedings of the regional meeting held at Tehran, Iran, 6–10 March 1975. IUCN, Gland, pp 107–114

Carpenter K (1997) The corals and coral reef fishes of Kuwait. Kuwait Institute for Scientific Research, Kuwait

Cavalcante GH, Feary DA, Burt JA (2016) The influence of extreme winds on coastal oceanography and its implications for coral population connectivity in the southern Arabian Gulf. Mar Pollut Bull 105:489–497. https://doi.org/10.1016/j.marpolbul.2015.10.031

Cavalcante G, Vieira F, Mortensen J, Ben-Hamadou R, Range P, Goergen E, Campos E, Riegl B (2020) Biophysical model of coral population connectivity in the Arabian/Persian Gulf. Adv Mar Biol 87(1):193–221. Academic. https://doi.org/10.1016/bs.amb.2020.07.001

Claereboudt MR (2019) Chapter 2—Oman. In: Sheppard C (ed) World seas: an environmental evaluation, 2nd edn. Academic, London, pp 25–47. https://doi.org/10.1016/B978-0-08-100853-9.00002-6

Clark TR, Roff G, Zhao J-x, Feng Y-x, Done TJ, McCook LJ, Pandolfi JM (2017) U-Th dating reveals regional-scale decline of branching *Acropora* corals on the Great Barrier Reef over the past century. PNAS 114:10350–10355. https://doi.org/10.1073/pnas.1705351114

Coles S (2003) Coral species diversity and environmental factors in the Arabian Gulf and the Gulf of Oman: a comparison to the Indo-Pacific region. Atoll Res Bull 507:1–19

Costanza R, de Groot R, Sutton P, van der Ploeg S, Anderson SJ, Kubiszewski I, Farber S, Turner RK (2014) Changes in the global value of ecosystem services. Global Environ Change 26:152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002

Crisp DJ (1976) Prospects of marine science in the Gulf area—the background paper Marine sciences in the Gulf area: UNESCO Technical Papers in Marine Science 26. UNESCO Division of Marine Science, Paris, pp 19–38

Dana EW, Margaret WM (2005) Coral disease outbreak: pattern, prevalence and transmission in Acropora cervicornis. Mar Ecol Prog Ser 301:119–128

de Groot R, Brander L, van der Ploeg S, Costanza R, Bernard F, Braat L, Christie M, Crossman N, Ghermandi A, Hein L, Hussain S, Kumar P, McVittie A, Portela R, Rodriguez LC, ten Brink P, van Beukering P (2012) Global estimates of the value of ecosystems and their services in monetary units. Ecosyst Serv 1:50–61. https://doi.org/10.1016/j.ecoser.2012.07.005

de Verneil A, Burt JA, Mitchell M, Paparella F (2021) Summer oxygen dynamics on a southern Arabian Gulf coral reef. Front Mar Sci 8:1676. https://doi.org/10.3389/fmars.2021.781428

Evans G, Kinsman DJJ, Shearman DJ (1964) A reconnaissance survey of the environment of recent carbonate sedimentation along the trucial coast, Persian Gulf. In: van Straaten LMJU (ed) Developments in sedimentology. Elsevier, Amsterdam, pp 129–135. https://doi.org/10.1016/S0070-4571(08)70477-1

Fanning LM, Al-Naimi MN, Range P, Ali A-SM, Bouwmeester J, Al-Jamali F, Burt JA, Ben-Hamadou R (2021) Applying the ecosystem services - EBM framework to sustainably manage Qatar's coral reefs and seagrass beds. Ocean Coast Manag 205:1–16. https://doi.org/10.1016/j.ocecoaman.2021.105566

Foster K, Foster G, Tourenq C, Shuriqi M (2008) Spatial and temporal recovery patterns of coral reefs within the Gulf of Oman (United Arab Emirates) following the 2007 cyclone disturbance. In: Proceedings of the 11th international coral reef symposium, 7–11 July 2008, Ft Lauderdale, FL, pp 731–734

Foster K, Foster G, Tourenq C, Shuriqi M (2011) Shifts in coral community structures following cyclone and red tide disturbances within the Gulf of Oman (United Arab Emirates). Mar Biol 158:955–968

Fox JW, Mourtada-Sabbah N, al-Mutawa M (2006) Heritage revivalism in Sharjah (Chapter 15). In: Globalization and the Gulf. Routledge, Oxon, UK, pp 266–287

Fritz HM, Blount CD, Albusaidi FB, Al-Harthy AHM (2010) Cyclone Gonu storm surge in Oman. Estuarine Coast Shelf Sci 86:102–106

Gilmour JP, Smith LD, Heyward AJ, Baird AH, Pratchett MS (2013) Recovery of an isolated coral reef system following severe disturbance. Science 340:69–71. https://doi.org/10.1126/science.1232310

Goudie AS, Parker AG, Al-Farraj A (2000) Coastal change in Ras Al Khaimah (United Arab Emirates): a cartographic analysis. Geograp J 166:14–25. https://doi.org/10.1111/j.1475-4959.2000.tb00003.x

Grandcourt EM, Al-Cibahy A, Al-Harthi S, Bugla I (2011) The abundance, status and bio-economic production potential of coral reef fisheries resources in Abu Dhabi (technical report for project 02-20-0002-11 & 02-21-0006-11). Environment Agency – Abu Dhabi, Abu Dhabi, UAE

Grizzle RE, Ward KM, AlShihi RMS, Burt JA (2016) Current status of coral reefs in the United Arab Emirates: Distribution, extent, and community structure with implications for management. Mar Pollut Bull 105:515–523. https://doi.org/10.1016/j.marpolbul.2015.10.005

Hawker RW (2006) Tribe, house style, and the town layout of Jazirat al-Hamra, Ras al-Khaimah, UAE. Proc Semin Arabian Stud 36:189–198

Hoegh-Guldberg O, Poloczanska ES, Skirving W, Dove S (2017) Coral reef ecosystems under climate change and ocean acidification. Front Mar Sci 4. https://doi.org/10.3389/fmars.2017.00158

Howells E, Remi N, Bauman AG, Mustafa Y, Watkins KD, Burt JA (2016a) Species-specific trends in the reproductive output of corals across environmental gradients and bleaching histories. Mar Pollut Bull 105:532–539. https://doi.org/10.1016/j.marpolbul.2015.11.034

Howells EJ, Abrego D, Meyer E, Kirk NL, Burt JA (2016b) Host adaptation and unexpected symbiont partners enable reef-building corals to tolerate extreme temperatures. Glob Change Biol 22:2702–2714. https://doi.org/10.1111/gcb.13250

Howells EJ, Dunshea G, McParland D, Vaughan GO, Heron SF, Pratchett MS, Burt JA, Bauman AG (2018) Species-specific coral calcification responses to the extreme environment of the southern Persian Gulf. Front Mar Sci 5:1–13. https://doi.org/10.3389/fmars.2018.00056

Howells EJ, Bauman AG, Vaughan GO, Hume BCC, Voolstra CR, Burt JA (2020) Corals in the hottest reefs in the world exhibit symbiont fidelity not flexibility. Mol Ecol 29:899–911. https://doi.org/10.1111/mec.15372

Howells EJ, Abrego D, Liew YJ, Burt JA, Meyer E, Aranda M (2021) Enhancing the heat tolerance of reef-building corals to future warming. Sci Adv 7:eabg6070. https://doi.org/10.1126/sciadv.abg6070

Hume B, D'Angelo C, Burt J, Baker AC, Riegl B, Wiedenmann J (2013) Corals from the Persian/Arabian Gulf as models for thermotolerant reef-builders: Prevalence of clade C3 *Symbiodinium*, host fluorescence and ex situ temperature tolerance. Mar Pollut Bull 72:313–322. https://doi.org/10.1016/j.marpolbul.2012.11.032

Hume B, D'Angelo C, Smith E, Stevens J, Burt J, Wiedenmann J (2015) *Symbiodinium thermophilum* sp. nov., a thermotolerant symbiotic alga prevalent in corals of the world's hottest sea, the Persian / Arabian Gulf. Sci Rep 5:1–8

Hume BCC, Voolstra CR, Arif C, D'Angelo C, Burt JA, Eyal G, Loya Y, Wiedenmann J (2016) Ancestral genetic diversity associated with the rapid spread of stress-tolerant coral symbionts in response to Holocene climate change. PNAS 113:4416–4421. https://doi.org/10.1073/pnas.1601910113

Hume BCC, D'Angelo C, Burt JA, Wiedenmann J (2018) Fine-scale biogeographical boundary delineation and sub-population resolution in the *Symbiodinium thermophilum* coral symbiont group from the Persian/Arabian Gulf and Gulf of Oman. Front Mar Sci 5. https://doi.org/10.3389/fmars.2018.00138

IUCN U-Wa (2022) Protected planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM). UNEP-WCMC, Cambridge, UK

Kendall C, Skipwith P (1969) Geomorphology of a recent shallow-water carbonate province: Khor Al Bazam, Trucial Coast, Southwest Persian Gulf. GSA Bull 80:865–892. https://doi.org/10.1130/0016-7606(1969)80[865:Goarsc]2.0.Co;2

King G (1997) The history of the UAE: The eve of Islam of the Islamic period perspectives on the United Arab Emirates. Trident Press, London, pp 74–94

Kinsman DJJ (1964a) Reef coral tolerance of high temperatures and salinities. Nature 202:1280–1282

Kinsman DJJ (1964b) The recent carbonate sediments near Halat El Bahrani, trucial coast, Persian Gulf. In: van Straaten LMJU (ed) Developments in sedimentology. Elsevier, Amsterdam, pp 185–192. https://doi.org/10.1016/S0070-4571(08)70485-0

Lachkar Z, Mehari M, Al Azhar M, Lévy M, Smith S (2021) Fast local warming is the main driver of recent deoxygenation in the northern Arabian Sea. Biogeosciences 18:5831–5849. https://doi.org/10.5194/bg-18-5831-2021

Lamine EB, Mateos-Molina D, Antonopoulou M, Burt JA, Das HS, Javed S, Muzaffar S, Giakoumi S (2020) Identifying coastal and marine priority areas for conservation in the United Arab Emirates. Biodivers Conserv 29:2967–2983. https://doi.org/10.1007/s10531-020-02007-4

Lincoln S, Buckley P, Howes EL, Maltby KM, Pinnegar JK, Ali TS, Alosairi Y, Al-Ragum A, Baglee A, Balmes CO, Hamadou RB, Burt JA, Claereboudt M, Glavan J, Mamiit RJ, Naser HAA, Sedighi O, Shokri MR, Shuhaibar B, Wabnitz CCC, Le Quesne WJF (2021) A regional review of marine and coastal impacts of climate change on the ROPME Sea area. Sustainability 13:13810. https://doi.org/10.3390/su132413810

Lorimer JG (1908) Gazetteer of the Persian Gulf, Oman, and Central Arabia. Superintendent Government Printing, Calcutta

Loya Y, Sakai K, Yamazato K, Nakano Y, Sambali H, Van Woesik R (2001) Coral bleaching: the winners and the losers. Ecol Lett 4:122–131

Maghsoudlou A, Araghi PE, Wilson S, Taylor O, Medio D (2008) Status of coral reefs in the ROPME sea area (The Persian Gulf, Gulf of Oman, and Arabian Sea) status of coral reefs of the world: 2008. Global Coral Reef Monitoring Network and Reef and Rainforest Research Center, Townsville, Australia

Mateos-Molina D, Antonopoulou M, Baldwin R, Bejarano I, Burt JA, Garcia-Charton JA, Al-Ghais SM, Walgamage J, Taylor OJS (2020) Applying an integrated approach to coastal marine habitat mapping in the north-western United Arab Emirates. Mar Environ Res 161:105095. https://doi.org/10.1016/j.marenvres.2020.105095

Mateos-Molina D, Ben Lamine E, Antonopoulou M, Burt JA, Das HS, Javed S, Judas J, Khan SB, Muzaffar SB, Pilcher N, Rodriguez-Zarate CJ, Taylor OJS, Giakoumi S (2021) Synthesis and evaluation of coastal and marine biodiversity spatial information in the United Arab Emirates for ecosystem-based management. Mar Pollut Bull 167:112319. https://doi.org/10.1016/j.marpolbul.2021.112319

Murray JW (1970) The Foraminifera of the hypersaline Abu Dhabi lagoon, Persian Gulf. Lethaia 3: 51–68. https://doi.org/10.1111/j.1502-3931.1970.tb01263.x

Petersen A (2012) Coastal Settlement in South-East Arabia during the Islamic Period. In: Potts DT, Hellyer P (eds) Fifty years of Emirates archaeology. Motivate, Dubai, pp 203–211

Pratchett MS, Baird AH, Bauman AG, Burt JA (2017) Abundance and composition of juvenile corals reveals divergent trajectories for coral assemblages across the United Arab Emirates. Mar Pollut Bull 114:1031–1035. https://doi.org/10.1016/j.marpolbul.2016.11.036

Purser BH, Evans G (1973) Regional sedimentation along the Trucial Coast, SE Persian Gulf. In: Purser B (ed) The Persian Gulf. Springer, Berlin, pp 211–231. https://doi.org/10.1007/978-3-642-65545-6_13

Pyle RL, Copus JM (2019) Mesophotic coral ecosystems: introduction and overview. In: Loya Y, Puglise KA, Bridge TCL (eds) Mesophotic coral ecosystems. Springer, Cham, pp 3–27. https://doi.org/10.1007/978-3-319-92735-0_1

Riegl B (1999) Corals in a non-reef setting in the southern Arabian Gulf (Dubai, UAE): Fauna and community structure in response to recurring mass mortality. Coral Reefs 18:63–73

Riegl B (2002) Effects of the 1996 and 1998 positive sea-surface temperature anomalies on corals, coral diseases and fish in the Arabian Gulf (Dubai, UAE). Mar Biol 140:29–40

Riegl B, Purkis S (2012) Environmental constraints for reef building in the Gulf. In: Riegl BM, Purkis SJ (eds) Coral reefs of the Gulf: adaptation to climatic extremes. Springer, Dordrecht, pp 5–32. https://doi.org/10.1007/978-94-007-3008-3_2

Riegl B, Purkis S (2015) Coral population dynamics across consecutive mass mortality events. Glob Change Biol 21:3995–4005. https://doi.org/10.1111/gcb.13014

Riegl BM, Purkis SJ, Al-Cibahy AS, Abdel-Moati MA, Hoegh-Guldberg O (2011) Present limits to heat-adaptability in corals and population-level responses to climate extremes. PLoS One 6: e24802

Riegl BM, Benzoni F, Samimi-Namin K, Sheppard C (2012) The hermatypic scleractinian (hard) coral fauna of the Gulf. In: Riegl B, Purkis S (eds) Coral reefs of the Gulf: adaptation to climatic extremes. Springer, Dordrecht, pp 187–224

Riegl B, Johnston M, Purkis S, Howells E, Burt J, Steiner S, Sheppard C, Bauman A (2018) Population collapse dynamics in *Acropora downingi*, an Arabian/Persian Gulf ecosystem-engineering coral, linked to rising temperature. Glob Change Biol 24:2447–2462. https://doi.org/10.1111/gcb.14114

Sheppard C, Loughland R (2002) Coral mortality and recovery in response to increasing temperature in the southern Arabian Gulf. Aquat Ecosyst Health Manag 5:395–402

Sheppard C, Sheppard A (1991) Corals and coral communities of Arabia. Fauna Arabia 12:3–170

Sheppard C, Price A, Roberts C (1992) Marine ecology of the Arabian region: patterns and processes in extreme tropical environments. Academic, Toronto

Sheppard CRC, Wilson SC, Salm RV, Dixon D (2000) Reefs and coral communities of the Arabian Gulf and Arabian Sea. In: McClanahan T, Sheppard C, Obura DE (eds) Coral reefs of the Indian Ocean: their ecology and conservation. Oxford University Press, Oxford, pp 257–292

Sheppard C, Al-Husiani M, Al-Jamali F, Al-Yamani F, Baldwin R, Bishop J, Benzoni F, Dutrieux E, Dulvy N, Durvasula S, Jones D, Loughland R, Medio D, Nithyanandan M, Pilling G, Polikarpov I, Price A, Purkis S, Riegl B, Saburova M, Namin K, Taylor O, Wilson S, Zainal K (2010) The Gulf: A young sea in decline. Mar Pollut Bull 60:13–38

Smith EG, Vaughan GO, Ketchum RN, McParland D, Burt JA (2017) Symbiont community stability through severe coral bleaching in a thermally extreme lagoon. Sci Rep 7:1–9. https://doi.org/10.1038/s41598-017-01569-8

Smith EG, Hazzouri KM, Choi JY, Delaney P, Al-Kharafi M, Howells EJ, Aranda M, Burt JA (2022) Signatures of selection underpinning rapid coral adaptation to the world's warmest reefs. Sci Adv 8:eabl7287. https://doi.org/10.1126/sciadv.abl7287

Souter D, Planes S, Wicquart J, Logan M, Obura D, Staub F (2021) Executive summary. In: Souter DPS, Wicquart J, Logan M, Obura D, Staub F (eds) Status of coral reefs of the world: 2020. GCRMN, Lausanne, pp 14–19

van Oppen MJH, Oliver JK, Putnam HM, Gates RD (2015) Building coral reef resilience through assisted evolution. PNAS 112:2307–2313. https://doi.org/10.1073/pnas.1422301112

Vaughan GO, Burt JA (2016) The changing dynamics of coral reef science in Arabia. Mar Pollut Bull 105:441–458. https://doi.org/10.1016/j.marpolbul.2015.10.052

Vaughan GO, Al-Mansoori N, Burt J (2019) The Arabian Gulf. In: Sheppard C (ed) World Seas: an environmental evaluation, 2nd edn. Elsevier, Amsterdam, pp 1–23. https://doi.org/10.1016/B978-0-08-100853-9.00001-4

Chapter 12
Oyster Beds and Reefs of the United Arab Emirates

Ivonne Bejarano, Daniel Mateos-Molina, Sandra L. Knuteson, Nadia Solovieva, Fadi Yaghmour, and Fatin Samara

12.1 Socio-cultural and Economic Value of Oyster Habitats in the Emirates

Oyster habitats are natural resources that were central to the prosperity and growth of the society of the United Arab Emirates (UAE) until the 1930s. Oyster beds and reefs have supported the local economy and culture through burial rights and aesthetics of societies since around 7500 YBP (Al-Matar et al. 1993; Heard-Bey 2001; Carter 2005; Hawker et al. 2005; Charpentier et al. 2012) and later transitioned into a major export commodity along the regional and Asian trade routes as pearls became popular in Indian markets (Heard-Bey 2001).

I. Bejarano (✉) · S. L. Knuteson · F. Samara
Department of Biology, Chemistry and Environmental Sciences, American University of Sharjah, Sharjah, United Arab Emirates
e-mail: ibejarano@aus.edu

D. Mateos-Molina
Emirates Nature - WWF, Dubai, United Arab Emirates

N. Solovieva
Higher Colleges of Technology, Sharjah Campus, University City, Sharjah, United Arab Emirates

F. Yaghmour
Hefaiyah Mountain Conservation Centre (Scientific Research Department), Environment and Protected Areas Authority, Kalba, Sharjah, United Arab Emirates

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_12

12.1.1 The Pearl Industry

Oyster habitats in eastern Arabia supported the traditional pearl diving industry, which, regionally, was the most lucrative economic activity during the eighteenth to twentieth centuries (Al-Matar et al. 1993; Carter 2005; Hawker et al. 2005). The pearls harvested at local oyster beds were of the highest quality in the world and had high commercial demand (Bowen 1951). In the Arabian Gulf, the pearl oyster fishery was large and supplied about 80% of the world's pearls at its peak (Al-Matar et al. 1993). These fisheries were run from traditional wooden vessels known locally as dhows and using breath-hold divers (Fig. 12.1) (Grandcourt 2012). Many local people (mostly men) moved from inland to coastal areas to join the pearling industry, which required a great human capital for the building and maintenance of the vast sea vessels used in pearl fishing, as well as for the large crews that traveled for months for the collection of pearls (Heard-Bey 2001). The local migration to coastal areas caused a rapid increase in the populations in some settlements. While Sharjah and Ras Al Khaimah were the first ports established for the pearling

Fig. 12.1 Pearling by breath-hold divers has a long tradition in the Arabian Gulf, and was the economic backstay of many Gulf nations in the nineteenth century. Photo credit: Pearl diver sculpture, Bahrain, by Denise Krebs, shared under Creative Commons (CC BY 2.0)

industry, even Abu Dhabi and Dubai had quick population growth around the pearl trade (Heard-Bey 2001). Abu Dhabi, for example, was founded in 1761 and grew to 400 houses within two years (Carter 2005). Rapid increases in coastal populations happened alongside growing demand for the oyster beds' pearl resources (Carpenter et al. 1997).

In the early 1900s, the local economy of the UAE was almost entirely dependent on oyster beds' pearl harvest. The pearling industry contributed approximately 95% of the local economy of Abu Dhabi and other emirates (Aqil 2018), transforming the coastal industry with the tribesman making up the largest portion of the workforce for this industry (Heard-Bey 2001). This economic activity was important in the region until 1930s, when it began its decline due to the introduction of cultured pearls, to become almost fully extinguished by the 1950s, after an economic depression in the 1930s and World War II, together with the discovery of oil and gas deposits across the Gulf (Bowen 1951; Grandcourt 2012; Al-Matar et al. 1993). Furthermore, regional and global impacts such as overfishing, extreme environmental conditions, and other anthropogenic stressors, contributed to the collapse of the oyster fishery in the region (Smyth et al. 2016). Many of the current ruling families of the UAE owe their standing to the pearling industry, either directly or indirectly through taxation as the industry was a part of their journey or historical influence (Carter 2005).

12.1.2 Architecture

The flourishing of the pearls industry played a major influential role in the early local architecture. The first UAE architecture style was developed in the nineteenth century (Hawker et al. 2005). Both the growing movement of people from neighboring countries (e.g., Iran, Bahrain, India, Iraq) for commercial pearling activities in the UAE, and the wealth obtained from the pearl trade, influenced interesting architectural innovations. Due to this, the local lifestyle became more residential, compared with the past pastoral nomadic lifestyles of the Bedoins (Hawker et al. 2005). Merchants from other countries or local settlers began constructing more permanent buildings to support these growing village populations, mostly near coastal areas of the UAE. The residents of higher status and the wealthy classes built homes of greater height which helped with ventilation. The Iranian merchants, on the other hand, built houses with wind towers which helped overcome the harsh summer weather. During that time villagers began building their homes, which were originally made of palm trunks and leaves (Areesh), and eventually from corals, including large coral-based wind tower structures (Rashdan and Mhatre 2019) (Fig. 12.2). This era was considered the "pearl era", which later was replaced by the "oil era", after the introduction of cultured pearls and the discovery of oil, changing the economy and architecture dramatically and making oil the major source of income (Mahgoub 1999). Interestingly, today there is a recurrence in the use of elements from past architecture in modern construction (Awad and Boudiaf 2020).

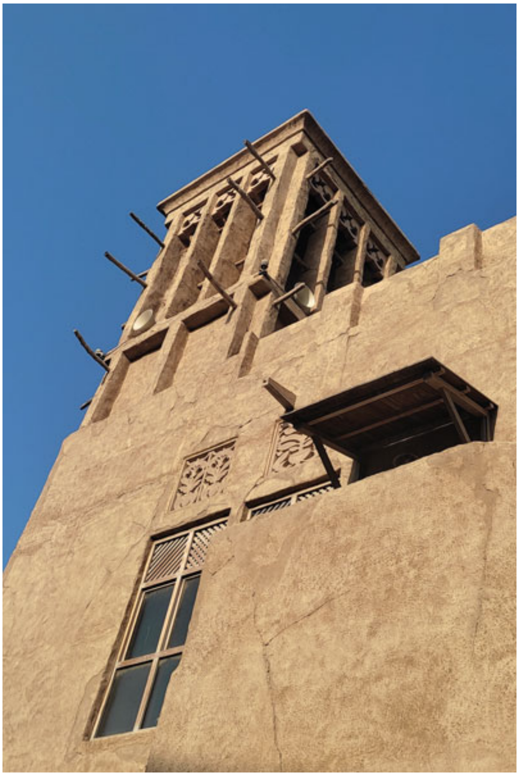


Fig. 12.2 Wind tower in Dubai. Source: Wind tower house, Al Seef, Dubai.jpg by RPSkokie, shared under Creative Commons (CC BY-SA 4.0)

12.1.3 Archaeological Records

The connection of indigenous people of the region to pearls, as well as their reliance on other oyster bed resources, is much older than the pearl industry. The earliest known evidence for pearling was found relatively recently in the UAE and reported in Beech et al. (2020). Archaeological surveys conducted over the last few decades on Marawah Island, in Abu Dhabi, found evidence that demonstrate that the area was inhabited by humans from around 8000 YBP, and that pearls and oysters were in use from that period (Beech et al. 2020). Similar findings are reported for archaeological settlements in other emirates. For example, burial excavations in Umm Al Quwain discovered pearls dated as old as 7500 years, which were found in the skeletal face and in the hands of human remains from the fifth and fourth millennium (Charpentier et al. 2012). Old archeological pearls have been found as well in Jebel Al Buhais (Sharjah), in settlements dated 7200–6000 YBP (Charpentier et al. 2012) (Fig. 12.3). These discoveries demonstrate a robust ancient oyster fishing tradition in the UAE.

Beyond pearl harvesting, oysters had very diverse historical use. Oyster shell was a common material for making jewelry, including items like beads, necklaces, pendants, and other personal ornaments such as buttons and belt buckles (Lidour

Fig. 12.3 A pearl deposited on the upper lip of an individual in the cemetery at Jebel Buhais, Sharjah, UAE. Photo credit: Adelina Kutterer

and Beech 2019; Barker and Hartnell 2000). Oyster shells have been found in archaeological middens in both coastal areas and inland sites of the UAE (Hellyer and Hull 2002), indicating that oyster habitats were historically important sources of seafood and trade items and fishing grounds for indigenous people. Oysters' meat was part of the diet of former inhabitants (Lidour and Beech 2019; Lidour et al. 2020) and oyster shells were used to make the earliest fish-hooks in the southeast Arabia (Charpentier and Mery 1997; Beech 2003; Méry et al. 2008) (Fig. 12.4). The fishing hooks made from oyster shells are effective for attracting fish with its shiny surface and allow capture of large individuals given the strength of the material (Beech 2003). Fishing and shellfish harvesting have been important subsistence activities in the region since the Neolithic (Grandcourt 2012; Lidour et al. 2020).

12.1.4 Non-pearl Fisheries in Oyster Habitats

Modern communities in the UAE continue fishing oysters for food and economic resources, albiet more as a traditional cultural practice rather than for economic benefit (Bento et al. 2022). A wide range of fish, e.g. bony fish, sharks and rays, as well as molluscs and crustaceans, use oyster habitats to spawn, breed, feed, and grow to maturity. For this reason, oyster beds and oyster reefs are considered major essential fish habitat (USDOC 1997).

The proximity of some oyster habitats to the coast and the high productivity that characterizes these areas makes UAE's oyster habitats good traditional fishing

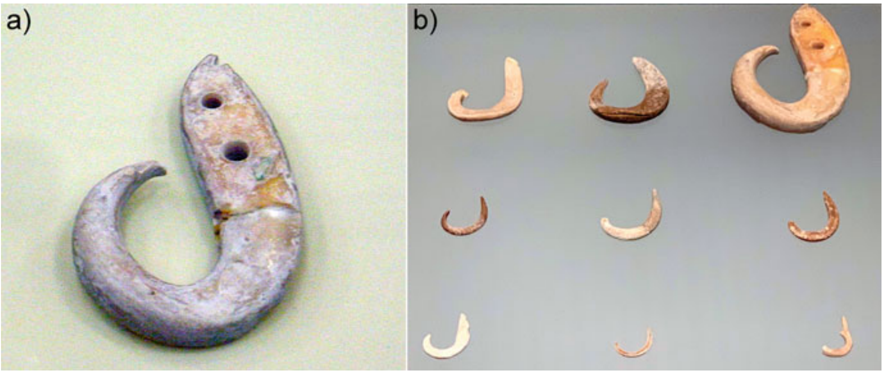


Fig 12.4 Early Neolithic fish hooks from Ras Al-Hamra, Oman (6000–4000 BCE). Photo credits: Mark Beech

grounds (Sheppard et al. 1992; Carpenter et al. 1997; Carter 2005; Al-Khayat and Al-Ansi 2008; Smyth et al. 2016; Bento et al. 2022). Fisheries around oyster beds and oyster reefs in the UAE are both recreational and commercial in their nature. These fisheries are socially and economically important because provide food to direct consumption, but also support the UAE's food security by providing additional income for the fisher's household (Bento et al. 2022) and for the coastal people involved in the post-harvesting activities. Oyster-bed fisheries are multi-species and multi-gear, with the most common fishing methods being handline (46%) and gargours (fish traps, 41%), given their success to catch the favorite local targets: rabbitfishes, mackerels, emperors, groupers, and snappers (Bento et al. 2022) (Fig. 12.5).

The taste for local oysters, and mollusks in general, remains in the UAE, though it is more limited now. Wild capture of native oysters (e.g. pearl oysters, hooded oysters) for human consumption still happen in some local coastal areas (Carpenter et al. 1997; Grizzle et al. 2018), and cultured oysters are produced in modern local aquaculture facilities for their meat and pearls production. For example, a mariculture farm established in Fujairah since 2016, produces and commercializes gourmet oysters for human consumption (Clarke 2021). Another farm in Ras al Khaimah cultivates pearl oysters with the aim for the re-establishment of the pearl industry in the UAE (Van Erde 2018).

12.2 Global and Local Distribution

Oyster habitats (i.e., beds and reefs) are structurally complex biogenic areas formed mostly by the clustering of large numbers of dead and live oysters and the fusion of their shells. These bioengineering habitats are distributed worldwide in coastal and marine areas (Korringa 1946; Beck et al. 2011), at intertidal to subtidal depths of up

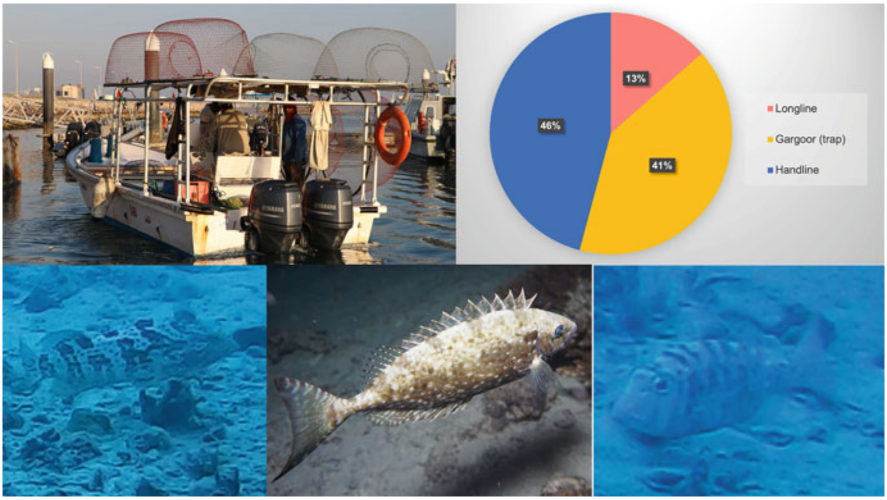


Fig. 12.5 Common fishing gear used in oyster-habitat fisheries in the UAE and examples for the most targeted fish species in these ecosystems. Above: (left) a UAE fishing boat with gargoors (fish traps). Photo: Daniel Mateos-Molina, (right) most frequently used fishing methods in UAE oyster grounds. Source: Rita Bento, unpubl. data. Below: (left) hamour/grouper (Epinephelidae), (center) rabbitfish (Siganidae), (right) emperor (Lethrinidae). Photos: Ivonne Bejarano

to 800 m (Van Rooij et al. 2010; Beck et al. 2011; Beuck et al. 2016; Taviani et al. 2019). Oyster habitats can form under an extensive range of salinity, spanning from brackish to extremely high saline waters (Wells 1961), although their distribution can be constrained by high turbidity (Emery 1956).

Recent efforts to estimate the current global distribution and condition of oyster ecosystems are limited geographically and don't include the eastern Arabia region (e.g., Beck et al. 2011). Sadly, these studies report vast global losses of oyster habitats in the last decades (see Sect. 12.5 of this chapter below).

The widespread distribution of oyster habitats throughout the region is reported in historical records and recent studies (Figs. 12.6 and 12.7). Oyster habitats occupy coastal and offshore areas in the Arabian Gulf, from Iran to Kuwait, the UAE and Oman (Somer 2003; Carter 2005; Al-Khayat and Al-Ansi 2008; Smyth et al. 2016) and are present in the east Gulf of Oman as well (Grizzle et al. 2018). In the UAE, oyster habitats occur on both coasts: the Arabian Gulf and the eastern Gulf of Oman (Grizzle et al. 2018). They are found on nearshore and offshore areas, on hard substrates, for example on submerged rocky cliffs (e.g. Khor Kalba), and soft bottoms (Grizzle et al. 2018; Mateos-Molina et al. 2020).

Despite the great technological advancement, the distribution of oyster beds in the UAE was much better documented in the past than it is today (Figs. 12.6 and 12.7). The current extent and condition of offshore oyster habitats in the Emirates is essentially unknown. However, the widespread abundance of oyster juveniles in

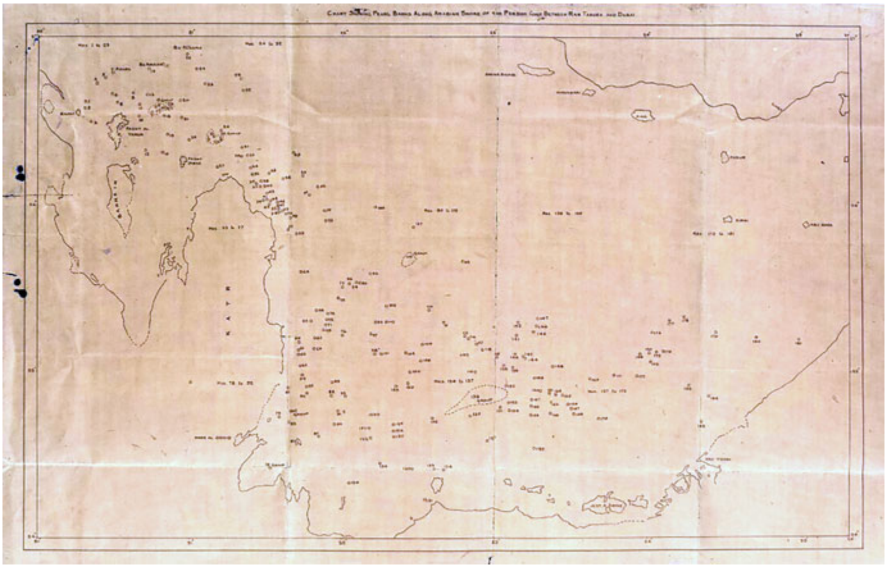


Fig. 12.6 Historical pearl oyster dive sites along the southern Arabian Gulf coast of the United Arab Emirates. Source: 'Chart Showing Pearl Banks Along Arabian Shore of the Persian Gulf between Ras Tanura and Dabai [Dubai]' [22r] (1/2), British Library: India Office Records and Private Papers, IOR/R/15/6/157, f 22, in Qatar Digital Library. https://www.qdl.qa/archive/81055/vdc_100076132425.0x00002c. Accessed 9 April 2023. Used under Open Government License

nearshore shallow habitats (e.g., seagrasses and macroalgae beds) suggest that UAE offshore oyster populations are still abundant (Grizzle et al. 2018).

Historical maps show vast areas of oyster habitats extending over approximately 3000 km^2 of the UAE waters of the Arabian Gulf, with the emirate of Abu Dhabi hosting the largest areas (80%) (Fig. 12.6). Some Abu Dhabi oyster habitats have been dramatically reduced due to rapid coastal and offshore development and to intense overfishing (Sheppard et al. 2012). However, recent field observations detected large oyster habitat patches in the emirate (unpublished data). Data on the current extent of these areas is not yet available and therefore it is not possible to assess spatio-temporal trends.

The extension of coastal oyster habitats up to 12 m depth in the Arabian Gulf coast was mapped in 2019 for the northern emirates of Dubai, Sharjah, Ajman, Umm Al Quwain, and Ras Al Khaimah (Mateos-Molina et al. 2020, 2021a, b) (Fig. 12.7). A total area of 40 km^2 of oyster habitats was charted, and the largest uniform patches were found in Dubai, Sharjah, and Ajman waters.

The mapping was done using multiple sources of information that included remote sensing, local ecological knowledge, underwater drop video cameras and existing information to increase mapping accuracy and overcome remote sensing constraints on detecting oyster habitat. This oyster habitat map is a critical baseline to quantitatively detect future changes in the distribution of these ecosystems and to support research, decision-making, and conservation actions (Mateos-Molina et al.

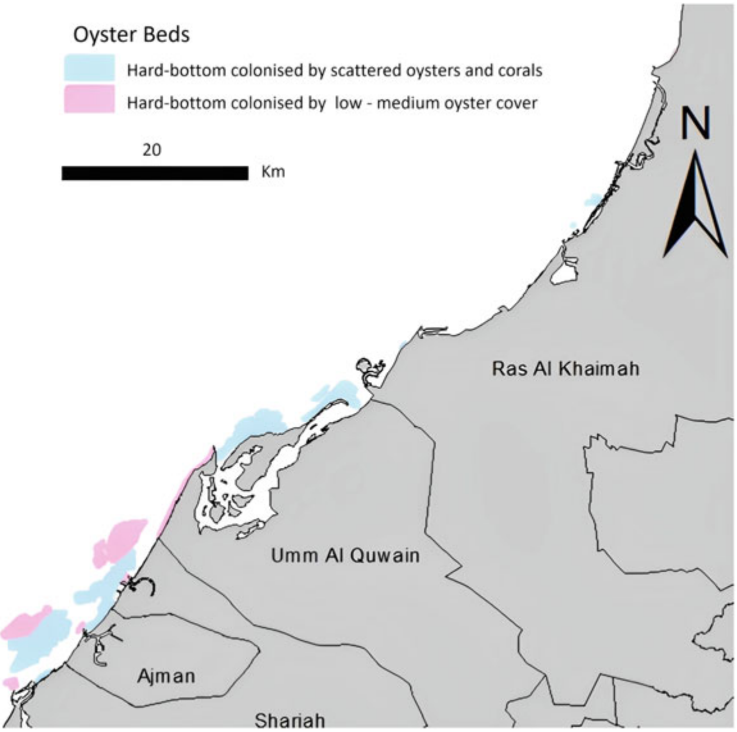


Fig. 12.7 Map of the location of oyster habitats areas in the Northern emirates of Sharjah, Ajman, and Umm Al Quwain. Arabian Gulf. Source: Source: Fig. 4 in Mateos-Molina et al. (2020), reproduced under Elsevier license 5515881307777

2020). It was recently used, for example, to support a study that obtained local ecological knowledge about UAE's oyster habitat fisheries from interviews with Sharjah and Ajman fishers in 2021, and which indicated that nearshore UAE's oyster habitats are an important fishing ground that was healthier, more productive, and more abundant in the past (Bento et al. 2022).

12.3 Diversity

The marine bivalve fauna of the UAE are Indo-Pacific in origin (Huber 2015; Grizzle et al. 2018) and consist of at least 80 species represented in 20 families and superfamilies (e.g. George 2005, 2012; Feulner and Hornby 2006; Grizzle et al. 2018) (Table 12.1). This number of species is low compared to both the global and regional diversities. The UAE's bivalve biodiversity represents about 2% of the species known for the Indo-Pacific region (the area with the highest bivalve species richness worldwide: 3300 species; Huber 2015), and less than 1% of the bivalve global diversity (approximately 8500 species; Huber 2015). The overall UAE's bivalve diversity is likely higher than 80 species, though. The majority of the collections are from the shallow nearshore areas of the Arabian Gulf coast and only some data is available from the Gulf of Oman (e.g., Grizzle et al. 2018).

Similar reduced local marine species richness compared with adjacent areas has been described for other different groups such as corals, algae, fish, and echinoderms (Kinsman 1964; Sheppard et al. 1992; Price and Izsak 2005; Burt et al. 2011). This biodiversity pattern is mostly attributed to the stress posed by the extreme environment of the area. In particular, the high and low temperatures and high salinities are major factors restricting the marine biodiversity in the UAE (Kinsman 1964; Burt 2014). In the Arabian Gulf, the biogeographic isolation and the short existence of the Gulf basin are additionally important for shaping marine biodiversity patterns (Riegl and Purkis 2012; Burt 2014).

The spatial distribution of bivalves, and molluscs in general, in the Gulf broadly follows environmental conditions. Like other groups (see Chap. 4), both species richness and community densities decrease moving from the northeast sites (Strait of Hormuz) to the southwest in the Arabian Gulf (Grizzle et al. 2018; Al-Khayat and Al-Ansi 2008). There are likely also differences between the two coasts, but available data preclude making definitive comparisons (Grizzle et al. 2018).

Marine oysters belong to the families Pteriidae (feathered oysters), Ostreidae (true oysters), Spondylidae (thorny oysters), Dimyidae (dimydarian oysters), and Placunidae (windowpane oysters). Previous studies report at least 11 species of oysters in the UAE coasts (e.g. Grizzle et al. 2018; George 2012; Feulner and Hornby 2006) (Table 12.1). Through underwater visual surveys and dive sampling, an ongoing study investigating oyster beds in the waters of Sharjah and Ajman is shedding light on their biodiversity. The study revealed that oyster beds in the region mostly consist of Gulf pearl oyster *Pinctada radiata* (Fig. 12.8) attaching to hard rock substrates along with a variety of scallop species and pen shells *Pinna muricata* (Fig. 12.9) anchored in surrounding sediment using a byssus. The larger Black-lip pearl oyster *Pinctada margaritifera* (Fig. 12.10) is more sporadically distributed, but commonly observed in oyster beds and rocky reef environments. Finally, the sturdy hooded oyster *Saccostrea cuccullata* (Fig. 12.11), is not observed in sublittoral oyster habitats but is common in the upper littoral zones of rocky areas in mangroves of the UAE.

Gulf Pearl Oyster

Pinctada radiata (Leach, 1814) (Fig. 12.8)

A square-like shell growing up to 65 mm, the Gulf pearl oyster has a lamellose sculpture consisting of radial rows of sharp appressed spines. It has a varied external colouration, often a combination of tan, brown and red, and a pearly interior with light brown and red edges. This fouling species is often attached by its byssus to rocks and other hard substrates on sub tidal zones, where it lives as an epifaunal suspension feeder (Bosch et al. 1995; Tlig-Zouari et al. 2009). At pearl trade's peak, annual exports to London from Kuwait, Bahrain and territories that are now the UAE would reach approximately 2000 tons, carrying a value of £750,000. Pearl

Table 12.1 Bivalves' families and species reported for the United Arab Emirates

Family Arcidae	*Acar plicata*
	Arca avellana
	Barbatia parva
	Barbatia setigera
Family Mytilidae	*Brachiodontes variabilis*
	Musculista senhousia
	Modiolus auriculatus
	Botula cinnamomea
	Gregariella sp.
	Leiosolenus cf. tripartitus
	Lithophaga robusta
	Lusculista senhousia
	Musculus cumingianus
	Musculus sp.
	Septifer bilocularis
Family Pteriidae	*Pinctada radiata*
	Pinctada margaritifera
	Pterelectroma cf. vexillum
	Pterelectroma zebra
	Pteria sp.
Family Malleidae	*Malvufundus normalis*
	Malvufundus regula
	Vulsella vulsella
	Parviperna nucleus
Family Isognomonidae	*Isognomon legumen*
	Isognomon sp.
Family Pinnidae	*Pinna muricata*
	Atrina vexillum
Superfamily Linoidea	*Lima sowerbyi*
	Limatulella viali
	Limaria fragilis
Family Pectinidae	*Chlamys livida*
Family Ostreidae	*Saccostrea cucullata*
	Alectryonella plicatula
	Alectryonella sp.
	Lopha cristagalli
	Ostrea sp.
Family Spondylidae	*Spondylus marisrubri*
Superfamily Plicatuloidea	*Plicatula australis*
Family Lucinidae	*Pillucina fischeriana*
	Pillucina vietnamica
	Anodontia edentula
	Cardiolucina semperianum

(continued)

Table 12.1 (continued)

	Ctena divergens
Family Ungulinidae	*Diplodonta* spp.
	Diplodonta subrotundata
Family Carditidae	*Beguina gubernaculum*
Family Chamidae	*Chama reflexa*
	Chama douvillei
	Chama brassica
	Chama sp.
	Chama aspersa
	Chama asperella
Family Mesodesmatidae	*Caecella qeratensis*
Family Tellinidae	*Tellina arsinoensis*
	Pinguitellina pinguis
	Cadella semen
	Tellidora lamellosa
Family Carditoidea	*Carditopsis majeeda*
Family Cardiidae	*Acrosterigma Lacunosa*
	Parvicardium sueziense
Family Psammobiidae	*Asaphis violascens*
	Hiatula mirbahensis
	Hiatula ruppelliana
	Hiatula rosea
	Psammosphaerica psammosphaerita
Family Semelidae	*Ervilia scaliola*
	Ervilia sp.
Superfamily Articoidea	*Trapezium sublaevigatum*
Family Veneridae	*Circenita callipyga*
	Amiantis umbonella
	Callista florida
	Dosinia alta
	Dosinia ceylonica
	Dosinia contracta
	Marcia flammea
	Cirse rugifera
	Cirse scripta
	Tivela callipyga
	Gafrarium pectinatum
	Irus macrophylla
	Microcirse sp.
Superfamily Gastrochaenoidea	*Gastrochaena gigantea*
	Gastrochaena sp.
Family Laternulidae	*Laternula erythraensis*
	Laternula navicula

Source: Feulner and Hornby (2006); George (2012); Grizzle et al. (2018)

Fig. 12.8 Gulf pearl oyster *Pinctada radiata*. Source: Fadi Yaghmour

harvesting in the Arabian Gulf was large and represented approximately 80% of the world's production of natural pearls (Al-Matar et al. 1993; Mohammed and Yassien 2003).

Pen Shell
Pinna muricata (Linnaeus, 1758) (Fig. 12.9)

Fig. 12.9 Pen shell. *Pinna muricata.* Source: Fadi Yaghmour

Fig. 12.10 Black-lip pearl oyster *Pinctada margaritifera*. Source: Pinctada margaritifera by Joop Trausel and Frans Slieker, licensed under Creative Commons (CC BY-NC-SA 4.0)

The pen shell is a large bivalve reaching lengths of up to 300 mm. They have a long and triangular shape with a narrow posterior that widens greatly to a fan shape. The coloration is pale with grey-black markings. Epibionts on pens include bryozoans, polychaete worms and smaller bivalves. The external surface of their valves is lightly ribbed, with the ribs radiating from the anterior end. This species is distinguished from other *Pinna* species by having the adductor scar not overlapped with the ventral nacreous layer. This species often anchors into sediments or wedged between rocks using bassus. Due to its large size, a dead anchored pen shell often serves as a refuge for small invertebrates that hide inside it. Cuttlefish eggs are also commonly attached inside dead pen shells.

Black-Lip Pearl Oyster

Pinctada margaritifera (Linnaeus, 1758) (Fig. 12.10)

Squarish to subcircular with straight dorsal margin, the black-lip pearl oyster grows up to 200 mm in length. It has a lamellose sculpture consisting of radial rows of wide appressed scales (Bosch et al. 1995). It has a grayish green external coloration with a vivid pearly interior with greenish gray edges and black along the margins. This oyster thrives in clear waters, e.g., in coral reefs and oyster habitats, where it attaches itself to hard substrate using byssal threads. They occur from intertidal zones to 75 m depth (Yukihira et al. 1999). Black-lip pearl oysters were once an important source of wealth in the Arabian Gulf. At the turn of the twentieth century, mother of pearl trade was at its peak with exports to London reaching around 150 tons annually, where it was used to make mother of pearl cutlery and inlay (Bosch et al. 1995).

Fig. 12.11 Hooded oyster *Saccostrea cuccullata*. Source: Fadi Yaghmour

Hooded Oyster

Saccostrea cuccullata (Born, 1778) (Fig. 12.11)

Growing up to 70 mm, the hooded oyster has variable morphologies with circular to oval shape and irregular margins. It has thick and solid valves. With the larger, lower valve attaches, while the upper valve is flat with pleated marginal lobes that aptly fits into those of the lower valve. The external coloration is purple black with white to pale radial streaks. Internally is white with a purple-back margin (Bosch et al. 1995). It is often found attached to the surface of rocks as well as the breathing roots (pneumatophores) and trunks of mangrove trees at the upper littoral zone of mangroves, both on the Arabian Gulf and the Gulf of Oman. Though edible, this species is not consumed in the UAE. They provide the ecosystem service of filtering and accumulating toxins such as heavy metals from surrounding waters (Azarbad et al. 2010).

12.4 The Biological, Ecological, and Scientific Importance of UAE's Oyster Beds

Oyster ecosystems provide essential goods and services for humanity in a strongly connected socio-ecological relationship that involves provision of products, regulation of ecological processes, and ecosystem use and conservation.

Fisheries, for example, is one of the human dimensions of oyster habitats. Fishers, merchants, and people in general, have for centuries benefited from catches of diverse and abundant invertebrates and fish that concentrate in oyster areas and represent sources of both food and income. Oysters, themselves, are valuable fishery resources for their meat, pearls and shells, and their skeletons form the main structural framework of oyster habitats, which is refuge and feeding ground for many other marine organisms (Wells 1961; USDOC 1997; Cranfield et al. 2001; Airoldi et al. 2008; Teng et al. 2019).

Oyster habitats themselves enhance oyster recruitment, growth, and survival (Coen et al. 1999). Oysters in these habitats are found in high densities, often grouped in clusters (Korringa 1946). This spatial arrangement is beneficial for their populations in different ways: for example, for aggregation of spawning stock, chemical induction of gregarious settlement, and as predator refugia (Coen et al. 1999). Oysters reproduce in synchronized spawning events, where sperm and eggs are released into the surrounding water around the same time for fertilization to take place and larvae to form. Larvae drift with the currents and those that find a hard and clean surface to settle into can recruit and establish themselves as new members of the oyster habitat community. Thus, larval settlement determines, to a good extent, the population dynamics of oyster habitats. The characteristic gregarious settlement of marine oysters is facilitated by the ability of oyster larvae to discriminate substrate types and choose where to settle (Crisp 1967; Zimmer-Faust and Tamburri 1994; Zhao et al. 2003). Specific chemical cues produced by conspecifics (Zimmer-Faust and Tamburri 1994) and microbial films (Doroudi and Southgate 2002; Zhao et al. 2003) are major inducers for such active selection of settlement sites. Therefore, in good environmental conditions, the higher the number of mature oysters in an area the higher the number of oyster larvae produced (Korringa 1946) and the greater the oyster settlement and recruitment. This allows population replenishment for oyster habitat maintenance and growth.

In addition, oysters and some other bioengineering molluscs create the complex primary structure of oyster habitats. The vertical relief rises to 0.2 m above the bottom in oyster beds, yet in oyster reefs the relief rises higher heights up to 6 m (Beck et al. 2009; La Peyre et al. 2019) (Fig. 12.12). The natural structure of oyster habitats provides other multiple social and ecological services like coastal protection, erosion prevention, and sediment stabilization.

This framework benefits coastal communities because it is a physical barrier that buffers shorelines against the energy of waves and currents that passes through it, enhancing the conditions for saltmarsh, seagrass, and mangrove to grow, which are ecosystems that provide important services such as carbon sequestration and storage (Zu Ermgassen et al. 2021). The physical service of oyster habitats also helps prevent property damage and erosion. For this reason, recently much attention is given to oyster beds as a nature based solution to mitigate climate change impacts (Hori et al. 2020). In the UAE, coastal defense is a valuable service to protect from threats such as strong storms and Shamal events (Meyer et al. 1997), becauseore than 85% of the UAE population lives in coastal areas, and numbers are projected to continue increasing (van Lavieren et al. 2011).

Oyster ecosystems also represent a widespread and very valuable resource that provide shelter, protection, and food to abundant and varied marine fauna, particularly in areas dominated by flat soft sediment bottoms (Lenihan et al. 1999; Beck et al. 2011; Samara et al. 2023). Oyster habitats are commonly associated to greater

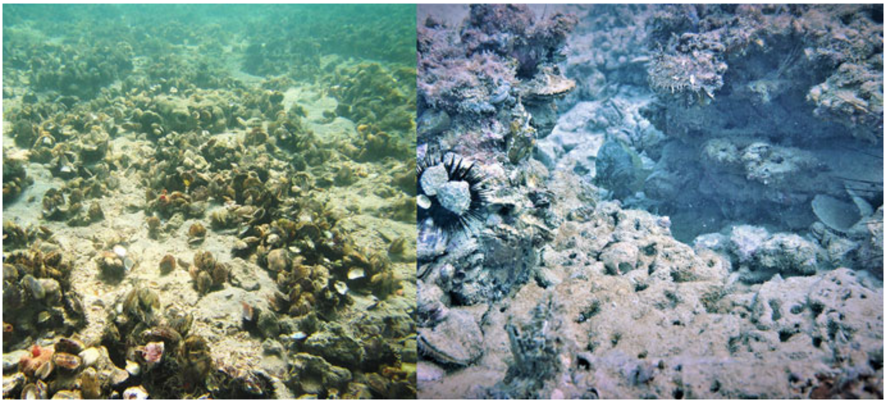


Fig. 12.12 Examples for oyster habitats in the United Arab Emirates. Left: oyster bed; right: oyster reef. Photos: Daniel Mateos-Molina

fauna densities compared to the surrounding areas (Craeymeersch and Jansen 2019). Studies in the Arabian Gulf region report an abundant biodiversity concentrated in oyster habitats that consist of mixtures of hundreds of benthic, epibiotic, sedentary and mobile species (e.g., Al-Khayat and Al-Maslamani 2001; Feulner and Hornby 2006; Al-Khayat and Al-Ansi 2008; Amini Yekta et al. 2014; Smyth et al. 2016; Grizzle et al. 2018). Important commercial and recreational fishery fauna make up good part of these communities (Ibrahim et al. 2018; Bento et al. 2022). In line with these studies, research investigating macro-biodiversity in UAE oyster reefs and beds in 2021–2022 has revealed that local oyster habitats are used by a diverse fauna that includes several valuable commercial species such pearl oysters (Pteriidae), hamours/groupers (Epinephelidae), emperors (Lethrinidae), and snappers (Lutjanidae). Other ecologically important species, like sea snakes, were also repeatedly observed in these areas (Samara et al. 2023) (Fig. 12.13).

Mollusks in oyster habitats also underpin other fundamentally important and inter-related services such as water filtration and cleaning, and sustaining production of upper consumers (George 2012). The vast filtration capacity of dense bivalve communities in oyster habitats contributes to good water quality by reducing turbidity, suspension matter, toxins, and nutrients content (Cressman et al. 2003; Nelson et al. 2004; Newell 2004). Good water quality is closely linked to healthy phytoplankton communities and habitat productivity. Phytoplankton forms the base of the food chain in the ocean (Stoecker 1998). It is the main contributor to the global oceanic primary production, i.e., fixes about 40% of global carbon annually (Falkowski et al. 2004; Thornton 2012) and is consumed by filter-feeders that are food for many other predators, e.g., oysters, shrimp larvae, fish, and humans (Epifanio 1979; Enright et al. 1986) influencing the diversity and abundance of life in an area. Therefore, the filter feeding activity in oyster habitats also contributes services such as biodiversity and fisheries (Ruesink et al. 2005; Grabowski and Peterson 2007; Laugen et al. 2015. See Sect. 12.1 above).

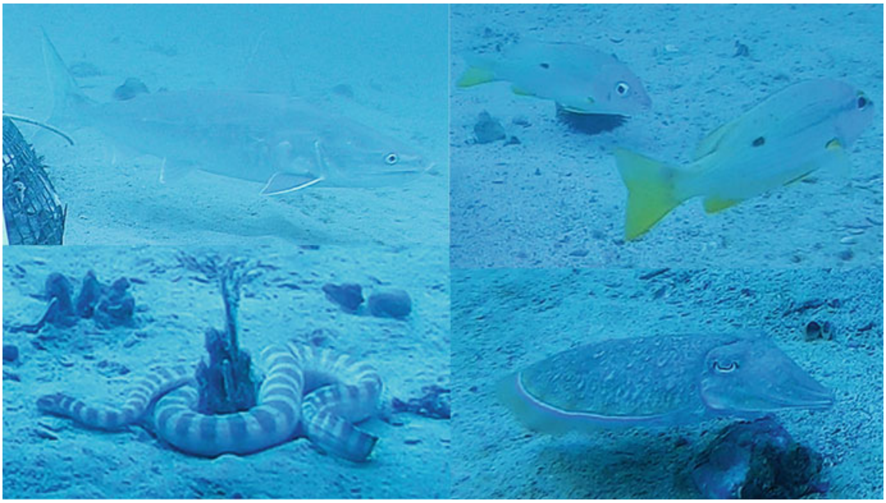


Fig. 12.13 Examples of fauna associated to oyster habitats in the United Arab Emirates. Above: (left) catfish, (right) snappers. Below: (left) Arabian Gulf Coral Reef Sea Snake, (right) cuttlefish. Photos: Ivonne Bejarano

A phytoplankton study investigating UAE oyster beds in Sharjah, Ajman, and Umm Al Quwain since 2021 has reported 117 taxa from four major taxonomic groups: diatoms, dinoflagellates, cyanobacteria and cryptophytes (Fig. 12.14). Similar to Kuwaiti and Qatari waters (e.g., Quigg et al. 2013; Al-Yamani and Saburova 2019), diatoms and dinoflagellates were abundant, had considerably higher taxonomic diversity compared to other algal groups, and were present throughout all seasons at all sampling sites (Samara et al. 2023) (Fig. 12.14).

Finally, oyster habitats are also great bioindicators of environmental conditions in marine environments, given their great filter feeding activity and potential to store high concentrations of pollutants, including microplastics (Zhu et al. 2020). Monitoring approaches in oyster habitats often include analyses of heavy metals (al-Madfa et al. 1998; Shirneshan et al. 2012), organic pollutants (Vaezzadeh et al. 2017), and microplastics (Bendell et al. 2020; Hammadi et al. 2022) in water, sediments, and oysters tissue, given the strong connection between them (Nasci et al. 1999). Seawater offers a mobile phase for the metals and toxic pollutants circulation, so the transfer and uptake of such pollutants from the sediments to the surrounding organisms and ecosystems is a common phenomenon (Aslam et al. 2020). Molluscs such as the Gulf pearl oyster *Pinctada radiata* have been previously used as biomarkers of heavy metal contamination (Karami et al. 2014; Nourozifard et al. 2020). Likewise, the hooded oyster *Saccostrea cucullata* and the Gulf pearl oyster have been used to monitor genotoxic endpoints and chemical pollution in the Gulf (De Mora et al. 2004, 2010; Farhadi et al. 2011; Leitão et al. 2017). In a larger scale context, the Regional Organization for the Protection of the Marine

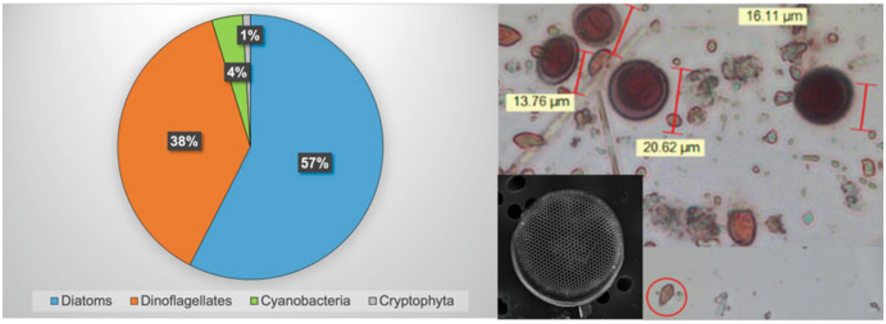


Fig. 12.14 Phytoplankton taxonomic diversity in oyster habitats in Sharjah, Ajman, and Um Al Quwain, United Arab Emirates. 2021–2022. Left: Percentage of species per group. Right: (above) light microscope photo of dinoflagellates *Prorocentrum balticum/nux*, (below-left) SEM micrograph of the diatom *Thallasiosira* sp., (below-right) light microscope of *Cryptophyta* spp. Source: Nadia Solovieva, (Samara et al. 2023)

Environment (ROPME) proposed in 2007 the implementation of a regional "Mussel Watch Programme" in the Arabian Gulf. The "Mussel Watch" approach was originally proposed by Edward Goldberg in 1975 and has since then been implemented in many countries to assess geographic status and temporal trends of chemical contamination in the coastal ocean.

Despite recognition of their great historical, cultural, economic and biological importance, oyster habitats are among the less studied ecosystems in the UAE (EA Abu Dhabi 2008; Hammadi et al. 2022). This is a research gap that requires immediate action.

12.5 Threats to the UAE's Oyster Habitats

A few centuries ago, oyster habitats were extensive in many coasts and oceans in the world (Korringa 1946; Beck et al. 2011). In contrast, these habitats are now one of the most endangered marine ecosystems (Beck et al. 2011) (Fig. 12.15). Many oyster habitats have been dramatically reduced or have even disappeared through diverse pressures that include overexploitation, habitat loss and degradation, diseases, climate change, ocean acidification, and invasive species, among others (Mallin et al. 2000; Ogburn et al. 2007; Krassoi et al. 2008; Beck et al. 2011; Zu Ermgassen et al. 2012; Al-Saadi 2013; Ruckelshaus et al. 2013; Scanes et al. 2016; Lemasson et al. 2017). Oyster habitat loss worldwide over the last century is extimated to be 85% (Beck et al. 2011).

In the Gulf, concerns of excessive oyster habitat exploitation have been raised since 1770 (Carter 2005). Overfishing caused reductions in pearls availability, which in turn led to increases in their price and further overharvesting, entering in a

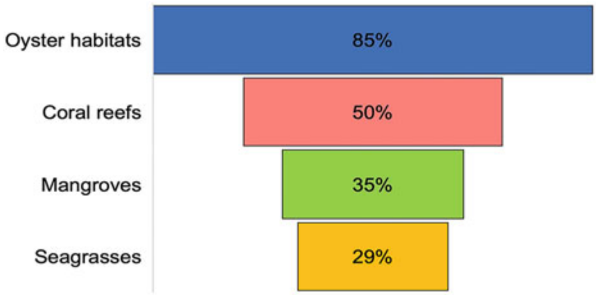


Fig. 12.15 Percentage of coastal marine ecosystems loss across the globe in the last decades. Data derived from Beck et al. (2011) for oyster habitats, Eddy et al. (2021) for coral reefs, Polidoro et al. (2010) for mangroves, and Waycott et al. (2009) for seagrasses

destructive spiral cycle that continued until pearling was not economically viable (Carter 2005). Unfortunately, there is no record of the recovery of oyster populations after pearling activities ceased in the 1930s.

The Gulf is a semi-enclosed marine basin (Sheppard et al. 2010; Coles and Riegl 2013) and one of the most rapidly developing regions at present (Fawzi et al. 2022). This, together with local natural extreme environmental conditions (Feary et al. 2010; Riegl and Purkis 2012) and the effect of global stressors like climate change (see Chap. 3), have caused further declines to oyster habitats in the region (Al-Khayat and Al-Ansi 2008; Hightower 2013; Smyth et al. 2015, 2016; Ibrahim et al. 2018). For example, extensive and highly productive oyster beds in Qatar have suffer dramatic loss due to habitat destruction and deterioration (Smyth et al. 2016). Likewise, patches of oyster habitats in Abu Dhabi have been reduced due to rapid coastal and offshore development and past intense overfishing (Sheppard et al. 2012).

In the northern emirates, fishers in Sharjah and Ajman have noticed a drastic reduction in the spatial extent of oyster habitat areas over the last two decades, together with decreases in their catches of over 50% (Bento et al. 2022). Fishers identified overfishing, coastal development, and pollution as the leading causes for these changes. In line with this, Grizzle et al. (2018) highlighted coastal development, industrial wastes, dredging, fishing, thermal bleaching, and harmful algal blooms as major causes of mollusc habitat loss in the UAE.

Recent studies investigating the environmental conditions in five oyster patches located along the coastline of Sharjah, Ajman, and Umm Al Quwain found good water quality in these habitats which did not suggest signs of pollution (Samara et al. 2020; Hammadi et al. 2022; Samara et al. 2023). Analyses of microplastics at the same oyster habitats revealed the ubiquity and previously unrecognized pollution issue that plastics pose to almost any marine ecosystem. A high diversity of microplastics was consistently found in the sediments and oysters' meat in these areas (Hammadi et al. 2022). In both oyster and sediments, the majority of the microplastics were black and blue in color and fiber in shape. Results suggests a risk from microplastics as a physical hazard and a vector for pollutants at local oyster beds (Barboza et al. 2018; Akdogan and Guven 2019; Peixoto et al. 2019; Goswami et al. 2021; Lin et al. 2021). The health effects that microplastics have in both marine organisms and humans are uncertain, but it has been suggested that there are two routes of toxicity, direct effects through the microplastic ingestion and as a vector for other pollutants, such as heavy metals, organic pollutants, or microorganisms, sorbed to the microplastics (Lin et al. 2021, Goswami et al. 2021). As a vector, smaller microplastics tend to have higher risk, with higher surface area for binding; while microplastics smaller than 0.15 mm may be able to cross the digestive tract lining, travel through the bloodstream, and enter and bioaccumulate in secondary organs of marine organisms or humans (Barboza et al. 2018; Akdogan and Guven 2019; Peixoto et al. 2019).

The loss of oyster habitat services can trigger environmental cascades where low densities of oysters may lead to increased phytoplankton blooms (Lenihan et al. 1999; Schulte et al. 2009). The proliferation of some phytoplankton taxa may be harmful for filter-feeders and their predators. Such sporadic events, known as harmful algal blooms (HAB) can be caused by about 300 species of diatoms, dinoflagellates, or cyanobacteria (Hallegraeff et al. 2004) and their incidence is more frequent in the past few decades globally (Hallegraeff 1993; Xiao et al. 2019) and regionally (Al-Azri et al. 2012).

In the UAE, large outbreaks of harmful dinoflagellates have caused massive die-offs of molluscs in 2008 and 2009 (Richlen et al. 2010; Al-Azri et al. 2012; Zhao and Ghedira 2014), due to the proliferation of the ichtiotoxic dinoflagellate *Cochlodinium polykrikoides* (Richlen et al. 2010) that caused the death of thousands of fish and mammals over about 1200 km of coastline of the Arabian Gulf and the Gulf of Oman. The magnitude of the event was such that water desalination plants were forced to close due to clogging of intake filters (e.g. Richlen et al. 2010; Zhao and Ghedira 2014). Other catastrophic HAB events have also occurred in the Gulf of Oman coastal waters in 2010 and 2011 (Al-Azri et al. 2012). These blooms have significantly altered the composition and abundance of UAE's mollusc communities (Grizzle et al. 2018).

In the northern Arabian Sea (off the coast of Oman and India) planktonic diatoms are increasingly being replaced with the large green dinoflagellate *Noctiluca scintillans*, which can cause hypoxic conditions in subsurface waters when blooms (Gomes et al. 2014). This change in the phytoplankton assemblage composition affects oyster communities (Johnson et al. 2009) by lower availability of oxygen and food, i.e., diatoms. A *N. scintillans* bloom was reported in January 2017 in the coastal waters off Dubai (Murugesan et al. 2017).

Phytoplankton assemblages in the waters of oyster habitats in Sharjah, Ajman, and Umm Al Quwain include several potential harmful algal bloom species, such as *Prorocentrum micans*, *Cochlodinium* sp., and *Alexandrium* sp., *Pseudonitzschia* sp., and *Prorocentrum balticum/nux* (Samara et al. 2023) (Fig. 12.16).

With the ongoing global climate change and increasing pressures on marine ecosystems in the Gulf region, it is likely that the incidents of HABs may occur at higher frequency in the future. This has important economic and environmental consequences, that pose additional stress to local oyster ecosystems.

Fig. 12.16 Light microscope photos of potentially harmful algal bloom species found in the waters of oyster habitats in Sharjah, Ajman, and Umm Al Quwain. 2021–2022. Above: (left) dinoflagellate *Dinophysis caudata*, (right) *Cochlodinium pulchellum*. Below: (left) *Prorocentrum micans*, (right) A chain of *Pseudonitzschia* sp. Photos: Nadia Solovieva

12.6 Management and Conservation and Future of Oyster Habitats

Despite the importance of UAE oyster habitats, there is limited comprehensive and up to date information on their distribution, condition, and trends. A recent review from Mateos-Molina et al. (2021a, b) shows the large gaps in spatio-temporal information in oyster habitats across the UAE waters, as well as the low accuracy of the existing data. The limited attention to documenting the spatial extent and status of oyster habitats hinders the uptake of effective conservation measures for the protection and preservation of this valuable habitat for human wellbeing and biodiversity (EAD 2008).

Mapping the spatial distribution of coastal habitats such as oyster beds has been highlighted as a priority action to support their management and conservation, but also to enable additional studies on their condition and trends (Convention on Biological Diversity (CBD 2010; UAE NBSAP 2014–2021). This information is essential to mitigate threats, make informed decisions, and allow these sensitive habitats to be effectively monitored and managed in terms of their extent and condition (Norse 2010). The major knowledge gap in the distribution of oyster habitat is for waters deeper than 7 m, given the limitation of cost-efficient mapping approaches (Mateos-Molina et al. 2020). Therefore, dedicated surveys to enhance our knowledge in the distribution of this important habitat in shallow and deeper waters is key to diversify conservation and management efforts (Mateos-Molina et al. 2021a, b).

Losses in oyster ecosystems make them less able to support the diverse abundance of life that they typically harbor, and to reductions in their filtering and cleaning services for good water quality and declines in coastal communities' protection. All of this is linked to direct and indirect ecological, economic, and social services losses. Therefore, conservation and management of oyster habitats is an urgent need to ensure the vital ecosystem functions and services that these habitats provide. In addition, recent studies recognizing the biodiversity and crucial ecosystem services provided by the oyster beds have highlighted specific sites in the UAE where restoring this habitat serves as nature-based solutions for enhancing food security, protection, and improving water quality (Pittman et al. 2022). The UAE's commitment to the CBD for a science-based design of ecologically representative and interconnected protected area networks (i.e., Aichi Target 11) should support the protection of this habitat. Under the definition of Areas of Particular Importance for Biodiversity by CBD, a recent study in the UAE identified oyster habitats as an important habitat with a critical role in life-stages of commercial and endangered species, and experts agree on the need of protecting 80% of the known area covered by this habitat (Ben Lamine et al. 2020). However, the existing available information on their distribution in the UAE does not overlap with the current extension of UAE Marine Protected Areas (MPAs) (Mateos-Molina et al. 2021a, b), indicating that they remain largely unprotected across the nation.

Unfortunately, it seems that, outside of laws that protect the marine environment in general, little action is currently in place to conserve the UAE's oyster beds, particularly those characterized by high densities of Gulf pearl oysters. However, other oyster species, such as hooded oysters enjoy a great deal of protection by virtue of their proximity to the highly protected mangroves.

12.7 The Future of UAEs Oyster Habitats

Moving forward, greater collaboration among scientists, fishers and policy makers is critical to compile all the existing knowledge on the past and current status of this important habitat at local but also regional scale (Fawzi et al. 2022). This would increase the availability of information to support immediate management and conservation actions and allow comprehensive ecosystem-based management approaches for transboundary conservation. Some of the management actions suggested by fishers and scientists consider the integration of oyster habitats within existing MPAs by extending their borders or establishing new MPAs to preserve oyster ecosystems ecological and socio-economic services (Mateos-Molina et al. 2020, 2021a, b; Bento et al. 2022) and restoration (Pittman et al. 2022). These management actions are especially viable considering the UAE's commitment to address the Kunming-Montreal Global Biodiversity Framework (GBF) targets that include 30% of land-sea protection by 2030 under the Global Biodiversity Framework (CBD 2022) and to the Global Ocean Alliance initiative that aims to protect at least 30% of the global ocean with MPAs and Other Effective area-based Conservation Measures by 2030.

12.8 Conclusions

Oyster habitats in the Emirates are very popular for their historical importance as sources of pearls. What is not so widely documented is that oyster habitats are highly productive ecosystems that also provide other key services like fisheries of diverse marine life, protection of the coastline from waves and currents, and improvement of water quality. UAE's oyster habitats still occur in coastal and offshore areas and distribute across both the Arabian Gulf and Gulf of Oman. The status of these habitats is known only for some emirates. In Sharjah and Ajman, oyster habitats have a good water quality, a diverse phytoplankton assemblage, and are home to a varied life that includes commercial species. Like in many other countries, oyster habitats in the UAE have been reduced and immediate management and conservation actions to protect these valuable habitats are required for us to continue receiving the numerous benefits they provide.

12.9 Recommended Readings

For those interested in learning more about the amazing oyster reefs of the UAE, we recommend Charpentier et al. (2012) and Carter (2005) for an excellent summary of the historic pearl trade, Bento et al. (2022) for information on the current socio-economic value of oyster habitats in the northern Emirates and Grizzle et al. (2018) for further information on other marine molluscs, in addition to oysters, in the UAE.

References

Airoldi L, Balata D, Beck MW (2008) The gray zone: relationships between habitat loss and marine diversity and their applications in conservation. J Exp Mar Biol Ecol 366(1-2):8–15

Akdogan Z, Guven B (2019) Microplastics in the environment: a critical review of current understanding and identification of future research needs. Environ Pollut 254:1–24. https://doi.org/10.1016/j.envpol.2019.11301

Al-Azri A, Piontkovski S, Al-Hashmi K, Al-Gheilani H, Al-Habsi H, Al-Khusaibi S, Al-Azri N (2012) The occurrence of algal blooms in Omani coastal waters. Aquat Ecosyst Health Manage 15(1):56–63. https://doi.org/10.1080/14634988.2012.672151

Al-Khayat JA, Al-Ansi MA (2008) Ecological features of oyster beds distribution in Qatari waters, Arabian Gulf. Asian J Sci Res 1(6):544–561. https://doi.org/10.3923/ajsr.2008.544.561

Al-Khayat J, Al-Maslamani I (2001) Fouling in the pearl oyster beds of the Qatari waters, Arabian Gulf. Egypt J Aquat Biol Fish 5(4):145–163

Al-Madfa H, Abdel-Moati MAR, Al-Gimaly FH (1998) Pinctada radiata (Pearl Oyster): a bioindicator for metal pollution monitoring in the Qatari waters (Arabian Gulf). Bull Environ Contam Toxicol 60:245–251

Al-Matar SM, Carpenter GR, Jackson R, Al-Hazeem SH, Al-Saffar AH, Abdul-Ghaffar AR, Carpenter C (1993) Observation on the pearl oyster fishery of Kuwait. J Shellfish Res 12(1): 35–40

Al-Saadi A (2013) Population structure and patterns of genetic variation in a pearl oyster (Pinctada radiata) native to the Arabian Gulf. Masters by Research thesis, Queensland University of Technology

Al-Yamani F, Saburova M (2019) Marine phytoplankton of Kuwait's waters. Vol 1 and 2. Kuwait Institute for Scientific Research, Kuwait

Amini Yekta F, Jalili M, Pourjomeh F, Hakim Elahi M, Rezaei H (2014) Distribution of molluscs in the eastern Persian Gulf, PG-GOOS cruise. J Persian Gulf 5(17)

Aqil K (2018) Pearl industry in the UAE region in 1869-1938: Its construction, reproduction, and decline. RUDN J Sociol 18(3):452–469. https://doi.org/10.22363/2313-2272-2018-18-3-452-469

Aslam S, Chan MWH, Siddiqui G, Boczkaj G, Kazmi SJH, Kazmi MR (2020) A comprehensive assessment of environmental pollution by means of heavy metal analysis for oysters' reefs at Hab River Delta, Balochistan, Pakistan. Mar Pollut Bull 153:110970. https://doi.org/10.1016/j.marpolbul.2020.110970

Awad J, Boudiaf B (2020) Re-using heritage elements in new buildings: Cases from the United Arab Emirates. Islamic Herit Archit Art III 197:11127. https://doi.org/10.2495/IHA200031

Azarbad H, Khoi AJ, Mirvaghefi A, Danekar A, Shapoori M (2010) Biosorption and bioaccumulation of heavy metals by rock oyster Saccostrea cucullata in the Persian Gulf. Int Aquat Res 2(1):61

Barboza LGA, Vethaak AD, Lavorante BR, Lundebye AK, Guilhermino L (2018) Marine microplastic debris: An emerging issue for food security, food safety and human health. Mar Pollut Bull 133:336–348. https://doi.org/10.1016/j.marpolbul.2018.05.047

Barker D, Hartnell T (2000) Notes on a decorated spiny oyster from Sharm. Arabian Archaeol Epigr 11(2):204–206. https://doi.org/10.1111/j.1600-0471.2000.aae110205.x

Beck MW, Brumbaugh RD, Airoldi L, Carranza A, Coen LD, Crawford C, Defeo O, Edgar GJ, Hancock B, Kay M, Lenihan H, Luckenbach MW, Toropova CL, Zhang G (2009) Shellfish Reefs at Risk: A Global Analysis of Problems and Solutions. The Nature Conservancy, Arlington VA, p 52

Beck MW, Brumbaugh RD, Airoldi L, Carranza A, Coen LD, Crawford C, Defeo O, Edgar GJ, Hancock B, Kay MC, Lenihan HS (2011) Oyster reefs at risk and recommendations for conservation, restoration, and management. Bioscience 61(2):107–116. https://doi.org/10.1525/bio.2011.61.2.5

Beech M (2003) The development of fishing in the UAE: a zooarchaeological perspective. In: Archaeology of the United Arab Emirates. Proceedings of the First international conference on the archaeology of the UAE, pp 289–308

Beech MJ, Cuttler RTH, Al Kaabi AK, El Faki AA, Martin J, Al Hameli NH, Roberts HM, Spencer P, Tomasi D, Brunet O, Crassard R (2020) Excavations at MR11 on Marawah Island

(Abu Dhabi, UAE): new insight into the architecture and planning of Arabian Neolithic settlements and early evidence for pearling. Arabian Archaeol Epigr 31(1):19–31. https://doi.org/10.1111/aae.12148

Ben Lamine E, Mateos-Molina D, Antonopoulou M, Burt JA, Das HS, Javed S, Muzaffar S, Giakoumi S (2020) Identifying coastal and marine priority areas for conservation in the United Arab Emirates. Biodivers Conserv 29(9):2967–2983. https://doi.org/10.1007/s10531-020-02007-4

Bendell LI, LeCadre E, Zhou W (2020) Use of sediment dwelling bivalves to biomonitor plastic particle pollution in intertidal regions; A review and study. PLoS One 15(5):e0232879. https://doi.org/10.1371/journal.pone.0232879

Bento R, Jabado RW, Sawaf M, Bejarano I, Samara F, Yaghmour F, Mateos-Molina D (2022) Oyster beds in the United Arab Emirates: important fishing grounds in need of protection. Mar Pollut Bull 182:113992

Beuck L, Aguilar R, Fabri M, Freiwald A, Gofas S, Hebbeln D, López Correa M, Ramos Martos A, Ramil F, Sanchez Delgado F, Taviani M (2016) Biotope characterisation and compiled geographical distribution of the deep-water oyster Neopycnodonte zibrowii in the Atlantic Ocean and Mediterranean Sea. Rapp Comm Int Mer Médit 41:462

Bosch DT, Dance SP, Moolenbeek RG, Oliver PG (1995) Seashells of eastern Arabia. DubaiMotivate, Dubai

Bowen RLB (1951) The pearl fisheries of the Persian Gulf. Middle East J 5(2):61–180

Burt J (2014) The environmental costs of coastal urbanization in the Arabian Gulf. City Anal Urban Trends Cult Theory Policy Action 18:760–770

Burt J, Feary D, Bauman A, Usseglio P, Cavalcante G, Sale P (2011) Biogeographic patterns of reef fish community structure in the northeastern Arabian Peninsula. ICES J Mar Sci 68:1875–1883

Carpenter KE, Krupp F, Jones DA, Zajonz U (1997) The living marine resources of Kuwait, Eastern Saudi Arabia, Bahrain, Qatar, and the United Arab Emirates, FAO species identification field guide for fishery purposes. FAO, Rome, 293 pp

Carter R (2005) The history and prehistory of pearling in the Persian Gulf. J Econ Soc Hist Orient 48(2):139–209. https://doi.org/10.1163/1568520054127149

CBD (2010) Strategic plan for biodiversity 2011-2020. https://www.cbd.int/sp/

CBD (2022) Kunming-Montreal Global Biodiversity Framework

Charpentier V, Mery S (1997) Hameçons en nacre et limes en pierre d'Océanie et de l'Océan Indien: analyse d'une tendance. Journal de la Société des Océanistes 105(2):147–156

Charpentier B, Phillips CS, Méry S (2012) Pearl fishing in the ancient world: 7500 BP. Arabian Architect Epigr 2012(23):1–6. https://doi.org/10.1111/j.1600

Clarke K (2021) Inside the UAE shellfish farm that is growing millions of oysters. The National, January 18. https://www.thenationalnews.com/uae/environment/inside-the-uae-shellfish-farm-that-is-growing-millions-of-oysters-1.1147704

Coen LD, Luckenbach MW, Breitburg DL (1999) The role of oyster reefs as essential fish habitat: a review of current knowledge and some new perspectives. In: American Fisheries Society symposium, vol 22, pp 438–454

Coles SL, Riegl BM (2013) Thermal tolerances of reef corals in the Gulf: A review of the potential for increasing coral survival and adaptation to climate change through assisted translocation. Mar Pollut Bull 72(2):323–332

Craeymeersch J, Jansen H (2019) Bivalve assemblages as hotspots for biodiversity. In: Smaal A, Ferreira JG, Grant J, Petersen JK, Strand O (eds) Goods and services of marine bivalves. Springer, Cham, pp 275–294

Cranfield HJ, Carbines G, Michael KP, Dunn A, Stotter DR, Smith DJ (2001) Promising signs of regeneration of blue cod and oyster habitat changed by dredging in Foveaux Strait, southern New Zealand. N Z J Mar Freshw Res 35:897–908

Cressman KA, Posey MH, Mallin MA, Leonard LA, Alphin TD (2003) Effects of oyster reefs on water quality in a tidal creek estuary. J Shellfish Res 22(3):753–762

Crisp DJ (1967) Chemical factors inducing settlement in Crassostrea virginica (Gmelin). J Anim Ecol 36(329-336):1974
De Mora S, Fowler SW, Wyse E, Azemard S (2004) Distribution of heavy metals in marine bivalves, fish and coastal sediments in the Gulf and Gulf of Oman. Mar Pollut Bull 49(5–6):410–424
De Mora S, Tolosa I, Fowler SW, Villeneuve J-P, Cassi R, Cattini C (2010) Distribution of petroleum hydrocarbons and organochlorinated contaminants in marine biota and coastal sediments from the ROPME sea area during 2005. Mar Pollut Bull 60:2323–2349. https://doi.org/10.1016/j.marpolbul.2010.09.021
Doroudi MS, Southgate PC (2002) The effect of chemical cues on settlement behaviour of blacklip pearl oyster (Pinctada margaritifera) larvae. Aquaculture 209(1–4):117–124. https://doi.org/10.1016/S0044-8486(01)00736-0
EAD (Environment Agency Abu Dhabi) (2008) Marine and coastal environment of Abu Dhabi Emirate, United Arab Emirates. Environment Agency, Abu Dhabi. 112 p
Eddy TD, Lam VW, Reygondeau G, Cisneros-Montemayor AM, Greer K, Palomares MLD, Bruno JF, Ota Y, Cheung WW (2021) Global decline in capacity of coral reefs to provide ecosystem services. One Earth 4(9):1278–1285
Emery KO (1956) Sediments and water of Persian Gulf. AAPG Bull 40(10):2354–2383
Enright GF, Enright CT, Newkirk GF, Craigie JS, Castell JD (1986) Evaluation of phytoplankton as diets for juvenile Ostrea edulis L. J Exp Mar Biol Ecol 96(1):1–13
Epifanio CE (1979) Growth in bivalve molluscs: Nutritional effects of two or more species of algae in diets fed to the American oyster Crassostrea virginica (Gmelin) and the hard clam Mercenaria mercenaria (L.). Aquaculture 18(1):1–12
Falkowski PG, Katz ME, Knoll AH, Quigg A, Raven JA, Schofield O, Taylor FJR (2004) The evolution of modern eukaryotic phytoplankton. Science 305(5682):354–360
Farhadi A, Farahmand H, Mirvaghefi A, Khalili B (2011) A genotoxicological study in Persian Gulf on Rock Oyster (Soccostrea cucullata) using micronuclei and RAPID assays. Int J Environ Res 5:567–572
Fawzi NAM, Fieseler CM, Helmuth B, Leitão A, Al-Ainsi M, Al Mukaimi M, Al-Saidi M, Al Senafi F, Bejarano I, Ben-Hamadou R, D'Addario J, Mohamed AMD, Giraldes BW, Glowka L, Johnson MD, Lyons BP, Mateos-Molina D, Marshall CD, Mohammed S, Naser HA, Range P, Shokri MR, Wong JMK, Pyensosn ND (2022) Diplomacy for the world's hottest sea. Science 376(6600):1389–1390
Feary DA, Burt JA, Bauman AG, Usseglio P, Sale PF, Cavalcante GH (2010) Fish communities on the world's warmest reefs: what can they tell us about the effects of climate change in the future? J Fish Biol 77(8):1931–1947
Feulner GR, Hornby RJ (2006) Intertidal mollusks in UAE lagoons. Tribulus 16(2):17–23
George DJ (2005) Marine invertebrates. In: Hellyer P, Aspinall S (eds) The Emirates: a natural history. Trident, London, pp 197–221, 356–360
George DJ (2012) Reef-associated macroinvertebrates of the SE Gulf. In: Riegl BM, Purkis SJ (eds) Coral reefs of the Gulf, adaptation to climatic extremes. Springer, New York, pp 253–307. https://doi.org/10.1007/978-94-007-3008-3
Gomes H, Goes JI, Matondkar SGP, Buskey EJ, Basu S, Parab S, Thoppil P (2014) Massive outbreaks of Noctiluca scintillans blooms in the Arabian Sea due to spread of hypoxia. Nat Commun 5. https://doi.org/10.1038/ncomms5862
Goswami P, Vinithkumar NV, Dharani G (2021) Microplastics particles in seafloor sediments along the Arabia Sea and the Andaman Sea continental shelves: First insight on the occurrence, identification, and characterization. Mar Pollut Bull 167:112311. https://doi.org/10.1016/j.marpolbul.2021.112311
Grabowski JH, Peterson CH (2007) Restoring oyster reefs to recover ecosystem services. Ecosyst Eng Plants Protists 4:281–298

Grandcourt E (2012) Reef fish and fisheries in the Gulf. In: Riegl BM, Purkis S (eds) Coral reefs of the Gulf: adaptation to climatic extremes. Springer, Dordrecht, pp 127–161. https://doi.org/10.1007/978-94-007-3008-3

Grizzle RE, Bricelj VM, AlShihi RM, Ward KM, Anderson DM (2018) Mollusks in nearshore habitats of the United Arab Emirates decadal changes and species of public health significance. J Coast Res 34:1157–1175. https://doi.org/10.2112/JCOASTRES-D-17-00119.1

Hallegraeff GM (1993) A review of harmful algal blooms and their apparent global increase. Phycologia 32(2):79–99

Hallegraeff GM, Anderson DM, Cembella AD, Enevoldsen HO (2004) Manual on harmful marine microalgae. UNESCO, Paris

Hammadi M, Knuteson S, Kanan S, Samara F (2022) Microplastic pollution in oyster bed ecosystems: An assessment of the northern shores of the United Arab Emirates. Environ Adv 8:100214. https://doi.org/10.1016/J.ENVADV.2022.100214

Hawker R, Hull D, Rouhani O (2005) Wind-towers and pearl fishing: architectural signals in the late nineteenth and early twentieth century Arabian Gulf. Antiquity 79:625–635. https://doi.org/10.1017/S0003598X00114565

Heard-Bey F (2001) The Tribal society of the UAE and its traditional economy. In: Al Abed I, Hellyer P (eds) United Arab Emirates: a new perspective. Trident, London

Hellyer, P. and Hull, D. 2002. The Archaeology of Abu Al Abyad, in The Island of Abu Al Abyad (R. Perry [ed.]), ERWDA. Abu Dhabi. pp. 17-38

Hightower VP (2013) Pearls and the Southern Persian/Arabian Gulf: a lesson in sustainability. Environ Hist 18(1):44–59

Hori M, Hamaguchi M, Sato M, Tremblay R, Correia-Martins A, Derolez V, Richard M (2020) Oyster aquaculture using seagrass beds as a climate change countermeasure. Bull Jap Fish Res Edu Agen No 50:123–133

Huber M (2015) Compendium of Bivalves 2. A full-color guide to the remaining seven families. A systematic listing of 8'500 bivalve species and 10'500 synonyms. ConchBooks, Harxheim

Ibrahim A-M, David S, Bruno G, Mark C, Mohammed A-M, Lewis LV (2018) Decline in oyster populations in traditional fishing grounds; is habitat damage by static fishing gear a contributory factor in ecosystem degradation? J Sea Res 140:40–51. https://doi.org/10.1016/j.seares.2018.07.006

Johnson MW, Powers SP, Senne J, K. Park K. (2009) Assessing in situ tolerances of Eastern oysters (Crassostrea virginica) under moderate hypoxic regimes: implications for restoration. J Shellfish Res 28:185–192

Karami AM, Riyahi Bakhtiari A, Kazemi A, Kheirabadi N (2014) Assessment of toxic metals concentration using pearl oyster, Pinctada radiata, as bioindicator on the coast of Persian Gulf, Iran. Iran J Toxicol 7(23) http://www.ijt.ir

Kinsman DJJ (1964) Reef coral tolerance of high temperatures and salinities. Nature 202:1280–1282. https://doi.org/10.1038/2021280a0

Korringa P (1946) The decline of natural oyster beds. Basteria 10(3/4):36–41

Krassoi FR, Brown KR, Bishop MJ, Kelaher BP, Summerhayes S (2008) Condition-specific competition allows coexistence of competitively superior exotic oysters with native oysters. J Anim Ecol 77(1):5–15. https://doi.org/10.1111/j.1365-2656.2007.01316.x

La Peyre MK, Aguilar Marshall D, Miller LS, Humphries AT (2019) Oyster reefs in northern Gulf of Mexico estuaries harbor diverse fish and decapod crustacean assemblages: a meta-synthesis. Front Mar Sci 6:666

Laugen AT, Hollander J, Obst M, Strand Å (2015) The Pacific oyster (Crassostrea gigas) invasion in Scandinavian coastal waters: impact on local ecosystem services. In: Biological invasions in aquatic and terrestrial systems: biogeography, ecological impacts, predictions, and management. De Gruyter Open, Berlin, pp 230–252

Leitão A, Al-Shaikh I, Hassan H, Ben Hamadou R, Bach S (2017) First genotoxicity assessment of marine environment in Qatar using the local pearl oyster Pinctada radiata. Reg Stud Mar Sci 11:23–31. https://doi.org/10.1016/j.rsma.2017.02.001

Lemasson AJ, Fletcher S, Hall-Spencer JM, Knights AM (2017) Linking the biological impacts of ocean acidification on oysters to changes in ecosystem services: A review. J Exp Mar Biol Ecol 492:49–62. https://doi.org/10.1016/j.jembe.2017.01.019

Lenihan HS, Micheli F, Shelton SW, Peterson CH (1999) The influence of multiple environmental stressors on susceptibility to parasites: an experimental determination with oysters. Limnol Oceanogr 44(3 part 2):910–924

Lidour K, Beech MJ (2019) At the dawn of Arabian fisheries: Fishing activities of the inhabitants of the Neolithic tripartite house of Marawah Island, Abu Dhabi Emirate (United Arab Emirates). Arabian Archaeol Epigr 31(1):140–150. https://doi.org/10.1111/aae.12134

Lidour K, Béarez P, Charpentier V, Méry S (2020) The prehistoric fisheries of Akab Island (United Arab Emirates): New insights into coastal subsistence during Neolithic in eastern Arabia. J Island Coast Archaeol 15(1):80–103. https://doi.org/10.1080/15564894.2018.1531330

Lin J, Xu X, Yue B, Xu X, Liu J, Zhu Q, Wang J (2021) Multidecadal records of microplastic accumulation in the coastal sediments of the East China Sea. Chemosphere 270:128658. https://doi.org/10.1016/j.chemosphere.2020.128658

Mahgoub Y (1999) Architecture of the United Arab Emirates, from The Architecture of the United Arab Emirates. http://victorian.fortunecity.com/dali/428/uaearch/uaearch1.htm

Mallin MA, Williams KE, Esham EC, Lowe RP (2000) Effect of human development on bacteriological water quality in coastal watersheds. Ecol Appl 10(4):1047–1056

Mateos-Molina D, Antonopoulou M, Baldwin R, Bejarano I, Burt JA, Garcia-Charton JA, Taylor OJS (2020) Applying an integrated approach to coastal marine habitat mapping in the north-western United Arab Emirates. Mar Environ Res 161:105095. https://doi.org/10.1016/j.marenvres.2020.105095

Mateos-Molina D, Lamine EB, Antonopoulou M, Burt JA, Das HS, Javed S, Judas J, Khan SB, Muzaffar SB, Pilcher N, Rodriguez-Zarate CJ (2021a) Synthesis and evaluation of coastal and marine biodiversity spatial information in the United Arab Emirates for ecosystem-based management. Mar Pollut Bull 167:112319. https://doi.org/10.1016/j.marpolbul.2021.112319

Mateos-Molina D, Pittman SJ, Antonopoulou M, Baldwin R, Chakraborty A, García-Charton JA, Taylor OJS (2021b) An integrative and participatory coastal habitat mapping framework for sustainable development actions in the United Arab Emirates. Appl Geogr 136:102568

Méry S, Charpentier V, Beech M (2008) First evidence of shell fish-hook technology in the Gulf. Arabian Archaeol Epigr 19(1):15–21. https://doi.org/10.1111/j.1600-0471.2007.00289.x

Meyer DL, Townsend EC, Thayer G (1997) Stabilization and erosion control value of oyster cultch for intertidal marsh. Restor Ecol 5:93–99

Mohammed SZ, Yassien MH (2003) 2003. Population parameters of the pearl oyster *Pinctada radiata* (Leach) in Qatari waters, Arabian Gulf. Turk J Zool 27(4):339–343

Murugesan K, Juma IM, Khan AS (2017) Blooms of Noctiluca scintillans and its association with Thalia sp (salps) in Dubai coastal waters. Res J Environ Sci 11:101–107

Nasci C, Da Ros L, Campesan G, Van Vleet ES, Salizzato M, Sperni L, Pavoni B (1999) Clam transplantation and stress-related biomarkers as useful tools for assessing water quality in coastal environments. Mar Pollut Bull 39:255–260

Nelson KA, Leonard LA, Posey MH, Alphin TD, Mallin MA (2004) Using transplanted oyster (Crassostrea virginica) beds to improve water quality in small tidal creeks: a pilot study. J Exp Mar Biol Ecol 298(2):347–368

Newell RI (2004) Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve molluscs: a review. J Shellfish Res 23(1):51–62

Norse EA (2010) Ecosystem-based spatial planning and management of marine fisheries: why and how? Bull Mar Sci 86(2):179–195

Nourozifard P, Mortazavi S, Asad S, Hassanzadeh N (2020) Using Saccostrea cucullata as a biomonitor of heavy metals (Cu, Pb, Zn, Cd, Ni, and Cr) in water and sediments of Qeshm Island, Persian Gulf. ECOPERSIA 8(3):181–190

Ogburn DM, White I, McPhee DP (2007) The disappearance of oyster reefs from Eastern Australian estuaries—impact of colonial settlement or mudworm invasion? Coast Manag 35(2–3): 271–287. https://doi.org/10.1080/08920750601169618

Peixoto D et al (2019) Microplastic pollution in commercial salt for human consumption: a review. Estuar Coast Shelf Sci 219:161–168. https://doi.org/10.1016/j.ecss.2019.02.018

Pittman SJ, Stamoulis KA, Antonopoulou M, Das HS, Shahid M, Delevaux J, Wedding LM, Mateos-Molina D. (2022) Rapid site selection to prioritize coastal seascapes for nature-based solutions with multiple benefits. Front Mar Sci 2022 Apr 29; 9:571

Polidoro BA, Carpenter KE, Collins L, Duke NC, Ellison AM, Ellison JC, Farnsworth EJ, Fernando ES, Kathiresan K, Koedam NE, Livingstone SR (2010) The loss of species: mangrove extinction risk and geographic areas of global concern. PLoS One 5(4):e10095. https://doi.org/10.1371/journal.pone.0010095

Price ARG, Izsak C (2005) Is the Arabian Gulf really such a lowspot of biodiversity?: Scaling effects and management implications. Aquat Ecosyst Health Manag 8(4):363–366. https://doi.org/10.1080/14634980500457757

Quigg A, Chin WC, Chen CS, Zhang S, Jiang Y, Miao AJ, Schwehr KA, Xu C, Santschi PH (2013) Direct and indirect toxic effects of engineered nanoparticles on algae: role of natural organic matter. ACS Sustain Chem Eng 1(7):686–702

Rashdan W, Mhatre V (2019) Impact of heritage on contemporary sustainable interior design solutions. WIT Trans Ecol Environ 238:47–58. https://doi.org/10.2495/SC190051

Richlen ML, Morton SL, Jamali EA, Rajan A, Anderson DM (2010) The catastrophic 2008–2009 red tide in the Arabian gulf region, with observations on the identification and phylogeny of the fish-killing dinoflagellate Cochlodinium polykrikoides. Harmful Algae 9:163–172

Riegl B, Purkis S (2012) Coral reefs of the Gulf: Adaptation to climatic extremes. Vol. 3, Coral reefs of the world. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-3008-3_194-007-3008-3_1

Ruckelshaus M, Doney S, Galindo H, Barry J, Chan F, Duffy J et al (2013) Securing ocean benefits for society in the face of climate change. Mar Policy 40:154–159

Ruesink JL, Lenihan HS, Trimble AC, Heiman KW, Micheli F, Byers JE, Kay MC (2005) Introduction of non-native oysters: Ecosystem effects and restoration implications. Annu Rev Ecol Evol Syst 2005(36):643–689

Samara F, Solovieva N, Ghalayini T, Nasrallah ZA, Saburova M (2020) Assessment of the environmental status of the mangrove ecosystem in the United Arab Emirates. Water 12(6): 1623. https://doi.org/10.3390/W12061623

Samara F, Bejarano I, Mateos-Molina D, Abouleish M, Solovieva N, Yaghmour F, Ali T, Saburova M (2023) Environmental assessment of oyster beds in the northern Arabian Gulf Coast of the United Arab Emirates. Mar Pollut Bull 195:115442. https://doi.org/10.1016/j.marpolbul.2023.115442

Scanes E, Johnston E, Cole V, O'Connor W, Parker L, Ross P (2016) Quantifying abundance and distribution of native and invasive oysters in an urbanised estuary. Aquat Invasions 11(4): 425–436. https://doi.org/10.3391/ai.2016.11.4.07

Schulte DM, Burke RP, Lipcius RN (2009) Unprecedented restoration of a native oyster metapopulation. Science 325(5944):1124–1128. https://doi.org/10.1126/science.1176516

Sheppard C, Price A, Roberts C (1992) Marine ecology of the Arabian region: patterns and processes in extreme tropical environments. Academic, London

Sheppard C, Al-Husiani M, Al-Jamali F, Al-Yamani F, Baldwin R, Bishop J et al (2010) The Gulf: a young sea in decline. Mar Pollut Bull 60(1):13–38. https://doi.org/10.1016/j.marpolbul.2009.10.017

Sheppard C, Al-Husiani M, Al-Jamali F, Al-Yamani F, Baldwin R, Bishop J, Benzoni F, Dutrieux E, Dulvy NK, Durvasula SRV, Jones DA (2012) Environmental concerns for the future of Gulf coral reefs. Coral Reefs of the Gulf: adaptation to climatic extremes, pp:349–373. https://doi.org/10.1007/978-94-007-3008-3_16

Shirneshan G, Riyahi Bakhtiari A, Kazemi A, Mohamadi M, Kheirabadi N (2012) Oyster Saccostrea cucullata as a Biomonitor for Hg Contamination and the Risk to Humans on the Coast of Qeshm Island, Persian Gulf, Iran. Bull Environ Contam Toxicol 88:962–966. https://doi.org/10.1007/s00128-012-0607-x

Smyth D, Ibrahim A-M, Bruno G, Mark C (2015) Investigating the biodiversity and current status of the historically renowned oyster beds of Qatar. QScience Proc 2015(5):23. https://doi.org/10.5339/qproc.2015.qulss2015.23

Smyth D, Al-Maslamani I, Chatting M, Giraldes B (2016) Benthic surveys of the historic pearl oyster beds of Qatar reveal a dramatic ecological change. Mar Pollut Bull 113(1-2):147–155. https://doi.org/10.1016/j.marpolbul.2016.08.085

Somer (2003) State of the marine environment report. ROPME/GC-11/003. Regional Organization for the Protection of the Marine Environment, Kuwait

Stoecker DK (1998) Conceptual models of mixotrophy in planktonic protists and some ecological and evolutionary implications. Eur J Protistol 34(3):281–290

Taviani M, Angeletti L, Cardone F, Montagna P, Danovaro R (2019) A unique and threatened deep water coral-bivalve biotope new to the Mediterranean Sea offshore the Naples megalopolis. Sci Rep 2019(9):12

Teng J, Wang Q, Ran W, Wu D, Liu Y, Sun S, Liu H, Cao R, Zhao J (2019) Microplastic in cultured oysters from different coastal areas of China. Sci Total Environ 653:1282–1292. https://doi.org/10.1016/j.scitotenv.2018.11.057

Thornton DCO (2012) Primary production in the ocean. In: Najafpour M (ed) Advances in photosynthesis—fundamental aspects. InTech, Rijeka, Croatia, pp 563–588

Tlig-Zouari S, Rabaoui L, Irathni I, Ben Hassine OK (2009) Distribution, habitat and population densities of the invasive species Pinctada radiata (Molluca: Bivalvia) along the Northern and Eastern coasts of Tunisia. Cahiers de Biologie Marine 50(2):131

UAE National Biodiversity Strategy and Action Plan, 2014–2021. https://beeatna.ae/en/national-biodiversity-strategy

USDOC (U.S. Department of Commerce) (1997) Magnuson-Stevens Fishery Conservation and Management Act, as amended through October 11, 1996. National Oceanic and Atmospheric Administration Technical Memorandum NMFS-F/SPO-23. U.S. Government Printing Office, Washington, DC

Vaezzadeh V, Zakaria M, Bong C, Masood N, Magam S, Alkhadher S (2017) Mangrove oyster (Crassostrea belcheri) as a biomonitor species for bioavailability of polycyclic aromatic hydrocarbons (PAHs) from sediment of the West Coast of Peninsular Malaysia. Polycyclic Aromat Comp 39:1–16. https://doi.org/10.1080/10406638.2017.1348366

Van Erde C (2018) Reviving the pearling industry in the UAE, May 17. The Gemmological Association of Britain. https://gem-a.com/gem-hub/around-the-world/pearl-industry-uae-dubai-bahrain-gulf

Van Lavieren H, Burt J, Feary D, Cavalcante G, Marquis E, Benedetti L, Trick C, Kjerfve B, Sale PF (2011) Managing the growing impacts of development on fragile coastal and marine systems: Lessons from the Gulf. A policy report. United Nations University – Institute for Water, Environment, and Health, Hamilton, ON

Van Rooij D, DeMol L, LeGuilloux E, Wisshak M, Huvenne VAI, Moeremans R, Henriet J-P (2010) Environmental setting of deep-water oysters in the Bay of Biscay. Deep Sea Res I Oceanogr Res Pap 57:1561–1572

Waycott M, Duarte CM, Carruthers TJ, Orth RJ, Dennison WC, Olyarnik S, Calladine A, Fourqurean JW, Heck KL Jr, Hughes AR, Kendrick GA (2009) Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc Natl Acad Sci USA 106(30):12377–12381

Wells HW (1961) The fauna of oyster beds, with special reference to the salinity factor. Ecol Monogr 31(3):239–266

Xiao X, Agustí S, Pan Y, Yu Y, Li K, Wu J, Duarte CM (2019) Warming amplifies the Frequency of harmful algal blooms with eutrophication in Chinese coastal waters. Environ Sci Technol 53(22):13031–13041

Yukihira H, Klumpp DW, Lucas JS (1999) Feeding adaptations of the pearl oysters Pinctada margaritifera and P. maxima to variations in natural particulates. Mar Ecol Prog Ser 182:161–173

Zhao J, Ghedira H (2014) Monitoring red tide with satellite imagery and numerical models: A case study in the Arabian Gulf. Mar Pollut Bull 79(1–2):305–313

Zhao B, Zhang S, Qian PY (2003) Larval settlement of the silver-or goldlip pearl oyster Pinctada maxima (Jameson) in response to natural biofilms and chemical cues. Aquaculture 220(1–4): 883–901

Zhu X, Qiang L, Shi H, Cheng J (2020) Bioaccumulation of microplastics and it's in vivo interactions with trace metals in edible oysters. Mar Pollut Bull 154:111079. https://doi.org/10.1016/j.marpolbul.2020.111079

Zimmer-Faust RK, Tamburri MN (1994) Chemical identity and ecological implications of a waterborne, larval settlement cue. Limnol Oceanogr 39(5):1075–1087

Zu Ermgassen PS, Spalding MD, Blake B, Coen LD, Dumbauld B, Geiger S et al (2012) Historical ecology with real numbers: past and present extent and biomass of an imperilled estuarine habitat. Proc Biol Sci 279(1742):3393–3400

Zu Ermgassen P, Bos O, Debney A, Gamble C, Glover A, Pogoda B, Pouvreau S, Sanderson W, Smyth D, Preston J (2021) European native oyster habitat restoration monitoring handbook. November 2021. Retrieved July 12, 2022, from https://www.decadeonrestoration.org/

Part III
Organisms and Their Environment

Chapter 13
The Vascular Flora of the United Arab Emirates

Gary Brown and Gary R. Feulner

13.1 Vascular Plant Species of the UAE

This chapter discusses the flora of the United Arab Emirates (UAE), i.e. various aspects of the individual plant species. Chapter 5, on the other hand, examines many of the typical plant assemblages (i.e. recurring combinations of different plant species) in the country and the underlying environmental factors determining their occurrence. Chapter 6 deals with specific issues relating to the mountain ecosystems.

Vascular plants comprise three major systematic groups, the angiosperms ('flowering plants'), the gymnosperms (evergreen plants that do not produce flowers or fruits) and the pteridophytes (ferns). Ferns are non-flowering plants that reproduce by spores, rather than seeds, but like the angiosperms and gymnosperms, they possess roots, stems and complex leaves.

Given the lack of English common names for most plant species of the Emirates, the scientific nomenclature follows that of Jongbloed et al. (2003) to allow non-specialist readers the opportunity to check plants in that widely used field guide.

Jongbloed et al. (2003) give an outline of 668 vascular plant species that are known from the UAE. In a few cases, species are included that were recorded from the immediately adjacent areas of Oman, but not necessarily from the UAE itself. In addition, the authors mention eight freshwater species, thus yielding a total of 676 species. This figure contrasts markedly with the ca. 500 species known just 15 years previously (see Western 1989). Although a number of additional species have been recorded in the meantime, many of these are casual weeds that occasionally put in a fleeting appearance (e.g. Aspinall 2006; Shahid 2014; Shahid and Rao

G. Brown (✉)
Centre for Biodiversity Monitoring and Conservation Science, Leibniz Institute for the Analysis of Biodiversity Change, Bonn, Germany

G. R. Feulner
Dubai Natural History Group, Dubai, UAE

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_13

2014a, b; Gairola et al. 2015; Mahmoud et al. 2015a, b, 2016; Sakkir et al. 2020). This means that the work by the earlier authors can be regarded as remarkably comprehensive and represents a powerful testimony to their dedication, especially as this was often undertaken on a voluntary basis by largely non-professional botanists. According to Shahid and Rao (2015), the total number of species found in the UAE, including casual weeds, stood at 809. However, at a recent workshop, the total number regarded as native species (defined as those present prior to the commencement of traditional agriculture at ca. 4500 BP) was whittled down to 598 (Allen et al. 2021).

The 676 listed species by Jongbloed et al. (2003) belong to about 85 families, the most species-rich being the Poaceae (grass family). As in many other parts of the world, grasses are one of the most important families in the UAE, both ecologically and economically. The family contains widespread perennial grasses of sand sheets such as *Panicum turgidum*, *Pennisetum divisum* and *Stipagrostis plumosa*. Other common grass species, at least locally, include *Cenchrus ciliaris*, *Enneapogon desvauxii*, *Stipagrostis hirtigluma* (all fairly widespread in the mountains) and *Dichanthium foveolatum* (coastal habitats and mountains).

In the meantime, the Chenopodiaceae (Goosefoot family or chenopods) have been incorporated into Amaranthaceae to give a relatively large, species-rich family. Whereas the members of the Amaranthaceae s. str. were typically species of disturbed or cultivated ground in the UAE, various members of the former Chenopodiaceae are dominant in widespread natural plant communities, such as *Haloxylon salicornicum*, *Haloxylon persicum* and *Salsola* spp. This group contains a number of distinctly halophytic (salt tolerant) species (e.g. *Arthrocnemum macrostachyum*, *Halocnemum strobilaceum*, *Halopeplis perfoliata*, *Salicornia sinus-persica*), and ones that generally avoid saline substrates (e.g. *Haloxylon salicornicum*, *Haloxylon persicum*). Recent studies from Qatar indicate that the *Salicornia* species in the region is not *S. europaea*, as was previously assumed, but *S. sinus-persica* (Richer et al. 2022).

The Asteraceae (Daisy family) is a large family containing several taxonomically difficult species. Based on fairly recent work, the species referred to in Jongbloed et al. (2003) as *Echinops* sp. is now known to be *Echinops erinaceus* (Fig. 13.1; Feulner 2014). *Helichrysum makranicum* is now regarded belonging to the more widespread *H. glumaceum*, and *Phagnalon viridifolium* is considered a synonym of *P. schweinfurthii*.

Unlike the former Chenopodiaceae and in contrast to some adjacent regions, there are no plants communities in the UAE in which members of Asteraceae predominate, with the possible exception of *Rhanterium epapposum*. This dwarf shrub was once locally dominant in small patches on sand sheets in the vicinity of Dubai and also on interdunal plains, but moderate to heavy grazing has led to the decline of this highly palatable species.

Although relatively poor in species, the taxonomically difficult Zygophyllaceae are well represented in terms of community presence, with *Fagonia indica*/*F. ovalifolia*, *Zygophyllum simplex* (Fig. 13.2) and *Z. qatarense* agg. widespread

Fig. 13.1 *Echinops erinaceus* in the Hatta Mountain Conservation Reserve. Photo credit: Gary Brown

Fig. 13.2 *Zygophyllum simplex* is a widespread species in the northern part of the UAE. Photo credit: Gary Brown

in the country. These species are generally avoided by livestock, which may explain their predominance.

The Pea family (Fabaceae) contains a number of genera that play a prominent ecological role in terrestrial habitats in the country. These include *Astragalus* (a species-rich genus), *Crotalaria*, *Indigofera*, *Lotus*, *Rhynchosia*, *Taverniera* and *Tephrosia*. Also often included are the native shrubs and trees *Acacia tortilis* (see Fig. 5.6, Chap. 5), *A. ehrenbergiana* and *Prosopis cineraria*. On account of their flower arrangement and structure, these are often placed in a separate subfamily or family (Mimosaceae). The Cyperaceae (Sedge family) is an example of a family that is extremely poor in terms of native desert species, but it does contain *Cyperus conglomeratus,* which is one of the most common and widespread species throughout the desert, albeit taxonomically difficult (see below). Conversely, the Brassicaceae (Mustard family) is a species-rich family that contains various perennial shrubs and desert annuals. What is striking about this family is that a number of genera contain just one (e.g. *Anastatica*, *Eremobium*, *Morettia*, *Notoceras*, *Savignya*, *Schimpera* and *Zilla*) or few native species (e.g. *Erucaria*). *Eremobium aegyptiacum* and to a lesser extent *Savignya parviflora* are two of the more widespread and common annuals of desert habitats in the country. Other species-rich families in the UAE are the Boraginaceae, Caryophyllaceae, Euphorbiaceae apart from the Poaceae mentioned above. As a result of recent studies, some families have been abandoned. Apart from the Chenopodiaceae, the gray mangrove *Avicennia marina* is now placed in the Acanthaceae (formerly Avicenniaceae).

Only two gymnosperms are known from the UAE, both belonging to the genus *Ephedra*. Whereas *E. foliata* is fairly widespread in the east of the country north of Al Ain, *E. pachyclada* is a mountain species restricted to just a few sites, predominantly in the Ru'us Al Jibal, but also on the summit ridge of Jebel Qitab, south-west of Fujairah city (Feulner 2014).

According to Jongbloed et al. (2003), the UAE is possibly home to eight species of fern. It is, however, likely that a few of these may not occur in the UAE itself but immediately over the border in the neighboring parts of Oman. Due to the extreme climate, native ferns typically have a requirement for shade and high moisture input, and so seven of the species are only found in the Hajar Mountains, where they find more amenable environmental conditions for growth. Only one species, *Ophioglossum polyphyllum*, is known from desert areas, especially close to the coast in the north-east of the country. Many of these sites have probably been lost to coastal development and degradation in the meantime. It has, however, also been found on abandoned agricultural terraces in one part of the Hajar Mountains (Feulner 2016), which represents a very different type of habitat. Perhaps the two most widespread mountain fern species are *Adiantum capillus-veneris* (Maidenhair fern), which is characteristic of freshwater habitats such as seeps and springs as well as irrigation channels, and *Onychium divaricatum*. The latter occurs in shaded microhabitats on mountain slopes where small pockets of soil accumulate, and it is therefore not associated with freshwater habitats.

New native species since the publication Jongbloed et al. (2003) include the annual *Silene arabica* on sand (Shahid and Rao 2014b). The record of this to date

Fig. 13.3 The rare *Schimpera arabica* is known in the UAE only from a few locations on near-coastal sands in Ajman and Umm Al Quwain. Photo credit: Gary Brown

overlooked species is not entirely surprising as it probably one of those that only occur in small numbers in particularly wet winters in the deserts of the north-east (Ras Al Khaimah, Umm Al Quwain, Sharjah), as is the case of some other species such as the grass *Cutandia dichotoma* (Brown et al. 2006) and the rare *Schimpera arabica* (Fig. 13.3), all of which are more frequent in the northern part of the Arabian Peninsula. In the mountains, Feulner and Karki (2009) recorded the perennial grass *Saccharum kajkaiense* in wadis in the Hajar Mountains, and the presence of *Launaea omanensis* in the UAE has been confirmed (Feulner 2014, 2016). Feulner (2011) added a list of 23 species (some unidentified) that are new to the Ru'us Al Jibal, as well as another 16 published Ru'us Al Jibal records that had been overlooked in prior compilations for the UAE and Oman, but it is possible that as many as 10 of that total may not occur within the UAE section of the Ru'us al Jibal due to special circumstances (e.g. collection at the very summit of Jebel Harim or in abandoned cultivation at ca.1600 m, or at the singular spring at Ain As-Si.

13.2 Taxonomic Issues Relating to the Flora of the UAE

A sound knowledge of the organisms present in a given geographical area is pivotal to effective biodiversity conservation. The seemingly simple assignment of individuals to distinct taxonomic groups is fraught with many and complex difficulties.

Despite, therefore, that the number of species in the UAE may appear rather limited, a number of those species are regarded as 'difficult' from a taxonomic perspective. Some of these are widespread and dominant taxa, such as *Cyperus conglomeratus*, *Fagonia indica* (Fig. 13.4) and *F. ovalifolia*, *Heliotropium bacciferum* and *H. kotschyi*, and *Zygophyllum qatarense* (Fig. 13.5). These can be referred to as 'critical plant groups', broadly defined as ones that are difficult to identify (Rich 2006).

The morphological species concept continues to prevail in plant conservation biology. This means that species are recognised primarily by morphological features, rather than based on, for instance, evolutionary history, which typically relies on genetic data. Strict adherence to the traditional morphological concept can

Fig. 13.4 *Fagonia indica* (now regarded by some as *Zygophyllum indicum*) is a highly variable species. Photo credit: Gary Brown

Fig. 13.5 The *Zygophyllum* taxon that grows on limestone rock on Jebel Hafeet is morphologically distinct from the desert forms of *Z. qatarense*. Moreover, it shows considerable morphological variation from one year to another. Photo credit: Gary Brown

underestimate the number of species present (e.g. cryptic species are overlooked), but ‘modern’, molecular-based approaches are not without their own problems (e.g. Freudenstein et al. 2017), not least because DNA bar-coding suffers severe limitations in some cases (e.g. Piredda et al. 2011).

There are several major issues that complicate the taxonomic treatment of species more generally. The first refers to the actual identity of a certain taxon. In some cases, it is difficult to know with certainty what the original author was referring to, if, for example, the type specimen has been lost (e.g. as in the case of *Cyperus conglomeratus*). A second, often neglected issue is that a ‘species’ as such is an artificial concept devised by humans to create order in an extremely complex system. Different experts frequently have different concepts of how to delimit certain species. What for one expert is a ‘good’ species, may be regarded by another as ‘only’ a subspecies of a broader species group. Such problems are frequently the result of morphological variation within a group of individuals, which is typically the rule, or simply that some taxa are inherently difficult. The problem of when to differentiate between two ‘good’ species is not always easy with plants, especially as the borders are sometimes ‘fuzzy’ (Mayr 1988). Although extremely useful in many cases, the application of molecular criteria (i.e. genetic analyses) does not offer a universal solution either. In fact, in some cases, the same problems persist, especially where to draw the line to delimit individuals and categorise them as members of separate species.

A third issue pertains to the naming of species, which can be frustrating for some taxa. Although this process should be based on scientific principles, it is clear that personal interpretation and preferences also play a role. Some taxa (e.g. *Caralluma* and related taxa in neighbouring Oman) are notorious regarding the plethora of different names that have been applied to them. However, *Caralluma arabica* (Fig. 13.6), a species largely confined to the Hajar Mountains, is fairly straightforward in that it currently has just one alternative name, *Desmidorchis arabica*.

The proposed splitting up of the genus *Acacia* into three separate genera (meaning that all Arabian species would be transferred to the genus *Vachellia*) elicited heated discussions at the International Botanical Congress in Vienna in 2005 and it is unclear whether the decision to approve the proposal was valid (Brummitt 2010). For compelling practical reasons of nomenclatural stability, it seems sensible to protect *Acacia* as a ‘conserved name’ (‘*nomen conservandum*’—a scientific name that has special nomenclatural protection), as suggested by Brummitt 2010.

‘Fans’ of the relatively new genus *Tetraena* are in for a disappointment. Based on the latest, generally accepted information (e.g. Kew: Plants of the World Online), members of this genus are once again regarded as belonging to *Zygophyllum*. This means that *Tetraena qatarensis* can be discarded and it reverts to its ‘old’ name, *Zygophyllum qatarense*. Not only that, but due to the lack of reliable distinguishing features, the entire genus *Fagonia* has been embedded in *Zygophyllum* (see, for example, Richer et al. 2022). The widespread *Fagonia indica* is therefore now referred to as *Zygophyllum indicum*. It is only a matter of time (typically 5–10 years) before other ‘new’—or even old—names are applied to these same taxa.

Fig. 13.6 *Caralluma arabica* is a stem succulent species restricted to the Hajar Mountains in the UAE. Photo credit: Gary Brown

With respect to the conservation of species, it is human nature that people are usually obsessed with species—lower ranks such as subspecies often get swept under the carpet. There are some exceptions to this general observation, especially in the animal kingdom in the UAE. For instance, organisations are (rightfully) very quick to emphasise the presence of the endemic subspecies of the White Collared Kingfisher at Kalba. But in general terms and certainly with plants, anything below the rank of a 'good' species is ignored. This is despite the fact that the Convention on Biological Diversity (Secretariat of the Convention on Biological Diversity 2005) explicitly underlines the importance of intraspecific variation, i.e. genetic variation within species. Moreover, despite the central role that plant taxonomy plays in biodiversity conservation, there has been a constant decline of classical taxonomic and ecological expertise over the past decades, which can be assumed to be highly detrimental to the cause of biodiversity protection (e.g. Akeroyd 2006).

13.3 Biogeographical Aspects of the Flora of the UAE

The current flora of the UAE has been shaped by all manner of events in the past, almost all of which continue to operate. The timescale of such events varies enormously, from just years or decades (in the case of many current anthropogenic impacts) to thousands if not millions of years (e.g. gradual shifts in macroclimate).

Apart from climate and the influence of man and his livestock, geological, topographical and soil factors have contributed to the establishment of the flora of the UAE and the wider region. As can be inferred from the preceding sentences, as environmental conditions continue to change, so will the flora. In other words, the current flora of the country represents a 'snapshot' of a much longer floral history, in that it captures the distribution of species at one particular time in relation to a set of specific environmental conditions. Although these conditions may appear to be quite similar over an area as small as the UAE, even slight differences in some factors may be large enough to exert a significant influence on species' distribution. Therefore, the concepts of temporal and spatial scale are key to understanding the current distribution patterns of species within the UAE.

On a broader geographical scale, Zohary (1973) divided Arabia into two floral regions. Whereas the interior, and therefore much of the UAE, was assigned to the Saharo-Arabian region, the Sudanian region, represented by the Nubo-Sindian Province, occupies a narrow coastal belt. However, based on more recent information, it is clear from the examples given below that the 'narrow coastal belt' needs to be expanded somewhat in the UAE to include near-coastal and some inland locations.

Typical representatives of the Saharo-Arabian region that occur in the country include *Anastatica hierochuntica*, *Haloxylon salicornicum*, *Helianthemum lippii*, *Neurada procumbens*, *Rhanterium epapposum*, *Savignya parviflora* and *Stipagrostis* spp. Characteristic of the Sudanian region are *Acacia tortilis*, *Calotropis procera*, *Lasiurus scindicus*, *Leptadenia pyrotechnica*, *Panicum turgidum* and *Pennisetum divisum*.

A number of species are floristically affiliated to Makran, i.e. the wider coastal desert strip of southern Iran and Pakistan. Kürschner (1986) considers these to be 'Omano-Makranian' elements, and they typically occur in the north-east of the UAE. Due to climatic constraints, several of these species do not occur west of the Hajar Mountains and the various outliers such as the inselberg Jebel Hafeet near Al Ain. Typical representatives of this distribution pattern in the country are *Physorrhynchus chamaerapistrum*, *Gaillonia* (= *Plocama*) *aucheri* and *Pseudogaillonia* (= *Plocama*) *hymenostephana*. Species such as *Prosopis cineraria* (*'ghaf'*) occur somewhat further westwards, but do not reach Abu Dhabi Island naturally (Fig. 13.7). *Cornulaca aucheri*, *Salsola drummondii* and *Sphaerocoma aucheri* are species of a narrow coastal strip that are found all the way the border with Saudi Arabia in the west.

Superimposed on this broad phytogeographical distribution pattern are local factors, edaphic, climatic or a combination of the two that can severely restrict the actual occurrence of species within a given phytogeographical region. This is well-illustrated by the occurrence of *Acacia tortilis* and *Leptadenia pyrotechnica*, which are both predominantly found in the north-east of the country.

The vicinity of the Hajar Mountains is probably instrumental in determining the distribution of certain species in the country, possibly due to the enhanced water supply in the subsurface layers due to runoff. For example, *Acacia tortilis* is found mainly east of the Al Ain road. A handful of trees also occur on the Sila'a Peninsula,

Fig. 13.7 *Prosopis cineraria* (*'ghaf'*), the national tree of the UAE, is a typical 'Omano-Makranian' element. Photo credit: Gary Brown

and these constitute the southern extension of the large Qatari population. *Leptadenia pyrotechnica* is also most common in the north-east, but scattered individuals occur elsewhere in the country, usually at the foot of dunes. It is presumably able to survive in such situations due to water seepage.

Prosopis cineraria is probably a good example of a relict species from a much wetter period in the distant past. With the general aridification of the climate over the past ca. 5000 years (see Chap. 3), this has led to a thinning out of what would have been a more continuous cover by the trees. Today's population is able to survive in sites where there are large amounts of water stored deep under the subsurface. As a consequence, it is found predominantly on dunes or on deep sand sheets, and mainly in the north-east of the country. One of the consequences of the harshness of the climate nowadays is that establishment from seedlings is probably extremely rare. Most regeneration of *ghaf* trees is from root suckers, which probably explains why trees are frequently observed in distinct groups (Brown and Böer 2005a).

The UAE has no nationally endemic plant species, but seven species found in the UAE are considered endemic to the mountains of the UAE and Northern Oman (Feulner 2016). These are *Echinops erinaceus* (although now also presumed to occur in Saudi Arabia), *Launaea omanensis*, *Lindenbergia arabica*, *Pteropyrum scoparium*, *Pulicaria edmondsonii*, *Rumex limoniastrum* and *Schweinfurthia imbricata*. An eighth species listed by Feulner (2016), *Caralluma arabica*, is also known from southern Yemen, from where it was originally described (Ghazanfar 2015).

Local endemism plays a role in the mountains in particular. Feulner (2011) gives an exhaustive list of local endemics that within the region are restricted exclusively, or nearly so, to the Ru'us Al Jibal.

With respect to a constantly changing environment, plant migrations have undoubtedly played a major role in the past, which helps to explain some current distribution patterns. Some species are more effective colonisers than others, whereas other species may be poor colonisers, but more effective competitors once established. The very rare *Pistacia khinjuk*, known from about a dozen specimens at just one locality in the Ru'us Al Jibal (see Feulner 2011) probably belongs to latter group.

In fact, within the UAE, the mountains with their varied habitats offer an excellent opportunity to study localised distribution patterns and examine the underlying factors governing such phenomena. In some cases, the causal link is clear. For instance, the orchid *Epipactis veratrifolia* requires a regular input of moisture and is therefore tied to moist, shady places. Some species need a distinctly cooler winter period and are therefore restricted to the highest mountain peaks in the UAE (e.g. *Gynandriris sisyrinchium* and *Roemeria hybrida* on Jebel Jais and above Wadi Qada'ah in the UAE). These species are often common down to near sea level in the northern part of Arabia, where winters are relatively cold.

In other cases, the precise reasons for localised occurrences are less apparent. For example, several plant species such as *Ehretia obtusifolia*, *Grewia tenax* and *Abutilon fruticosum* are known in the UAE only from Jebel Qitab. This might suggest a preferred association with gabbro substrate, but the total number of records is small, and one must generalize with great caution. In fact, all three species are found in protected situations on carbonate substrate in the southern Ru'us Al Jibal in Wadi Khabb Shamsi, Oman, and *G. tenax* is associated with *Olea europaea* on the carbonate slopes of Jebel Ghaweel in Wilayat Mahdhah, Oman.

In addition, field work uncovered *E. obtusifolia* growing as a half dozen small trees (with single, individual trunks) at more than 700–1000 m along the spine of the Northern Hajar, east of Jebel Hatta, in an upper tributary of Wadi Qahfi, Oman, near the Hatta border, securely within the ultrabasic harzburgite. There the trees occupied a steep, rubble-filled gulley that evidently had advantageous hydrology, because along one edge of the gulley was a lush seep with abundant *Adiantum capillus-veneris* (Maidenhair Fern) and even the remains of *Epipactis veratrifolia* that had flowered earlier. Further up the gulley were some six dozen Wild Olives (*Olea europaea*) and, above ca. 1000 m, smaller numbers of *Ephedra pachyclada*. The latter is unknown from harzburgite rocks in the UAE, but it appears that this is not a matter of geochemistry but of elevation.

No studies to date have attempted a rigorous assessment of the effects of bedrock lithology on the distribution of plant species in the UAE mountains. However, Feulner (2011) highlights distinct physical and geochemical differences between the carbonate rocks of the Ru'us Al Jibal and the ophiolitic Hajar Mountains as a probable explanation for why many typical Hajar Mountain species are absent or very rare in the former area. Some obvious examples include *Aizoon canariense*, *Convolvulus virgatus*, *Lindenbergia arabica* and *L. indica*, *Physorrhynchus*

Fig. 13.8 The attractive flowering tree *Tecomella undulata* is typically found in the vicinity of old villages, such as near Hatta. Photo credit: Gary Brown

chamaerapistrum, *Prosopis cineraria* and *Pulicaria glutinosa*, all of which are scarce or absent in the Ru'us Al Jibal. Conversely, it should be noted that, within the UAE, common Ru'us Al Jibal species such as *Prunus arabica*, *Convolvulus acanthocladus*, *Artemisia sieberi*, *Astragalus fasciculifolius* and *Lactuca orientalis* are absent from the Hajar Mountains outside the Ru'us Al Jibal. More information on these topics are found in Chap. 6.

The current distribution pattern of some species remains enigmatic. For instance, the attractive flowering tree *Tecomella undulata* (Arabic: '*farfar*') is found in a few wadis in the mountains of the UAE and northern Oman. It is striking that, in some cases, the trees are clustered in the vicinity of old villages, some of them, such as near Hatta, which have been abandoned for some time (Fig. 13.8). It is therefore tempting to think that the species has been introduced from Iran or Pakistan, especially as it produces valuable timber (Desert Teak). Like *Prosopis cineraria*, this species grows in clusters because it reproduces primarily from root suckers in the UAE. Sadly, the oldest and most mature population in the UAE, in upper Wadi Qowr, is now in pitiful condition as a result of water abstraction, lopping for wood or forage, and apparent neglect.

With respect to the finer-scale distribution of plant species in the UAE therefore, much remains to be discovered. However, degradation of large parts of the desert and broader coastal belt will impede any such undertaking. Current anthropogenic impacts are far larger than naturally operating ones. As a consequence, newly insularised or fragmented populations of plants are being created far more rapidly than historically.

13.4 Keystone and Foundation Plant Species in the UAE Desert

A keystone species is defined as one whose impact on its community is large, and disproportionately so relative to its abundance (Power et al. 1996). The concept has frequently been applied to animal predators, less so to the effects of plants on their environment. In the case of the latter, Munzbergova and Ward (2002) consider the three species of *Acacia* in the Negev Desert, including *A. tortilis*, which is widespread in the east of the UAE, to be keystone species on the basis that they greatly improve soil conditions and increase plant species diversity under their canopies. Whether this is in keeping with the original definition is open to question, and in the meantime, possibly more appropriate terms have been introduced, as explained below. Some authors have modified the original definition of a keystone species somewhat to expand its applicability. Accordingly, Narango et al. (2020) refer to four keystone plant genera that support the majority of Lepidoptera (butterfly and moth) species in the USA and without these genera, the Lepidoptera populations would collapse. In the UAE, much more basic research is required to understand these and related issues.

Plant communities in the UAE are often characterised by certain species that predominate, at least physiognomically (e.g. *Haloxylon salicornicum*). Due to the extreme environmental conditions, such species rarely dominate by excluding others, as is the case in more temperate parts of the world. In fact some, including *H. salicornicum* (e.g. Brown and Porembski 1997), possibly facilitate the occurrence of others. Such species are referred to as 'foundation species' (Ellison 2019). *Acacia tortilis* is probably another good example of a foundation species, whereas ones that have no or few apparent beneficial effects on ecosystem functioning, typical indicators of severe degradation such as *Rhazya stricta* and *Calotropis procera*, are not.

Whereas the native tree *Prosopis cineraria* can be regarded an important foundation species, the alien invasive *Prosopis juliflora* is certainly not. Various plant species, not to mention a host of animal species, are associated with the native *ghaf* trees. However, the phytotoxic effects of *Prosopis juliflora* on plants have been well documented (Goel et al. 1989).

13.5 Autecology

All plants, irrespective of their environment, are subject to varying degrees of stress. Grime (2001) defines stress as the external constraints that limit the rate of dry matter production of all or part of the vegetation. In non-desert environments with abundant resources, stress is often the result of inter- and intraspecific competition for those resources. In general terms, the main stress factors to which desert plants are exposed are low, variable, and often unpredictable precipitation, frequently resulting in droughts during the hot months, high temperatures, extremely high potential evapotranspiration and high light intensities. In addition, substrate salinity may be a major issue locally.

Particularly during the hot summer months in the UAE, therefore, when there is virtually no effective rainfall, the desert environment imposes severe restrictions on plant growth and survival.

13.5.1 Drought Survival Strategies

How plants adapt to their environment and to changes in the underlying conditions is one of the fundamental questions in plant science. A variety of mechanisms have evolved in desert plants to help them cope with drought. At a fairly basic, but nonetheless ecologically useful level, Larcher (2003) summarised survival mechanisms of plants in dry regions according to their autecological adaptations and life-forms (see below), and this system can be applied to plants in the UAE:

1. Arido-active plants are ones that remain active throughout the year and delay desiccation by various mechanisms, such as deep rooting systems, succulence (storage of water), and reduction of transpirational loss (epicuticular waxes, reflective leaf surfaces, reduction of leaf size). This means that the degree of physiological activity varies enormously depending on a number of factors including, amongst others, photosynthetic pathway and water availability. Examples include *Acacia tortilis*, *Euphorbia larica*, *Haloxylon salicornicum* and *Panicum turgidum*.
2. Arido-passive plants spend the unfavourable season in an inactive state, either as seed (desert annuals) or as a storage organ, usually as a subterranean bulb, corm or rhizome (geophytes, which are perennial plants). Seeds do not store significant quantities of water, just nutrients and energy. This makes them highly resistant to drought and heat. Seeds are therefore strongly dependent on external water for the initiation of growth. In contrast, the storage organ of geophytes often contains a relatively large amount of water, but even so, many, if not most species in the UAE, are reliant on precipitation to initiate growth. Examples of widespread desert annuals include *Arnebia hispidissima* and *Neurada procumbens*, whereas *Dipcadi biflorum* and *Gynandriris* (= *Moraea*) *sisyrinchium* are perennials with bulbs.
3. Arido-tolerant plants can tolerate desiccation of their organs without suffering any apparent physiological damage and resume normal physiological activity upon rehydration. In the UAE, this group of plants is quite rare and local. It is represented primarily by cryptogams (lichens and some bryophytes), which are found mainly in the mountains. In addition, there are several species of poikilohydric ferns that occur locally in the mountains, and these typically inhabit rock clefts and crevices. Examples include *Ceterach officinarum*, *Cheilanthes pteridioides* (Fig. 13.9) and *C. vellea*. These ferns are characteristic 'resurrection plants'. During periods of drought, they curl up and turn brown, entering a state of

Fig. 13.9 The fern *Cheilanthes pteridioides* is a typical resurrection plant. Photo credit: Gary Brown

dormancy. Once water is received, they almost immediately resume normal physiological activity.

13.5.2 Physiological, Morphological and Anatomical Adaptations to Arid Desert Ecosystems

In the following, the focus is on individual features that confer superior fitness for coping with the harsh desert conditions.

13.5.2.1 Photosynthetic Pathways

A fundamental characteristic of plants is their photosynthetic pathway and the manner in which the primary fixation of CO_2 proceeds in the chloroplasts. There are three main pathways, C_3, C_4 and CAM, with the abbreviations alluding to either the first photosynthetic compound produced after initial CO_2 fixation or the main storage compound.

In desert environments such as in the UAE, C_3 plants display their main period of active growth during the cooler part of the year when water is generally more abundant and potential evapotranspiration is much lower. Although many are arido-active species, some, such as *Farsetia aegyptia* and *Rhanterium epapposum*, discard all their leaves and green tissues on the stems during the hot part of the year and reduce their physiological activity to an absolute minimum.

Fig. 13.10 The seedlings of *Haloxylon salicornicum* exhibit the C_3 mode of photosynthesis, adult plants the C_4 mode. Photo credit: Gary Brown

C_4 plant species are distinctly active during the hotter part of the year when water is a limiting factor (Larcher 2003). They display reduced physiological activity during the cooler, moister period. This pathway is more efficient at higher temperatures than the 'normal' C_3 pathway, allowing plants to acquire more atmospheric CO_2 for the same amount of water lost through transpiration (von Willert et al. 1992). This enables the plants to extend their growth season into the late spring months and longer. Such species include the dwarf shrub *Haloxylon salicornicum* and most of the perennial grasses in the country (e.g. *Lasiurus scindicus*, *Panicum turgidum*, *Pennisetum divisum*). In addition, the small woody succulent *Zygophyllum simplex* has evolved C_4 photosynthesis.

In some cases, different photosynthetic pathways have evolved within relatively small families. For instance, whereas members of the small genus *Pteropyrum* (Polygonaceae), which has a very limited distribution and is represented in the UAE by *P. scoparium*, are typical C_3 species, C_4 photosynthesis has evolved in the closely related genus *Calligonum* (Doostmohammadi et al. 2020).

Of particular ecophysiological interest is the fact that the seedlings of both *Haloxylon persicum* (Pyankov et al. 1999) and *H. salicornicum* (Fig. 13.10) exhibit the C_3 mode of photosynthesis, allowing them to grow rapidly during the cooler part of the year when soil moisture is more available (Brown and Al-Mazrooei 2001). Once established, the seedlings discard their leaves and become leafless, semi-succulent C_4 species. Photosynthesis is subsequently conducted in the green stems, and growth is more rapid in the late spring and early summer months.

CAM plants in the UAE are typically found in the 'true' or drought succulents in the mountains. However, it is known that the coastal annual *Mesembryanthemum nodiflorum* (rare in the UAE) undergoes a transition in its metabolism from C_3 to CAM photosynthesis, which is induced by salt stress (Guan et al. 2020).

As can be inferred from the above information, photosynthetic pathways can be assessed and monitored to study the impacts of climate change. Any long-term increase in temperatures could shift the competitive advantage of plants with different photosynthetic pathways, changing species distributions and community composition in ecosystems (e.g. Munroe et al. 2021).

13.5.2.2 Succulence

Two distinct types of succulence can be distinguished, salt succulence and drought succulence (Larcher 2003). Salt succulence is a means of coming to terms with high salinity in the substrate, as described below, and is typical of plants of coastal and some inland desert environments. In contrast, drought succulents (or true succulents) generally grow in the mountains of the UAE. The best examples are given by the stem succulents *Caralluma arabica* and *C. flava*, both of which resemble small cactus-like plants (but without the spines). Salt succulents are usually characterised by the C_3 or C_4 photosynthetic pathway. A frequent question is why there are no cacti or cacti-like plants in the deserts of the UAE, as they are often regarded as being typical of arid environments. In general terms, succulents thrive in areas with low rainfall, but precipitation needs to be 'predictable', i.e. occurring at fairly regular intervals (von Willert et al. 1992). In the UAE, this is not the case, except to a certain extent in the mountains. The south of Oman exhibits an abundance of succulents with the CAM pathway because the summer monsoon provides a regular and 'predictable' source of moisture input.

13.5.2.3 Reduction of Leaf Size

A typical feature of many desert plant species that survive throughout the hot summer months is that they are for all intents and purposes leafless or have small, narrow leaves that help substantially reduce transpirational water-loss (Larcher 2003). In such cases, the stems, which are less exposed to intensive sunlight, play an important role in photosynthesis. Various perennial grass species have small, narrow leaf blades (e.g. *Lasiurus scindicus*, *Panicum turgidum*, *Pennisetum divisum*). Shrubs and dwarf shrubs exhibit a more varied approach: for instance, there are those with small leaves (e.g. *Farsetia aegyptia*, *Rhanterium epapposum*), others that are de facto leafless (e.g. *Calligonum crinitum*, *Haloxylon persicum*—see Fig. 5.7, Chap. 5–, *H. salicornicum*), leafless representatives with, erect, whip-like stems ("spartinoid" growth-form) such as *Leptadenia pyrotechnica* (Fig. 13.11), *Ochradenus arabicus*, *Periploca aphylla* and a small group of leafless succulents (e.g. *Caralluma arabica*, *Euphorbia larica*).

Fig. 13.11 The shrub *Leptadenia pyrotechnica* is virtually leafless to reduce excessive water loss. The green stems are responsible for conducting photosynthesis, respiration and transpiration. Photo credit: Gary Brown

13.5.2.4 Rooting Depth

Plants with deeper rooting systems are able to access water stored in the subsurface layers. Plants that obtain a significant amount of water from the groundwater or the saturated capillary fringe above the water table, rather than relying on rainwater stored in the upper substrate layers, are referred to as phreatophytes. On account of its extensive rooting system, *Prosopis cineraria* is a good example of a phreatophyte. *Ziziphus spina-christi* grows primarily in wadi beds and is also regarded as a phreatophyte (Le Houérou 2009). Somewhat surprisingly, as a species of hot, arid environments, *Salvadora persica* has large leaves. This is possible because it is a phreatophyte, and so it can use the regular supply of water to maintain its considerable foliage throughout the hot summer period.

Citrullus colocynthis is also a phreatophyte, but it grows in situations where the groundwater is relatively close to the surface. In fact, *Citrullus* needs to transpire huge amounts of water to cool its large leaves, which are located on the desert surface (Althawadi and Grace 1986). Temperatures on desert surfaces can exceed 70 °C in the summer months (Nobel and Geller 1987).

Species such as *Acacia tortilis* are facultative phreatophytes. Whereas in the winter months their lateral roots exploit water close to the soil surface, in the summer a much deeper rooting system can extract water stored at considerable depths (down to at least 25 m, Do et al. 2008). Ross and Burt (2015) observed that populations of *Acacia tortilis* in the UAE have an unusual tilted canopy architecture compared with the flat or dome-shaped morphology typical throughout its pan-tropical range. The authors suggested that the conspicuous south-facing tilt is a plastic response that maximizes soil shading and reduces soil temperature around the base of the tree.

Stem succulents, such as *Caralluma arabica* and *C. flava*, are species that do not maintain an extensive rooting system, but store water in their succulent stem tissues. When it rains, they rapidly develop a shallow rooting system to profit from water temporarily stored in the upper surface layers. This is typical of many succulents (von Willert et al. 1992).

It is generally assumed that desert annuals, with their very short life span, do not invest substantial amounts of resources in producing an extensive rooting system. Nonetheless, there are marked differences in root architecture within this group. At the one end of the spectrum, there are species that develop a very shallow, fibrous rooting system. Examples from the UAE include *Ifloga spicata* and *Schismus barbatus*. In contrast, other species produce a distinctly thickened and deeper taproot with thinner lateral roots. This is the case in some species of *Launaea* and *Anastatica hierochuntica* (see Fig. 13.20).

13.5.2.5 Adaptations to Mobile Sand

Mobile sand constitutes a highly unfavourable medium for plants, therefore limiting the number of species able to colonise such substrates (Danin 1996). This is due to the potential exposure of roots and the threat of desiccation as well as 'sand-blasting', abrasion of plant tissues from wind-blown sand. In addition, mobile sand is usually characterised by pronounced nutrient deficiency.

Although there are no species that actually require sand accumulation in the UAE (as opposed to parts of Africa), several species are resistant to sand cover and removal. *Calligonum comosum* (and the closely related *C. crinitum*) is highly adapted to such situations in that it can produce numerous adventitious roots and shoots from buried stems (Danin 1996). Its well-developed lateral rooting system can extend more than 25 m. Because the main lateral roots become stout and woody, they form a useful support to protect the plant from sand deflation. The species also forms characteristic nebkhas, i.e. mounds of wind-blown sand that accumulate around the base of the plant. *Cyperus conglomeratus* (Fig. 13.12) is a widespread and common sedge in the sand seas of the UAE with anatomical features of the rhizome that enable it to endure mild to moderate sand movement (Danin 1996). The same applies to the perennial grass *Centropodia forsskalii*, although this species is less tolerant of more mobile substrates than *Cyperus*. Other perennials in the UAE that show some degree of resistance to sand mobility include the perennial grasses *Lasiurus scindicus*, *Panicum turgidum*, *Pennisetum divisum* and *Stipagrostis plumosa* as well as the dwarf shrubs *Heliotropium digynum* and *Moltkiopsis ciliata*.

Species such as *Cornulaca monacantha*, *Haloxylon persicum* and *Haloxylon salicornicum* typically thrive on the more stable sand sheets. In marked contrast, the species that is often referred to as *Cornulaca arabica* on the megadunes in the southern part of the UAE is highly resistant to mobile sand. This species is regarded by others (e.g. Miller and Cope 1996) as conspecific with *C. monacantha*, which is more characteristic of stable sand sheets.

Fig. 13.12 The sedge *Cyperus conglomeratus* is one of the few species that is highly tolerant of mobile sand. The roots are enclosed by a rhizosheath (see below), which provides mechanical support. Photo credit: Gary Brown

The rather delicate *Eremobium aegyptiacum* can be locally abundant on sand dunes after plentiful rainfall. It is one of the few desert annuals able to colonise mobile, sandy substrates. It is furnished with a dense covering of short, star-like hairs. Apart from protecting the plant from solar radiation, the hairs also trap small sand grains, reducing the potential of injury to the plant from 'sand-blasting'. The seeds of this species are yellow and therefore well-camouflaged amongst the sand grains, thus affording them some degree of protection from various granivores.

13.5.2.6 Rhizosheaths

Most perennial graminoids (grasses and sedges) and some annual grass species display a remarkable adaptation that helps them come to terms with the special conditions of sandy substrates. Such species include *Centropodia forsskalii*, *Coelachyrum piercii*, *Cyperus conglomeratus* (Fig. 13.12), *Enneapogon desvauxii* (Fig. 13.13), *Lasiurus scindicus*, *Panicum turgidum*, *Pennisetum divisum* and *Stipagrostis* spp. (e.g. *S. drarii, S. hirtigluma*—a mountain species, *S. plumosa* and *S. uniplumis*). The roots of these species are enclosed within a rhizosheath.

Fig. 13.13 The small perennial grass *Enneapogon desvauxii* is primarily a species of mountains and sandy rocky slopes in the east of the UAE. It develops a distinctive rhizosheath. The actual roots (white) are seen in the bottom right of the image. Photo credit: Gary Brown

This is composed of root hairs and sand grains (Danin 1996) and is glued together by a mucilage produced by the roots. The 'rhizosheath-root system' can be regarded as a xerophytic adaptive trait (Wullstein et al. 1979).

Not only do such structures absorb water from the surrounding sand more efficiently, they also create specific nano-environmental conditions that encourage the growth of nitrogen-fixing bacteria (Wullstein et al. 1979). In other words, the micro-environment of the roots becomes enriched with nitrogen compounds that can be utilised by the plants.

13.5.2.7 Adaptation of Plants to Highly Saline Substrates

Soils with elevated salinity are a common phenomenon in coastal environments in the UAE, but also locally inland where high evaporation rates can lead to an increase of salt in the surface layers (Brown 2006). Sabkha is a good example of a highly saline ecosystem that is widespread in some coastal regions and on interdunal plains. Typically, the main salt present in coastal saline soils is NaCl, but other salts also occur in smaller concentrations. Saline substrates can pose substantial physiological problems for plants, and such substrates therefore exert a strong selective influence on species able to colonise them. However, soil salinity levels fluctuate widely, especially away from the immediate coastline. After heavy rainfall, salts are leached from the surface layers allowing species to germinate or to resume growth.

Plants able to complete their life cycles on saline substrates are referred to as halophytes; those that avoid such conditions as glycophytes. The definition, however, of what precisely constitutes a halophyte is somewhat open to interpretation. In the more specialised scientific literature, plants are regarded as halophytes if they are able to survive to reproduce at NaCl concentrations exceeding 200 mM NaCl, i.e. at least a third of the NaCl concentration of sea-water (Flowers and Colmer 2008). Tolerance to salinity is not an all-or-nothing response but is presumably dependent on the concentration of salts in the substrate, at least within certain species-specific thresholds. Determining, therefore, the thresholds that deem a plant to be a halophyte is somewhat arbitrary. According to Barbour et al. (1987), most plants that are regarded as halophytes are in fact intolerant of salinity. Under controlled laboratory conditions, they often display maximum growth at low salinity and declining growth with increasing salinity. The same author appears to suggest that obligate halophytes (i.e. actually requiring excessive concentrations of salt for normal growth) are perhaps non-existent.

The most tolerant of halophytes, however defined, can thrive in soils containing NaCl concentrations equivalent to, or even higher than, those found in sea-water. This is the clearly case for a number of plant species in the UAE that inhabit coastal marshlands, for example *Arthrocnemum macrostachyum*, *Avicennia marina*, *Halocnemum strobilaceum*, *Halopeplis perfoliata*, *Limonium axillare* and *Salicornia sinus-persica*. However, it is far from clear whether these species require high levels of salt in the substrate for their survival. Whereas the chenopods amongst these species come to terms with substrate salinity through varying degrees of succulence—most prominently seen in *Halopeplis perfoliata* (Fig. 13.14)—*Avicennia marina* and *Limonium axillare* possess specialised salt-excreting glands.

Fig. 13.14 The salt succulent *Halopeplis perfoliata* is characteristic of highly saline environments. Photo credit: Gary Brown

As a more unspecific response to high salinity, the shedding of leaves once an internal threshold concentration of salt has been reached is a good example.

Some plant species are able to germinate on sandy sabkha surface after heavy rainfall because the input of freshwater leads to a temporary reduction of salt concentrations in the substrate. For instance, even *Zygophyllum qatarense* (mildly to at best moderately halophytic) can germinate under such conditions, and once the plants have become established, they can probably survive for years in a state of dormancy by discarding their succulent leaves when salt concentrations rise above a certain threshold level. After further heavy downpours, they are able to develop new leaves and resume growth for limited periods of time (Brown 2006).

Despite its name, *Haloxylon salicornicum* can be assumed to be a glycophyte in the UAE and throughout Arabia because it avoids saline soils (but apparently that is not the case in other parts of its distributional range). The same applies to *Haloxylon persicum*.

13.6 Main Life Forms, Plant Functional Groups and Plant Strategies

In the above sections, basic plant 'strategies' were introduced to group plants of arid deserts in terms of how they deal with drought. In addition, some fundamental mechanisms were described to explain how plants survive in hot, arid environments. Although much work is still required on species in the UAE and the wider region, the general significance of distinctive anatomical, morphological and physiological features that facilitate the survival of plants in different environments has long been understood. In the following, theoretical concepts are discussed, which aim to bring together individual adaptative mechanisms and to group plants according to relevant life history patterns. These can be of high predictive value for forecasting how plants come to terms with their environment in response to various factors. Such factors include the complex issue of climate change, which is highly relevant to the UAE (see Chap. 3). Instead, therefore, of investigating how individual species react to certain changes in environmental factors, it is often more instructive to assess groups of species with similar demands, such as plant functional types (e.g. Box 1996). This topic is dealt with in brief below.

From a theoretical point of view, it is tempting to think that if it were possible to design a plant to cope with all the harsh environmental conditions encountered in the UAE desert, there would be an 'ideal' solution, i.e. one plant type that possesses a single set of superior characteristics enabling it to withstand even the most severe conditions. However, even a superficial examination of the flora of the country reveals that there are many approaches (or 'strategies') that enable plants to survive, as is the case with most ecosystems on the planet. Each ostensible beneficial trait brings with it a trade-off. A trade-off is the 'cost' paid in terms of fitness when a beneficial change in one trait is linked to a detrimental change in another (Stearns

1989). For example, a desert annual with its potentially high reproductive output each season has the capacity to dominate ecosystems. However, the downside of the annual growth form is that the growing season is typically short, severely limiting the potential for plant growth, and moreover, each season must commence with the germination and successful establishment of the species.

Although, therefore, the number of plant species in the UAE is relatively high, each with its own unique combination of traits, there is only a limited set of general approaches to coping with the stressful environment. In this context, desert annuals and geophytes, both arido-passive plants as explained above, are two examples of so-called 'life-forms'.

Various systems exist to classify life-forms. Perhaps the most appealing and widely used is one that on the surface appears rather simplistic. It can, however, reveal a large amount of information on how plants come to terms with their environment. This is the system devised by Raunkiaer (1934), initially for northern Europe, but later expanded to include other parts of the world. It revolves around the position of the perennating bud (the bud that produces new shoots) in relation to the soil surface to survive the harsh season. For the vast majority of plant species in deserts, this is the hot summer period when drought occurs. For the UAE, the relevant life-forms are shown in Table 13.1 (Fig. 13.15).

Table 13.1 Relevant life-form categories of plants in the UAE

Life-form	Description of life-form	Position of perennating bud	Example(s)
Phanerophyte	Woody perennials	>0.5 m above the ground	*Acacia tortilis* *Calligonum comosum* *Lycium shawii* *Prosopis cineraria*
Chamaephyte	Woody perennials	<0.5 m above the ground	*Haloxylon salicornicum* (Fig. 13.15a) *Helianthemum lippii* *Indigofera intricata* *Zilla spinosa*
Hemicryptophyte	Perennials, woody or herbaceous	On the surface of the ground	*Corchorus depressus* (Fig. 13.15b)
Geophyte	Perennials with bulb, corm, rhizome etc.	Under the ground	*Dipcadi erythraeum* *Halopyrum mucronatum*
Annual	Herbaceous, short-lived plant. Rarely becoming lignified.	n/a (seed)	*Hippocrepis areolata* *Plantago boissieri* *Sisymbrium irio* *Viola cinerea*
Stem succulent	Typically herbaceous	<0.5 m above the ground. A form of chamaephyte	*Caralluma arabica* *Caralluma flava*
Liana	Perennial, twining plant, growing on trees/shrubs or rocks	Well above the surface of the ground if growing on trees/shrubs	*Cocculus pendulus* *Pentatropis nivalis*

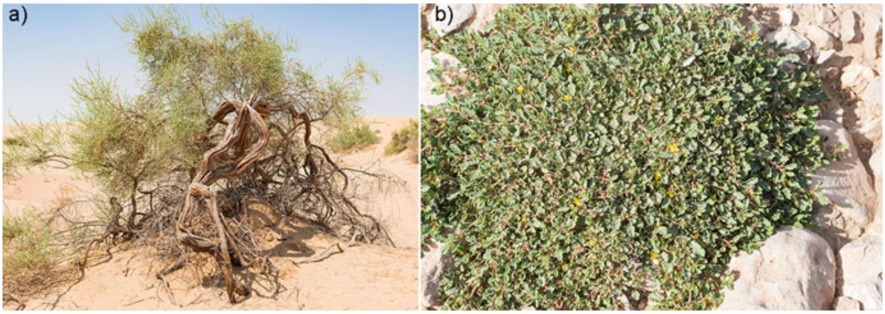


Fig. 13.15 Example of a chamaephyte, the dwarf shrub (*Haloxylon salicornicum*, **a**), and a hemicryptophyte (*Corchorus depressus*, **b**). Photo credits: Gary Brown

Such morphological, rather than taxonomic, classifications are often useful in certain contexts, for instance in terms of understanding more encompassing 'plant functional types', as explained below. Life forms can also be used in geographic areas where taxonomic knowledge of the species present is inadequate. In such cases, rather than attempt to identify all the species present, a functional analysis of the flora can be undertaken, from which ecologically relevant information can be gleaned.

Life-forms are principally based on a limited set of morphological and anatomical characteristics, but as outlined above, physiological traits are also indicative of certain environmental conditions. The significance of the various combinations of these features to facilitate the survival of plants in different environments has long been recognised, and the value of this information for predicting their responses to stress should not be underestimated. In this context, plant functional types (PFTs) are sets of species that exhibit similar responses to environmental conditions and having similar effects on dominant ecosystem processes. One of the major challenges is being able to identify key plant attributes to characterise relevant plant functional types. This has so far not been attempted in the UAE or the wider region, and so a massive research opportunity exists.

Examples of attributes that are undoubtedly relevant to the response of plants to climate change are, among many others: (a) type of photosynthetic pathway, (b) water-use efficiency, (c) cardinal temperatures for germination and growth, (d) degree of desiccation tolerance, (e) rooting depth, (f) reproductive rate, (g) life-form, (h) leaf area, specific leaf area (i.e. ratio of leaf area to leaf mass), etc. There are other characteristics that are much less obvious, but may be equally if not more important to some of those already listed. One such characteristic is the extent of mycorrhizal infection, especially as it has been suggested that mycorrhizal fungal–plant interactions may mitigate the effects of climate change (e.g. Bennett and Classen 2020). It is clear that some of these attributes are difficult to assess if fundamental data are lacking. Given the potential seriousness of the problem of climate change, financing programmes that aim to produce standardised data on relevant, but less obvious species attributes should be seen as a priority.

13.7 Interesting Features of Reproductive Biology in Desert Plants: Pollination, Dispersal and Germination

Due to the extremely wide-ranging nature of these topics, they can only be covered briefly.

13.7.1 Pollination

Flowers are the among the most defining structures of angiosperms, and pollination syndromes are characteristic traits of floral structures that have evolved to take advantage of different vectors involved in the pollination process. Most plant species in the UAE are either pollinated by invertebrates, primarily insects, or by the wind. Water pollination is typical of seagrasses (see Chap. 9). Self-pollination is another mechanism to ensure fertilisation of the ovary, but this topic is not dealt with here.

Wind pollination is highly typical of the graminoids (Poaceae—Fig. 13.16a–, Cyperaceae, Juncaceae), but it also occurs in various other families, including in chenopods such as *Cornulaca monacantha* (Fig. 13.16b), *Haloxylon salicornicum* and *H. persicum*. A typical feature of wind-pollinated plants is that obvious flowering structures such as petals are greatly reduced. Often the number of flowers is increased to produce large amounts of pollen due to the unspecific nature of the pollen transfer mechanism.

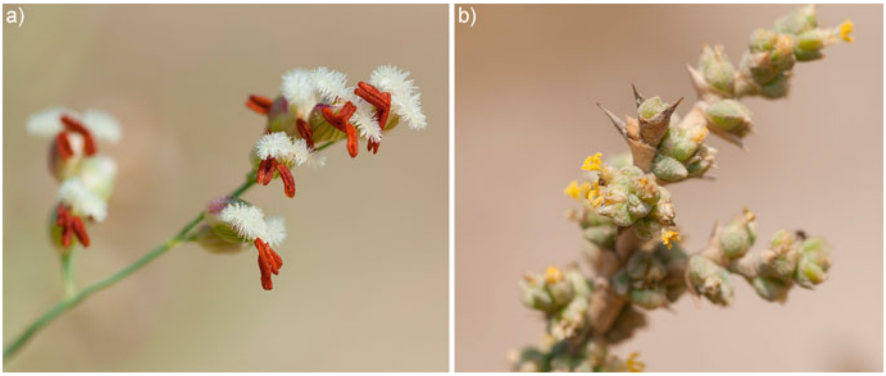


Fig. 13.16 Wind pollination is highly typical of the grasses such as (**a**) *Panicum turgidum*, and also of many chenopods (now Amaranthaceae) such as (**b**) *Cornulaca monacantha*. Photo credits: Gary Brown

With respect to animal pollination, plant-pollinator interactions belong to the classical pollination syndromes and are an excellent example of co-evolution (Olesen and Jordano 2002). Plants have adapted in varying degrees to their pollinator, whilst in turn pollinators have adapted to plants. With animal pollination, the necessity to produce lots of pollen is greatly reduced, as the pollinator typically assumes the role of transporting the pollen quite specifically from one flower another. The most common groups involved in animal pollination in the UAE are bees and wasps (Hymenoptera), beetles (Coleoptera), flies (Diptera) and butterflies/moths (Lepidoptera).

Insect pollination is dealt with in more detail in Chap. 17, and so for the present, several interesting phenomena are discussed.

In many parts of the world, trees are typically wind-pollinated, but this is not necessarily the case in the UAE. For instance, Adgaba et al. (2016) found that most visitors to the inflorescences of *Acacia tortilis* and *A. ehrenbergiana* were members of the Hymenoptera, which were attracted by significant amounts of nectar secreted by both species.

Perhaps one of the more remarkable examples of co-evolution is found in members of the fig family. Figs, including the native species such as *Ficus salicifolia*, possess a unique pollination system that involves tiny, highly specific fig wasps (Agaonidae). The pollination mechanism, including in *Ficus salicifolia*, has been described by Nefdt and Compton (1996).

On account of a number of striking features, the genus *Silene* has been used as a model system for studies in insect pollination and evolution for some time, in fact dating back to the genetic and ecological work of Mendel and Darwin (Bernasconi et al. 2009). Typically, two contrasting flower phenotypes have been described in *Silene*, nocturnal and diurnal (Prieto-Benítez et al. 2016). Diurnal species usually have pink or red petals, and flowers usually remain open during the day and night. Nocturnal species possess white or pale-coloured flowers that often close during the day. Native species belonging to the latter group are present in the UAE, including *Silene arenosa*, *S. austro-iranica* and *S. villosa*.

Hawkmoth pollination is prominent in *Rhazya stricta*, and this involves several diurnal species, including Silver-striped Hawk Moths (*Hippotion celerio*), which can be locally abundant (Fig. 13.17).

Fly pollination is a characteristic feature of the two stapeliads known from the mountains of the UAE, *Caralluma arabica* and *C. flava*. It is also found in *Periploca aphylla* (Fig. 13.18) and *Cynomorium coccineum*. These insects are attracted by the smell or colour of the flowers.

Aphidophagous hoverflies (Syrphidae) are possibly involved in deceptive pollination in the UAE's only native orchid, *Epipactis veratrifolia*. This and other members of the genus are frequently infested with black aphids on their vegetative organs. The complex flowers of the orchid produce small black swellings imitating aphids that dupe the hoverflies to visit specific regions of the flower, thus facilitating the transport of pollinaria (a cohesive mass of pollen grains typical of the Orchidaceae). This phenomenon has been described in detail by Jin et al. (2014) from the Eastern Himalayas.

Fig. 13.17 Hawkmoth pollination, here with *Hippotion celerio*, is prominent in *Rhazya stricta*. Photo credit: Gary Brown

Fig. 13.18 Fly pollination is a characteristic feature of *Periploca aphylla*. Photo credit: Gary Brown

Bird pollination systems are often dominated by specialist nectarivores. In the UAE, bird pollination is very poorly represented. However, Purple Sunbird is thought to play a role in the pollination of *Aloe vera*, and the same bird species is also known to occasionally visit the flowers of *Lycium shawii*.

13.7.2 Seed Dispersal

Seed dispersal and germination of desert plants, in particular desert annuals, are topics that have been the focus of much research work throughout the world, especially on account of the more fascinating solutions that have evolved in some species. These processes are fundamental to maintaining populations of many species. Desert annuals in particular are heavily reliant on germinating in the right place and at the right time. In the following, the term ‘seed’ is often used loosely to denote the diaspore, i.e. the unit of dispersal. In the flora of the UAE, diaspores vary from being an individual seed, often a fruit, and in one case (*Brassica tournefortii*), the entire plant.

As sedentary organisms, plants face a certain challenge to ensure that their seeds are dispersed to sites that have the potential to facilitate germination and establishment. Often, such sites are located in the immediate vicinity of the mother plant, but in others, dispersal away from the adult plant is promoted to limit competition. Seed dispersal therefore involves various mechanisms, including (1) ones that promote long-distance dispersal (telechory), (2) no obvious features to promote dispersal (atelechory), and (3) mechanisms that actively suppress dispersal (antitelechory). Seed dispersal can be achieved by abiotic factors (e.g. wind), mediated through organisms (zoochory) or the plant itself assumes responsibility (autochory). All of these mechanisms are represented in the flora of the UAE. As indicated above, timing of germination is of crucial importance to desert annuals in particular. Navarro et al. (2021) provided an outline of species with delayed seed dispersal in the UAE, where the seeds are retained in maternal plant structures for varying lengths of time, and a few prominent examples are given below.

With respect to telechoric species, although specific adaptations to extreme long-distance dispersal may be rare or even absent in the flora of the UAE, dispersal away from the mother plant for considerable distances is achieved by various means.

Wind dispersal (anemochory) is a common phenomenon, and this can be facilitated for example by small, light seeds (e.g. *Diplotaxis harra*, *Schismus barbatus*) or by seeds that have an appendage to help them fly. Some species possess a pappus (i.e. modified calyx characteristic of the Asteraceae—e.g. *Senecio glaucus*), as typically found in the Asteraceae, others an equivalent structure (e.g. the perennial shrubs *Calotropis procera*, *Leptadenia pyrotechnica*, *Periploca aphylla* or the grass *Imperata cylindrica*). Yet other species have winged diaspores, such as the perennials *Haloxylon salicornicum*, *H. persicum*, *Pteropyrum scoparium* (Fig. 13.19a) and *Salsola drummondii* (Fig. 13.19b).

Wind dispersal is also a characteristic feature of *Brassica tournefortii* (Brassicaceae), the most prominent tumbleweed in the UAE. This annual species is restricted to agricultural environments in the far east of the country. When the seeds are mature, the entire dry plant breaks off from a predefined weak point in the stem just above the soil surface. The plant is then blown across the desert by gusts of winds, with seeds being spread at the same time. To a certain extent, the

Fig. 13.19 (**a**) Winged fruits of *Pteropyrum scoparium* and (**b**) *Salsola drummondii*. Photo credits: Gary Brown

Brassicaceae *Physorrhynchus chamaerapistrum* can also behave as a tumbleweed in that the upper parts of the plant break off and blow around in mountain wadis.

Balloon fruits can be dispersed by wind and gravity. Such fruits are produced by various perennials in the UAE, including *A. fasciculifolius* and *Pseudogaillonia hymenostephana*. The fruits of *Citrullus colocynthis* are also probably best assigned to the balloon type category. Although they are initially very heavy, on drying the fruits become extremely light and brittle, and are then easily blown across the surface, breaking up and scattering seeds in the process. A common desert annual in the mountains of the UAE with balloon fruits is *Rumex vesicarius*.

A particularly interesting dispersal mechanism is found in amphicarpic species. Amphicarpy is a form of heterocarpy, i.e. the plant produces two markedly different types of diaspore, typically to facilitate both telechory and atelechory (Gutterman 1993). With amphicarpic species, one type of diaspore is located below-ground. These underground fruits are heavy and antitelechoric. In contrast, the aerial diaspores are typically light and are more adapted for short-distance dispersal. Two amphicarpic species are characteristic of the region, at least locally, *Emex spinosa* and *Gymnarrhena micrantha*. *Emex* is locally abundant in desert areas of the northeast of the country, whereas *Gymnarrhena* is extremely rare in the UAE, so far known only from Jebel Hafeet. In addition, a third, potentially amphicarpic species, *Enneapogon desvauxii,* occurs in the mountains of the UAE. This is usually a distinctly small perennial/facultative annual grass. Studies conducted by Stopp (1958) indicate that it is amphicarpic in other parts of its distributional range (e.g. Africa). Strictly speaking, however, it is not an amphicarpic species as the antitelechoric diaspores develop in the densely packed basal leaf axils at the surface of the ground (rather than below-ground). Nonetheless, it is unclear whether the plants in the UAE, which are distinctly smaller than in other parts of its distributional range, are amphicarpic as we have not observed the phenomenon in material in the UAE so far.

The retention of seeds in the canopy of the mother plant to delay seed dispersal is referred to as bradyspory (van Rheede van Oudtshoorn and van Rooyen 1999), and this phenomenon is not generally widespread in desert plants. However, in the UAE, there are several classic examples of species with bradyspory, which enable the plants to carefully regulate seed dispersal to occur gradually over an extended period of time.

Asteriscus hierochunticus (= *Asteriscus pygmaeus*) is such a species with an aerial seedbank. It is typically associated with rocky habitats and silty-gravelly wadis in the UAE. Details of seed dispersal and germination, which are tightly regulated by rainfall long after the mother plant has died and dried out, have been summarised in Gutterman (1993). During development of the fruits, the involucral bracts (the leaves that enclose the flowerheads) gradually become woody and completely enclose the capitulum (flowerhead), protecting the seeds from herbivores. The woody involucral bracts are sensitive to rainwater: within minutes of wetting, they open, and fruits, beginning with the peripheral whorls, are released. The action of raindrops bouncing on the achenes (small fruits) helps to dislodge them from the capitulum. Following periods of moisture, the bracts close again, returning to their original shape. This process of opening and closing can continue for up to 20 years, with the seeds remaining viable throughout (Gutterman 1994).

A variation of this theme is found in the Brassicaceae *Anastatica hierochuntica* (Fig. 13.20a). It is one of the few annuals (as with *Asteriscus hierochunticus*) that is known to become lignified (Danin 1983). The fruits remain attached to the dead mother plant. On drying, the woody branches become incurved, forming a spherical structure (Fig. 13.20b). This is anchored in the ground by a strong, woody taproot. The fruits (silicula) are enclosed in the centre of the structure and are well-protected from herbivores by the thick, densely interwoven branches. After rainfall, the branches rapidly expand to open, and wetting weakens the sutures of the silicula. Some fruits are torn open, especially if continued rainfall occurs, and a few seeds are released. On drying, the plant returns to its original spherical structure. Only a handful of seeds are released in any one season, so that seed dispersal takes place over a number of years (Danin 1983). Apart from ensuring that seeds are dispersed at a favourable time of the year to facilitate seedling establishment, this mechanism

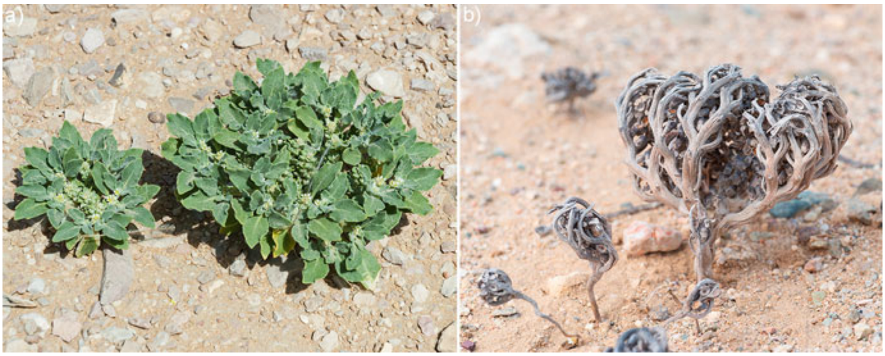


Fig. 13.20 (**a**) The Brassicaceae *Anastatica hierochuntica* is a typical annual species when flowering. (**b**) Aerial seed bank on the in-curled, lignified branches. Photo credits: Gary Brown

Fig. 13.21 *Blepharis ciliaris* is a cushion plant that possesses an aerial seedbank and a 'ballistic' seed dispersal mechanism. Photo credit: Gary Brown

minimises the exposure of seeds to granivores. As with *Asteriscus*, this species is typically associated with rocky habitats and silty-gravelly wadis in the east of the country.

Blepharis ciliaris (Fig. 13.21) is a cushion plant that is primarily associated with the Hajar Mountains in the UAE. The species also possesses an aerial seedbank with the seeds remaining on the dead maternal plant. Gutterman (1994) describes in detail the remarkable 'double safety autochorous mechanism' involving both the dried calyx and capsule, which ensures that only a limited number of seeds will be dispersed during any one precipitation event of sufficient duration to facilitate germination. A certain amount of continuous wetting is required to trigger the autonomous, 'ballistic' dispersal mechanism. The exploding capsule can eject seeds for distances of up to a metre and possibly more.

Like many other members of the genus (Webster 1994), *Euphorbia larica*, a species of the Hajar Mountains, is presumably autochorous due to explosion of the ballistic fruits. The same applies to various members of the Geraniaceae in the UAE.

Zoochory refers to the dispersal of seeds by animals, and this phenomenon is one of the prime examples of animal-plant interactions. The major advantage of zoochory is that it facilitates long-distance dispersal. Zoochory is a fairly prevalent phenomenon in desert ecosystems. As a broad categorisation, it is possible to distinguish between endozoochory, i.e. transported within an animal after ingestion and deposited later, epizoochory (transported externally on an animal) and myrmecochory (dispersed by ants).

Although there are no specific studies from the UAE, the results of Rohner and Ward (1999) strongly suggest that endozoochory is probably widespread in *Acacia tortilis*. This species frequently regenerates from seed in the east of the UAE (as opposed to *Prosopis cineraria*). Camels eat large quantities of the pods. Not only are the seeds dispersed in the dung of the animals, but sterilisation of the seeds that survive passage through the digestive tract takes place. This is important because almost all pods of *A. tortilis* are infested with bruchid beetles, whose larvae damage a large percentage of the seeds. Seedlings emerge after rainfall, often from camel droppings. However, camels eat most of the seedlings, meaning that very few become established. Endozoochory possibly also plays a role in mountain plant species that develop fleshy fruits, such as *Ochradenus arabicus*. These are then eaten, and the seeds dispersed by birds. Frugivorous lizards are known to be involved in the dispersal of *Capparis spinosa* seeds in other parts of the world (e.g. Fici and Lo Valvo 2004), and the same almost certainly applies to the UAE.

Epizoochory is conspicuous in a few species. *Neurada procumbens* is a common desert annual in the UAE, occurring primarily on sandy substrates. The fruit is disc-shaped and asymmetrical (Fig. 13.22), with spiny processes on the upper surface that become very sharp as the fruit dries out. The lower surface is flat and non-spinose. The dry fruits remain on the desert surface and become attached to the feet of animals or the tyres of vehicles. In this way, they can be transported for considerable distances before falling loose.

With *Rhanterium epapposum*, the dried capitulum is the unit of dispersal (which contains several to many seeds). This is either blown for short distances across the desert surface or transported over longer distances in the fur of animals. Thalen (1979) lists sheep, goats, camels and hares (*Lepus capensis*) as being instrumental in long-distance dispersal in this species. Hooked diaspores are typical of *Medicago laciniata* (Fig. 13.23a, left) and the alien *Cenchrus echinatus* (Fig. 13.23b, right).

Myrmecochory is probably a fairly widespread phenomenon in the UAE, but it has not been reported so far. In Kuwait, the role of harvester ants in seed dispersal has been described in detail by Brown et al. (2012) in an intact *Rhanterium epapposum* community.

Fig. 13.22 The fruits of the common desert annual *Neurada procumbens* are disc-shaped and readily attach to the hooves of larger animals. Photo credit: Gary Brown

Fig. 13.23 (**a**) The fruits of the desert annual *Medicago laciniata* and (**b**) the alien *Cenchrus echinatus* are readily transported by unsuspecting animals. Photo credits: Gary Brown

13.7.3 Germination

A widespread mechanism that prevents germination occurring at the wrong time of the year in desert ecosystems is dormancy (Gutterman 1993). This mechanism stops seeds, which are usually produced at the end of the spring before the onset of the summer drought, from germinating in response to isolated rainfall events in the summer period. Any seedlings germinating then would inevitably perish. Many desert annuals, belonging to a diversity of plant families, have seeds with physiological dormancy (i.e. the embryo itself is incapable of developing), and this is gradually broken over the hot, dry season (Baskin and Baskin 1998).

Predictive germination, defined as germination that is directly sensitive to environmental factors associated with conditions favourable for immediate seedling growth (Smith et al. 2000), is an important strategy that allows plant populations to thrive in highly variable environments. Gutterman (1993) indicates that the amount and temporal distribution of available soil moisture are primary environmental variables on which predictive germination is likely to be based. Brown and Al-Mazrooei (2001) showed that the seeds of the perennial *Haloxylon salicornicum*, which are produced to coincide the start of the following rainy season, did not require dormancy but could germinate at very high percentages immediately. In this study, highest germination rates were below 20 °C, but above 30 °C, germination was severely retarded. This is in agreement with the general statement concerning many desert annuals, namely that high temperatures result in thermal-inhibition of germination, even though in this group of plants, high temperatures are required to first break dormancy.

A second important mechanism that enables desert plants to persist in their harsh environment is fractional (= delayed) germination (Baskin and Baskin 1998). With fractional germination, only a certain proportion of germinable seeds will actually germinate, even under ideal conditions. This strategy buffers a population from the consequences of near or complete reproductive failure in unfavourable years, and has been well-documented from American desert annuals (Venable and Lawlor 1980). Fractional germination is also known from plants of the UAE, such as in *Spergularia diandra* (Gutterman 1996). It is also probably a widespread mechanism in plants of the region, as has been demonstrated for species such as *Plantago boissieri* by Brown (2001).

Fractional germination is generally regarded as a bet-hedging strategy (Baskin and Baskin 1998). This means that in a 'bad' year, only a certain proportion of the seeds will germinate, but the non-germinating fraction will be carried over until another season. In this manner, overall seedling mortality is reduced. However, in a 'good' year, not all seeds that would have been capable of producing offspring germinate either. Fractional germination has therefore been characterised as a 'cautious' germination strategy (Gutterman 1993).

13.8 Recommended Readings

Readers interested in the plant species occurring in the United Arab Emirates should refer to Jongbloed et al. (2003). Brown and Böer (2005b) give an overview of various aspects of plants in the country (e.g. adaptations, traditional use, etc.). Danin (1996) provides exhaustive details of how plants come to terms with sand dune environments in arid zones.

References

Adgaba N, Al-Ghamdi AA, Awraris SG, Al-Madani M, Ansari MJ, Sammouda R, Radloff S (2016) Pollination ecology, nectar secretion dynamics, and honey production potentials of *Acacia ehrenbergiana* (Hayne) and *Acacia tortilis* (Forsk.) Hayne, Leguminosae (Mimosoideae), in an arid region of Saudi Arabia. Trop Ecol 57:429–444

Akeroyd JR (2006) Plant taxonomy and reintroduction. In: Leadlay E, Jury S (eds) Taxonomy and plant conservation. Cambridge University Press, Cambridge

Allen DJ, Westrip JRS, Puttick A, Harding KA, Hilton-Taylor C, Ali H (2021) UAE National Red List of Vascular Plants. Technical Report. Ministry of Climate Change and Environment, United Arab Emirates

Althawadi AM, Grace J (1986) Water use by the desert cucurbit *Citrullus colocynthis* (L.) Schrad. Oecologia 70:475–480

Aspinall S (2006) Soldier's orchid *Zeuxine strateumatica* marches on. Tribulus 16:19

Barbour MG, Burk JH, Pitts WD (1987) Terrestrial plant ecology, 2nd edn. Benjamin/Cummings, Menlo Park, CA

Baskin CC, Baskin JM (1998) Seeds: ecology, biogeography, and evolution of dormancy and germination. Academic, London
Bennett AE, Classen AT (2020) Climate change influences mycorrhizal fungal–plant interactions, but conclusions are limited by geographical study bias. Ecology 101. https://doi.org/10.1002/ecy.2978
Bernasconi G, Antonovics J, Biere A, Charlesworth D, Delph LF, Filatov D, Giraud T, Hood ME, Marais GAB, McCauley D, Pannell JR, Shykoff JA, Vyskot B, Wolfe LM, Widmer A (2009) *Silene* as a model system in ecology and evolution. Heredity 103:5–14. https://doi.org/10.1038/hdy.2009.34
Box E (1996) Plant functional types and climate at the global scale. J Veg Sci 7:309–320
Brown, G (2001) Vegetation ecology and biodiversity of degraded desert areas in north-eastern Arabia. Habilitation thesis, Rostock University
Brown G (2006) The sabkha vegetation of the United Arab Emirates. In: Khan MA, Böer B, Kust GS, Barth H-J (eds) Sabkha ecosystems, vol II. Springer, Berlin
Brown G, Al-Mazrooei S (2001) Germination ecology of *Haloxylon salicornicum* from Kuwait. Bot Jahrb Syst Pflanzengesch Pflanzengeogr 123:235–247
Brown G, Böer B (2005a) Terrestrial habitats. In: Hellyer P, Aspinall S (eds) The Emirates: a natural history. Trident, London
Brown G, Böer B (2005b) Terrestrial plants. In: Hellyer P, Aspinall S (eds) The Emirates: A natural history. Trident, London
Brown G, Porembski S (1997) The maintenance of species diversity by miniature dunes in a sand-depleted *Haloxylon salicornicum* community in Kuwait. J Arid Environ 37:461–473
Brown G, Aspinall S, Gardner D (2006) *Cutandia dichotoma* (Forssk.) Trabut, a remarkable new species of annual grass for the UAE. Tribulus 16:30–31
Brown G, Scherber C, Ramos P Jr, Ebrahim EK (2012) The effects of harvester ant (*Messor ebeninus* Forel) nests on vegetation and soil properties in a desert dwarf shrub community in north-eastern Arabia. Flora 207:503–511
Brummitt RK (2010) *Acacia*: a solution that should be acceptable to everybody. Taxon 59:1925–1926
Danin A (1983) Desert Vegetation of Israel and Sinai. Cana Publishing House, Jerusalem
Danin A (1996) Plants of desert dunes. Springer, Heidelberg
Do FC, Rocheteau A, Diagne AL, Goudiaby V, Granier A, Lhomme J-P (2008) Stable annual pattern of water use by *Acacia tortilis* in Sahelian Africa. Tree Physiol 28:95–104
Doostmohammadi M, Malekmohammadi M, Djamali M, Akhani H (2020) Is *Pteropyrum* a pathway to C_4 evolution in Polygonaceae? An integrative approach to the taxonomy and anatomy of *Pteropyrum* (C_3), an immediate relative of *Calligonum* (C_4). Bot J Linn 192:369–400
Ellison AM (2019) Foundation species, non-trophic interactions, and the value of being common. iScience 13:254–268
Feulner GR (2011) The flora of the Ru'us al-Jibal—the mountains of the Musandam Peninsula: An annotated checklist and selected observations. Tribulus 19:4–153
Feulner GR (2014) The Olive Highlands: A unique "island" of biodiversity within the Hajar Mountains of the United Arab Emirates. Tribulus 22:9–34
Feulner GR (2016) The flora of Wadi Wurayah National Park, Fujairah, United Arab Emirates: An annotated checklist and selected observations on the flora of an extensive ultrabasic bedrock environment in the northern Hajar Mountains. Tribulus 24:4–84
Feulner GR, Karki N (2009) Hidden in plain view: First UAE record of the wadi grass *Saccharum kajkaiense* and notes on its distribution in the UAE and neighbouring Oman. Tribulus 18:50–55
Fici S, Lo Valvo F (2004) Seed dispersal of *Capparis spinosa* L (Capparaceae) by Mediterranean lizards. Naturalista Siciliano 28:1147–1154
Flowers TJ, Colmer TD (2008) Salinity tolerance in halophytes. New Phytol 79:945–963
Freudenstein JV, Broe MB, Folk RA, Sinn BT (2017) Biodiversity and the species concept—lineages are not enough. Syst Biol 66:644–656

Gairola S, Mahmoud T, El-Keblawy A (2015) *Sphaeralcea bonariensis* (Malvaceae): A newly recorded introduced species in the flora of the United Arab Emirates. Phytotaxa 213:151–154
Ghazanfar S (2015) Flora of Oman. Vol. 3. Scripta Botanica Belgica 55. National Botanic Garden of Belgium, Meise
Goel U, Saxena DB, Kumar B (1989) Comparative study of allelopathy as exhibited by *Prosopis juliflora* Swartz and *Prosopis cineraria* (L) Druce. J Chem Ecol 15:591–600
Grime JP (2001) Plant strategies, vegetation processes and ecosystem properties. Wiley, Chichester
Guan O, Tan B, Kelley TM, Tian J, Chen S (2020) Physiological changes in *Mesembryanthemum crystallinum* during the C_3 to CAM transition induced by salt stress. Front Plant Sci 11:283. https://doi.org/10.3389/fpls.2020.00283
Gutterman Y (1993) Seed germination in desert plants. Springer, Berlin
Gutterman Y (1994) Strategies of seed dispersal and germination in plants inhabiting deserts. Bot Rev 60:373–425
Gutterman Y (1996) Environmental influences during seed maturation and storage affecting germinability in *Spergularia diandra* genotypes inhabiting the Negev Desert, Israel. J Arid Environ 34:313–323
Jin X-H, Re Z-X, Xu S-Z, Wang H, Li D-Z, Li Z-Y (2014) The evolution of floral deception in *Epipactis veratrifolia* (Orchidaceae): From indirect defense to pollination. BMC Plant Biol 14: 63. https://doi.org/10.1186/1471-2229-14-63
Jongbloed MVD, Feulner GR, Böer B, Western AR (2003) The comprehensive guide to the wild flowers of the United Arab Emirates. ERWDA, Abu Dhabi
Kürschner H (1986) A study of the vegetation of the Qurm Nature Reserve, Muscat area, Oman. AGJSR 4:23–52
Larcher E (2003) Physiological plant ecology. Springer, Berlin
Le Houérou HN (2009) Bioclimatology and biogeography of Africa. Springer, Berlin
Mahmoud T, Gairola S, El-Keblawy A (2015a) *Parthenium hysterophorus* and *Bidens pilosa*, two new records to the invasive weed flora of the United Arab Emirates. JNBR 4:26–32
Mahmoud T, Gairola S, Shabana H, El-Keblawy A (2015b) *Sesbania bispinosa* (Jacq.) W. Wight and *Trifolium repens* L. (Fabales Fabaceae) two new legume records for natural flora of the United Arab Emirates. Biodivers J 6:719–722
Mahmoud T, Gairola S, Shabana H, El-Keblawy A (2016) Contribution to the flora of United Arab Emirates*: Glinus lotoides* L. (Molluginaceae) and *Senna occidentalis* L. (Fabaceae) two new records. Biodivers J 7:223–228
Mayr E (1988) Toward a new philosophy of biology: observations of an evolutionist. Belknap Press of Harvard University Press, Cambridge, MA
Miller AG, Cope TA (1996) Flora of the Arabian Peninsula and Socotra, vol 1. Edinburgh University Press, Edinburgh
Munroe SEM, McInerney FA, Andrae J, Welti N, Guerin GR, Leitch E, Hall T, Szarvas S, Atkins R, Caddy-Retalic S, Sparrow B (2021) The photosynthetic pathways of plant species surveyed in Australia's national terrestrial monitoring network. Sci Data 8:97. https://doi.org/10.1038/s41597-021-00877-z
Munzbergova Z, Ward D (2002) *Acacia* trees a keystone species in Negev desert ecosystems. J Veg Sci 13:227–236
Narango DL, Tallamy DW, Shropshire KJ (2020) Few keystone plant genera support the majority of Lepidoptera species. Nat Commun 11:5751. https://doi.org/10.1038/s41467-020-19565-4
Navarro T, Shabana HA, El-Keblawy A, Hidalgo-Triana N (2021) Delayed seed dispersal species and related traits in the desert of the United Arab Emirates. J Arid Land 13:962–976
Nefdt RJC, Compton SG (1996) Regulation of seed and pollinator production in the fig-fig wasp mutualism. J Anim Ecol 65:170–182
Nobel PS, Geller GN (1987) Temperature modelling of wet and dry desert soils. J Ecol 75:247–258
Olesen JM, Jordano P (2002) Geographic patterns in plant-pollinator mutualistic networks. Ecology 83:2416–2424

Piredda R, Simeone MC, Attimonelli M, Bellarosa R, Schirone B (2011) Prospects of barcoding the Italian wild dendroflora: oaks reveal severe limits to tracking species identity. Mol Ecol Resour 11:72–83
Power ME, Tilman D, Estes JA, Menge BA, Bond WJ, Scott Mills L, Daily G, Castilla JC, Lubchenco J, Paine RT (1996) Challenges in the quest for keystones: Identifying keystone species is difficult—but essential to understanding how loss of species will affect ecosystems. BioScience 46:609–620
Prieto-Benítez S, Dötterl S, Giménez-Benavides L (2016) Circadian rhythm of a *Silene* species favours nocturnal pollination and constrains diurnal visitation. Ann Bot 118:907–918
Pyankov VI, Black CC Jr, Artyusheva EG, Voznesenskaya EV, Ku MSB, Edwards GE (1999) Features of photosynthesis in *Haloxylon* species of Chenopodiaceae that are dominant plants in Central Asian Deserts. Plant Cell Physiol 40:125–134
Raunkiaer C (1934) Life forms of plants and statistical plant geography. Clarendon Press, Oxford
Rich TCG (2006) The role of the taxonomist in conservation of critical vascular plants. In: Leadlay E, Jury S (eds) Taxonomy and plant conservation. Cambridge University Press, Cambridge
Richer R, Knees S, Norton J, Sergeev A (2022) Hidden beauty. An exploration of Qatar's native and naturalised flora. Akkardia, Edinburgh
Rohner C, Ward D (1999) Large mammalian herbivores and the conservation of arid *Acacia* stands in the Middle East. Conserv Biol 13:1162–1171
Ross Z, Burt J (2015) Unusual canopy architecture in the umbrella thorn acacia, *Vachellia tortilis* (= *Acacia tortilis*), in the United Arab Emirates. J Arid Environ 115:62–65
Sakkir S, Ghazanfar SA, Al Mehairbi M, Soorae P (2020) New records of alien plant species in Abu Dhabi Emirate, UAE. Tribulus 28:19–25
Secretariat of the Convention on Biological Diversity (2005) Handbook of the convention on biological diversity including its cartagena protocol on biosafety, 3rd edn, Montreal
Shahid M (2014) New records for two alien Asteraceae species in the United Arab Emirates. JNBR 3:115–119
Shahid M, Rao NK (2014a) *Datura ferox* and *Oldenlandia corymbosa*: New record to the UAE flora. JNBR 3:170–174
Shahid M, Rao NK (2014b) New records of Caryophyllaceae in the flora of the United Arab Emirates. Tribulus 22:66–68
Shahid M, Rao NK (2015) New records of eight plant species in the United Arab Emirates. Tribulus 23:122–128
Smith SE, Riley E, Tiss JL, Fendenheim DM (2000) Geographical variation in predictive seedling emergence in a perennial desert grass. J Ecol 88:139–149
Stearns SC (1989) Trade-offs in life-history evolution. Funct Ecol 3:259–268
Stopp K (1958) Die verbreitungenshemmenden Einrichtungen in der südafrikanischen Flora. Bot Stud 8:1–103
Thalen DCP (1979) Ecology and utilization of desert shrub rangelands in Iraq. Dr W Junk, The Hague
van Rheede van Oudtshoorn K, van Rooyen MW (1999) Dispersal biology of desert plants. Springer, Berlin
Venable DL, Lawlor L (1980) Delayed germination and dispersal in desert annuals: Escape in time and space. Oecologia 46:272–282
von Willert DJ, Eller BM, Werger MJA, Brinckmann E, Ihlenfeldt H-D (1992) Life strategies of succulents in deserts with special reference to the Namib Desert. Cambridge University Press, Cambridge
Webster GL (1994) Classification of the Euphorbiaceae. Ann Mo Bot Garden 81:3–32

Western AR (1989) The flora of the United Arab Emirates—an introduction. United Arab Emirates University, Al Ain

Wullstein LH, Bruening ML, Bollen WB (1979) Nitrogen fixation associated with sand grain root sheaths (rhizosheaths) of certain xeric grasses. Physiol Plant 46:1–4

Zohary M (1973) Geobotanical foundations of the Middle East. Gustav Fischer, Stuttgart

Chapter 14
Terrestrial Mammals of the United Arab Emirates

Jacky Judas

14.1 Introduction

About 6400 living species of mammals have been described in the world, distributed in 23 orders and 162 families (Burgin et al. 2018). In the United Arab Emirates, more than 50 species have been recorded, which represents less than 1% of the global mammalian diversity (Fig. 14.1). This relatively low diversity can be attributed to the difficult environment, with an arid and harsh climate with very hot summer temperatures in which these species occur (see Chap. 3). Mammals are generally less well represented in desert environment than insects or reptiles (Cunningham 2004). Low and unpredictable rainfall limits the growth of plants, resulting in low primary production, which cascades onto the whole food chain. Scarce water and food availability constrain the species diversity, abundance and carrying capacity in these habitats. Most mammal species are native, but over the time of occupations by humans, several species have been introduced. These introductions of non-native species have increased, particularly in the last few decades. Through this chapter, we will describe which mammal species live in the country, how they adapt to the arid environment, threats they are facing, our relations with them, and how we can protect these fascinating and important animals.

14.2 Diversity and Biogeography

In the book *The Emirates: A Natural History*, published by the Environmental Agency of Abu Dhabi in 2005 (Hellyer and Aspinall 2005), Dr Chris Drew and his wife, who authored the chapter on mammals, listed 43 species known from UAE,

J. Judas (✉)
Soudah Development, Abha, Saudi Arabia

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_14

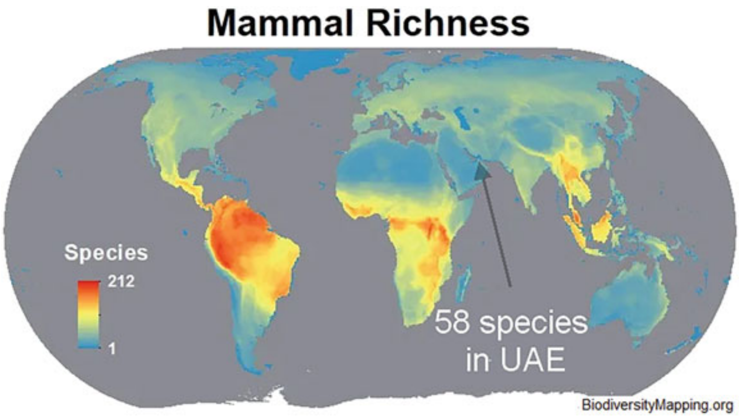


Fig. 14.1 Worldwide mammal diversity map, showing the relative low species diversity in the UAE. Source: Modified from BiodiversityMapping.org derived using mammal species range data from IUCN Red List, reused with permission

of which 5 were extinct. As of 2022, the list now contains 58 species of mammals known to occur or to have occurred in recent decades in the nation (Appendix), adding 15 new species in the past 17 years. Four are feral species, which were already present in the natural environment, but not previously listed; four (Northern Palm-Squirrel, Indian Desert Jird, Patagonian Mara and Aoudad) are newly reported introduced species, of which the Northern Palm-Squirrel is already well-established, while the seven remaining are new addition to the native fauna, and previously unrecorded. Of these 58 species overall, 44 are native species distributed among six orders and 18 families, of which 10 are endemic or near endemic to the Arabian Peninsula (Fig. 14.2a). When adding the 12 feral or well-established introduced non-native species, the number of mammalian orders represented in the UAE fauna raises to eight and the number of families to 21 (Fig. 14.2b). Six species, and probably seven if we include the Honey Badger, can be considered as locally extinct. Among the 37 extant (i.e. still living) native species, bats are the most diversified with 13 species, followed by the rodents with nine species, and the carnivores with seven species. The geographic position of the United Arab Emirates, at the crossroad of different continents and biogeographic realms, is reflected in its mammal fauna. Without entering in the phylogenetic origin of the species, but broadly considering their extant distribution ranges, the native mammalian fauna of UAE has a more important palearctic origin (55% of species), than afro-tropical (32%), while the Indomalaya origin accounts for only two species (the Indian Crested Porcupine and the White-tailed Mongoose). Spatially, mammal diversity is the highest in the Hajar Mountains (Fig. 14.3), with 19 species regularly using mountainous habitats, but only four of them are strictly confined to this ecosystem, most of them are also using other habitats, like shrublands, farms or forested areas.

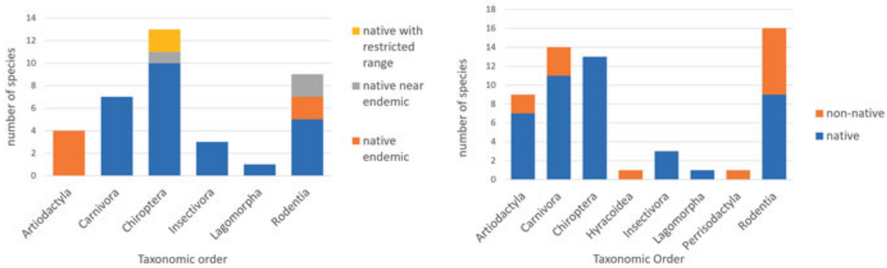


Fig. 14.2 (**a**) Number of native species recorded in UAE per taxonomic order, with reference to their endemicity. (**b**) Number of native and introduced mammal species, recorded in UAE per taxonomic order

Fig. 14.3 Typical landscape in the Hajar Mountains, here in wadi Shees (Sharjah Emirate). Photo credit: Jacky Judas

14.2.1 Native Rodents

Nine species of native rodents are known in UAE, distributed among three families: the porcupine family (Hystricidae, one species), the Jerboa family (Dipodidae, one species), and the mouse and rat family (Muridae, seven species). In this last family, the sub-family of Gerbils and Jirds (Gerbillinae) is the most diverse with six species, while only one true native mouse is present, the Arabian Spiny Mouse (*Acomys dimidiatus*, Fig. 14.4). The latter is a nocturnal sociable species, that forages at night for seeds, and sometimes insects and grasses. It is mainly found in the wadi beds of the Hajar mountains, and more rarely in farms or shrubby areas. It has been reported

Fig. 14.4 Arabian Spiny-mouse (*Acomys dimidiatus*). Photo credit: Jacky Judas

from Nad Al Sheba in Dubai. The Wagner's Gerbil (*Gerbillus dayurus*) is the secund most common species of native rodent found in the mountains, where it prefers rocky slopes and terraces than wadi beds and is generally more abundant than the Spiny Mouse at higher elevation (Melville and Chaber 2016). This species, also active at night, spends the day in holes, often under the perennial bushy spurge, *Euphorbia larica*, one of the dominant plants growing on the slopes of the mountains.

The Indian Crested Porcupine is the third and largest native species of rodent found in mountainous habitats. This species was only recently discovered in UAE. In April 2014, Alexander Cloke, working for Emirates Nature-WWF, briefly observed at night an animal, that he identified as a Porcupine, fleeing away from the roadside near the entrance of Wadi Wurayah National Park, some 600 km from the species' nearest known distribution range edge in Arabia. It was only in 2015–2016 that the presence of this species was confirmed by pictures obtained from a network of camera traps deployed by Emirates Nature-WWF and Fujairah Municipality in the National Park, and from interviews of residents conducted by the park staff (Chreiki et al. 2018). In 2018, Indian Crested Porcupine was also recorded by camera traps in Abu Dhabi emirate in some coastal areas near Mirbah (Al Dhaheri et al. 2018).

The Lesser Jerboa, which looks like a miniature kangaroo with its disproportionately large hind legs is a nocturnal and secretive species; it is found in the inter-dunal plains of sandy areas. Data are lacking to establish its status in UAE. The species was listed as 'Near Threatened' in the UAE National Red Data List published by Richard Hornby in 1996, and as Data Deficient for the Abu Dhabi Red List in 2005 (Drew and Tourenq 2005).

Gerbils and Jirds are well-adapted to live in sandy deserts, able to cope with high temperatures and food scarcity. All UAE species, except the Wagner's Gerbil which is a mountain species, are found in sand dunes and interdunal gravel plains that offer some vegetation cover. The most common are certainly the Baluchistan and Cheesman's Gerbils. The Baluchistan or Dwarf Gerbil, rather similar in appearance to the Wagner's Gerbil, with a yellow-grey back and white belly, is a solitary nocturnal animal. Cheesman's Gerbil is slightly larger, with an orange back. Both lives in burrows during the days and go out at night to forage for seeds and other plant materials. Three species of Jirds are present in UAE. The Arabian Jird (*Meriones arimalius*), endemic to central and East Arabia, was for some time considered a sub-species of the Lybian Jird (*Meriones lybicus*) found further north in Arabia. Based on genetic analysis, it is now considered a valid species (Cassola 2016). Very little is known on this species, except for a few records in sandy deserts. The Sundevall's Jird (*Meriones crassus*) is a more common and widespread species of sand deserts, living in colonies or alone according to environmental conditions. Fat Jird (*Psammomys obesus*) is another recent addition to the mammal fauna of UAE. Mentioned by Cunningham (2004) as a good candidate species to be found in UAE, as it was known from Qatar and South-eastern Saudi Arabia, it was effectively discovered by wildlife researchers of the Environmental Agency of Abu Dhabi (EAD) in June 2019 by camera trapping (EAD, pers. Comm.).

Rodents play important role in their ecosystems as they disperse seeds on which they feed and are an important food resource for numerous predators, like owls, diurnal raptors, and mammalian carnivores.

14.2.2 Bats: An Under-studied Group in the UAE

Bats constitutes a difficult taxonomic group to study, which explains the paucity of information related to these species in UAE. Very little is known, even the list of species present is not yet fully established (Judas et al. 2018). Most of the knowledge on UAE bats fauna date back from field surveys conducted by Paul Harrison in the 1950s and published in its authoritative book on Mammals of Arabia (Harrison and Bates 1991). Surveys conducted by Emirates Nature-WWF in 2018–2019 contributed to the addition of three new species to the UAE fauna, the Geoffroy's Bat (*Myotis emarginatus*), the Botta's Serotine bat (*Eptesicus bottae*, Fig. 14.5), the Egyptian Tomb Bat (*Taphozous perforatus*), and some more species likely remain to be found (Judas, pers.info). As of 2022, 13 species belonging to 4 families have been identified, including 4 additional species to add to the 9 species listed by Harrison.

The Vespertilionidae is the most represented bat family, with seven species. The most common species is the Kuhl's pipistrelle (*Pipistrellus kuhlii*, Fig. 14.6), a widespread species, that benefits from human development and urbanization (see also Chap. 23). If you see a bat flying in the urban streets or parks (Dubai, Sharjah or Abu Dhabi) at dusk or night, it will most probably be this species. They live in colonies of a few dozen to some hundred individuals under the roof of villas or building that they access through very tiny holes. The Sind Serotine (*Rhyneptesicus nasutus*) seems to also be widespread throughout the UAE, although in lower abundance than the Kuhl's Pipistrelle. They live alone or in small family groups,

Fig. 14.5 Botta's Serotine Bat (*Eptesicus bottae*). Image: Jeremy Dechartre

Fig. 14.6 Kuhl's Pipistrelle (*Pipistrellus kuhlii*). Photo credit: Gabor Csorba

probably hiding in small rock crevasses or under the bark of trees. Little is known on their habitat and ecology. The Common Pipistrelle (*Pipistrellus pipistrellus*), one of the most common and widespread species in Western Europe and across Turkey up to West Asia, has been recorded once in 2018 in Abu Dhabi Western Region, during surveys conducted by a private environmental assessment company (Smithson, pers. comm.). The Parti-coloured Bat (*Vespertilio murinus*) has also been recorded only once in Sharjah, from a dead individual found in May 2014 (Monadjem et al. 2016). This migrant species lives in steppes, mountains, and forested areas from Western-Central Europe across central Asia up to North-East China. This record, presumed to be from a vagrant individual, was the first for the Arabian Peninsula. The Hemprich's Long-Eared Bat (*Otonycteris hemprichii*), specialized in capturing arthropods from the ground, including scorpions, was also only recorded once in Ras Al Khaimah in the 1970s (Harrison and Bates 1991). It was identified from bones collected in an owl pellet. The lack of further records might simply be due to the absence of surveys.

Fig. 14.7 Egyptian Tomb Bat (*Taphozous perforatus*). Photo credit: Jeremy Dechartre

The Sheath-tailed Bats family, or Emballonuridae, is represented by two species: the Naked-bellied Tomb Bat (*Taphozous nudiventris*) and the recently discovered Egyptian Tomb Bat (*Taphozous perforatus*, Fig. 14.7). The first occurs in colonies in desert rocky outcrops, and along the Western foothills of the Hajar Mountains. Paul Harrison described a new subspecies from the UAE, named *Taphozous nudiventris zayedi* in honour of the late Sheikh Zayed bin Sultan Al Nahyan, who procured him some specimen from Al Ain and showed him their roost (Harrison 1955). The Naked-belly Tomb Bat seems to prefer the higher elevation of the Hajar Mountains. It has been recorded in Fujairah and Ras Al Khaimah.

The Old-World Leaf-nosed Bats family, or Hipposideridae, is represented by two species, the Geoffroy's Trident Leaf-nosed Bat (*Asellia tridens*, Fig. 14.8) and the Persian Leaf-nosed Bat (*Triaenops persicus*). Both were present in numbers in the 1950s (Harrison 1955), feeding at night in Al Ain/Buraimi oasis and roosting in the underground network of '*falaj*' (the traditional irrigation system) (Fig. 14.9). The Geoffroy's Trident Leaf-nosed Bat is still present at that location in much smaller numbers and can also be found in small caves within the Hajar Mountains. Not recorded from more than 50 years, the echolocation calls of the Persian Leaf-nosed Bat was recorded once by this author during surveys conducted near Jebel Hafit in 2017.

The Muscat Mouse-tailed Bat (*Rhinopoma muscatellum*, Fig. 14.10), the only representative of the Mouse-tailed Bats family, or Rhinopomatidae, is relatively widespread in the eastern mountains of the UAE, where it lives in small colonies in

Fig. 14.8 Geoffroy's Trident Leaf-nosed Bat (*Asellia tridens*). Photo credit: Eric Sansault

Fig. 14.9 Traditional underground irrigation system in Al Ain–Buraimi (Falaj) used as roosting site by Geoffroy's Trident Leaf-nosed Bat and Persian Leaf-nosed Bat. Photo credit: Jacky Judas

Fig. 14.10 Muscat Mouse-tailed Bat (*Rhinopoma muscatellum*). Photo credit: Jacky Judas

Fig. 14.11 Egyptian Fruit Bat (*Rousettus aegyptiacus*). Photo credit: Jeremy Dechartre

caves or abandoned buildings. It can also be found on the Arabian Gulf coast in Sharjah and Dubai, as well as in Jebel Hafit.

The Egyptian Fruit Bat (*Rousettus aegyptiacus*, Fig. 14.11), from the Old-World Fruit Bat family, Pteropodidae, also lives in the Mountains of Fujairah and Ras Al Khaimah, visiting orchards and farms at night in search of fruits, roosting in trees or in caves during the day. This species, the largest found in UAE, is also common in gardens and parks of Al Ain, but more rarely in Abu Dhabi.

14.2.2.1 Bats as Viral Vectors

The Covid-19 pandemic of 2020–2022 (and continuing at the time of writing) has raised growing concerns and fear about bat populations worldwide, driven by the strong suspicion that the novel coronavirus SARS-Cov-2 at the origin of the outbreak took its origin in bats near Wuhan, China. Bats are known to host a large diversity of viruses (Anthony et al. 2017; Markotter et al. 2020) and their implication in several zoonotic outbreaks has been demonstrated. They are the natural reservoir for the Marburg, Nipah and Hendra viruses, which have caused human diseases and outbreaks in Africa, Malaysia, Bangladesh and Australia. They are thought to be the natural reservoir for the Ebola virus. They also carry the rabies virus, but in that case, contrarily to other viruses, the bats are also affected by the disease. The probability of a new bat-borne virus to jump from bats to humans is believed to be greater in areas of higher bats diversity, where active habitat encroachment favors closer contacts between wildlife and humans, like in the tropical forests of Africa or Asia. However, in 2012, the emergence of the Middle East Respiratory Syndrome (MERS), caused by a bat coronavirus, showed that outbreaks can also occur in areas of low bat diversity and low human population density, like in Arabia. In 2013, bats were the known reservoirs of more than 60 viruses that can infect humans (Woo and Lau 2019), and there have been at least 30 bat coronaviruses discovered in the last 15 years after the SARS epidemic in 2003. There are clearly some links between bats, human health, and national security. Bats and humans have lived together for thousands of years without records of such emergence of bat-borne viruses' outbreaks. It is the human disturbances in the environment that are facilitating emergence of these diseases, through activities like deforestation, destruction of their natural feeding and roosting habitats, and hunting animals out of some areas. It is our interactions with these species that are causing diseases to jump. Their ability to coexist with viruses that can spill over to other animals, in particular humans, can have devastating consequences, when we eat them, trade them in livestock markets and invade their territory (Chan et al. 2013). While bats populations are in severe decline worldwide (Tuttle 2017) and often misleadingly feared (Tuttle 2020), cases of bats being killed by fear, ignorance, and sometimes superstition, have multiplied during the Covid-19 pandemic. Yet, bats are important to humans by playing important ecological functions in their ecosystems and a major role in agriculture since they pollinate fruit trees (Whittaker and Jones 1994; Kelm et al. 2008) and help controlling populations of insects (Leelapaibul et al. 2005; Kalka et al. 2008). By consuming tons of insects, they also control insects carrying diseases, like mosquitoes. Except the Egyptian Fruit Bat, which as its name indicates is frugivorous, all other species are insectivorous.

As such, it is important to increase our knowledge of bats and to ensure the development of responsible mitigation strategies to not only minimize risks of infection but also ensure the conservation of the species and maintain their crucial role in ecosystem services. With the wide recognition of the links between bats and the potential emergence of new bat-borne virus outbreaks, it becomes urgent to get a better understanding of how bats use their environment, and what are the critical habitats they are using. Tracing the origin and taking action to combat further outbreaks may depend partly on knowledge and monitoring of bats. At the 6th Public Health Conference at Arab Health 2019 in Dubai, it was agreed that infectious diseases should remain a public health priority and future research and ongoing surveillance is required. While bats must be studied, their physiology understood, and the viruses they harbor monitored for the sake of public health, that does not mean that they are to blame for outbreaks; studying them would also bring in to implement conservation measures to limit disturbance and interactions with humans, protect and restore their habitats.

14.2.3 Insectivores

Three native mammal species, belonging to the Insectivora Order, have been recorded in the UAE, two species of hedgehogs and one shrew.

The Ethiopian Hedgehog, or Desert Hedgehog (*Paraechinus aethiopicus*), lives in arid deserts across the whole Arabian Peninsula and in North Africa. It is relatively widespread in the Abu Dhabi emirate, often found in farms and suburbs gardens, where insects, its preferred food, are more easily available.

The Brandt's Hedgehog (*Paraechinus hypomelas*) is a mountain species of Asian origin. Its distribution encompasses a large part of Iran, South Turkmenistan, West Afghanistan and Pakistan (Bhattacharyya et al. 2016). In Arabia, its distribution is not well-known, but has been recorded from Saudi Arabia, Yemen, Oman and UAE, where it lives in the Hajar Mountains. It is well represented in Wadi Wurayah National Park and has been noted on Jebel Hafit (Aspinall and Hellyer 2004). Surprisingly, this species is a very good climber, finding shelters among small cavities in steep cliffs.

The Savi's Pygmy Shrew, or White-toothed Pygmy Shrew (*Suncus etruscus*), considered the smallest mammal species in the world, weighs only 1.8 g. It ranges from the Mediterranean basin, both in Africa and Europe, through the Middle East up to Southern Asia, Thailand, and Malaysia. This cryptic species, firstly observed in Sharjah in 2001, is known from very few records in UAE (Jongbloed et al. 2002).

14.2.4 Carnivores

Eight extant native species, belonging to four families represent the Carnivora Order in UAE. Three species belongs to the dog family (Canidae).

The Red Fox is the most widespread and abundant of the carnivores (Fig. 14.12). This ubiquitous species is well-adapted to live in human vicinity and has largely benefitted from development. Although often persecuted due to his habit of visiting henhouses and killing their inhabitants, red foxes use a large variety of habitats from

Fig. 14.12 Arabian Red Fox (*Vulpes vulpes arabica*). Photo credit: Jacky Judas–ENWWF

wadis, mountains, farms, gravel plains, sand desert, up to parks and gardens of the largest cities (Abu Dhabi, Al Ain, Dubai, Sharjah, Fujairah and Ras Al Khaimah), and it thrives over the whole country, benefitting from litter and food waste. It also reaches some of the not-too-distant Abu Dhabi islands, where it can be seen wandering on the beaches. This is mainly a crepuscular or nocturnal species, but it is not rare to see them during daylight, particularly during their breeding season, when they have cubs in spring (March to May). The Arabian subspecies (*Vulpes vulpes arabica*) is smaller and slender, than his European counterpart. The Blanford's Fox (*Vulpes cana*, Fig. 14.13) is a mountain species with a distribution range, quite similar to the Brandt's Hedgehog, occurring over Iran with some overlaps on the neighbouring countries, as well as in the mountains of the Arabian Peninsula (Hajar, Dhofar, Asir). Their presence in UAE, and in Arabia more generally, has been detected only recently (Smith et al. 2003). They were first trapped in Wadi Wurayah in 1995. Later surveys have shown their larger distribution through the Hajar Mountains of UAE, although in low density, and they have also been recorded on Jebel Hafit (Aspinall and Hellyer 2004). This species is quite distinctive from the more abundant Red Fox by their smaller size, wide ears, and long bushy tail that is nearly equal to the length of the body. The Ruppell's Sand Fox (*Vulpes rueppellii*) is another small fox that prefers to live in desert and semi-desert regions of North Africa and the Arabian Peninsula up to Iran. This is a rare species in UAE, known from only few locations in the western region of Abu Dhabi.

Fig. 14.13 Blanford's Fox (*Vulpes cana*). Photo credit: Jacky Judas–ENWWF

Fig. 14.14 Caracal (*Caracal caracal*). Photo credit: Jacky Judas–ENWWF

The Cats family, Felidae, is also represented by three extant native species. The largest, the Caracal (*Caracal Caracal*, Fig. 14.14), which weigh between 8 and 15 kg, remains in low numbers in the Hajar Mountains. Successful breeding has been confirmed by camera trapping in Wadi Wurayah in 2014, and a male has been recorded at Jebel Hafit in 2019 (EAD 2021). Its population, as for many other carnivores, has suffered from human persecution, with animals being trapped, killed and hung in trees. It's a secretive, nocturnal species, and is very difficult to observe. The status of Arabian Wildcat (*Felis lybica*) is unclear. Feral cats, similar in appearance to wildcats by their size, fur pattern and general morphology, have been trapped or photographed. However, given the spread of feral cats in all habitats, sometimes deep in the mountains, it is becoming more difficult, perhaps even impossible without genetic analysis, to distinguish in the field between a native Arabian Wildcat, and a feral cat, whose morphology and appearance are very similar to the wild native species. Moreover, as has been demonstrated in Europe, wild populations of another Wildcat, *Felis sylvestris*, crossbreed with feral cat populations (Randi et al. 2001). Pure-bred Arabian Wildcats may already have vanished or become extremely rare. Only genetic screening of the wild population can clarify this. The Sand Cat, *Felis margarita*, inhabits sandy and rocky deserts across North Africa, Middle East, the Arabian Peninsula up to West Asia. In UAE, it is known from several locations, mainly in the Abu Dhabi western region, as well as in Dubai Desert Conservation Reserve. The species was reported around Sweihan a few decades ago but has not been confirmed recently (Eishaker pers. comm.).

The White-tailed Mongoose (*Herpestes albicaudus*) is the only native representant of the Civets and Genets (the Viverridae family). It used to be relatively widespread in the UAE a few decades ago, with records from the agricultural areas of Ras Al Khaimah along its Gulf coast, and in Al Ain, Masafi, and several locations in the Hajar Mountains (Jongbloed et al. 2002). More recently, it has been observed in Wadi Shawka (Ras Al Khaimah emirate, but geographically near to Sharjah, Sawaf pers. comm.).

The Honey Badger (*Mellivora capensis*), from the Mustelidae family that includes weasels, ferrets, otters, martens, and minks among others, used to be present in various habitats from the Hajar Mountains to the desert sands of Abu Dhabi. The last record in Abu Dhabi might date back some 20 years ago, from second-hand information reported by Abu Dhabi rangers. More recently, it has been reported from Wadi Shawka in the Hajar Mountains (Buzas, pers. comm.). The paucity of recent records might reflect an important population decrease, which might ultimately lead the species to local extinction, if it is not already the case.

Larger carnivores have already experienced the same fate as the Honey Badger. The most famous example is certainly the case of the Arabian Leopard (*Panthera pardus nimr*), which once roomed in the Hajar Mountains, but has been led to local extinction from the UAE in the 1990s by constant persecution by hunters and habitat loss. The last record of a wild living leopard in the UAE is probably from an individual killed in Ras Al Khaimah in 1992 (Hellyer and Aspinall 2005). The Striped Hyena and the Arabian Wolf have also paid the price of human–wildlife conflict, and their populations have been extirpated by persecution. Larger carnivores are often among the first species to disappear from areas where human development occurs. The need for large territories to sustain their food requirements, coupled with their relative low densities, make their populations much more sensitive to the loss of few individuals.

Fig. 14.15 Arabian Tahr (*Arabitragus jayakari*). Photo credit: Jacky Judas

14.2.5 Ungulates

Ungulates refer to a group of large mammals with hooves, which have morphological similarities, but are not necessarily related to each other genetically and taxonomically. This group contains the Artiodactyla, or even-toed Ungulate, which are represented by four extant native species in the UAE, all from the Bovidae family.

The Arabian Tahr (*Arabitragus jayakari*, Fig. 14.15) is a goat-like mammal, endemic to the Hajar Mountains of the UAE and Oman. It lives on steep slopes at higher elevations in small matriarchal groups, composed of adult females, sub-adult males and females as well as new-borns (Munton 1985). Adult males remain alone most of the year except during the mating season. The Arabian tahr has been brought close to extinction by over-hunting and poaching, and only few individuals still roam in a few locations of the mountains of UAE. It has probably vanished from Wadi Wurayah National Park, which used to be one of the strongholds for the UAE population. The last individual was photographed by camera trapping in 2012 (Judas 2016).

Two species of gazelles can be found in UAE: the Arabian Mountain Gazelle (*Gazella arabica*) and the Arabian Sand Gazelle (*Gazella marica*, Fig. 14.16). The taxonomy of these two species is quite complex and has been the subject of many debates and publications in the last few decades (Lerp et al. 2013). From the most recent genetic analyses, they are both now both considered as endemic species of the Arabian Peninsula. Both species have been subject to captive-breeding, transfers and releases in many parts of the country. It is now very difficult, if even possible, to

Fig. 14.16 Arabian Sand Gazelle (*Gazella marica*). Photo credit: Jacky Judas

know which populations are wild, translocated, or reintroduced. The Arabian Mountain Gazelle was previously considered a subspecies of the Mountain Gazelle (*Gazella gazella*), and lives in the Mountains and interior sand and gravel plains. They also used to leave in coastal plains, but have been extirpated from these heavily developed areas. Their favoured habitat coincides with the distribution of the Umbrella Thorn Acacia (*Vachellia tortilis*), that provides them food and shelter. The Arabian Sand Gazelle was considered a subspecies of the Asian Goitered Gazelle (*Gazella subgutturosa*) up until 2010 (Wacher et al. 2010), and lives in sand dunes and gravel plains, but avoid rocky areas. They are mainly found in the Abu Dhabi western region, including deep in the Rub Al Khali desert, but they have also been reintroduced and kept in semi-captivity in Dubai.

The iconic Arabian oryx (*Oryx leucoryx*, Fig. 14.17) is the largest Ungulate found in UAE, weighing up to 70 kg. They live in sand dunes and inter-dunal gravel plains. All populations present in UAE are issued from captive-breeding and reintroduction programmes. Some few hundred animals are distributed among few protected areas of Dubai (Al Marmoum Protected Area) and Abu Dhabi (Umm Al Zoumoul Protected Area).

Fig. 14.17 Arabian Oryx (*Oryx leucoryx*). Photo credit: Jacky Judas

14.2.6 Non-native Species

Human activities and development have brought their share of non-native species to UAE, intentionally or accidentally. Some of these species have established viable populations, and have become invasive (an *invasive* species is a non-native species that causes harm to the environment, human health, the economy, etc). Others introduced species that survive, might breed several consecutive years when conditions are suitable, and eventually vanished when conditions become too challenging. Due to the harsh arid environment, few non-native species manage to thrive in the natural environment of UAE, particularly if they are not originating from a region with similar environmental conditions. However, they can adapt to live in artificial habitats, such as farmlands and urbanized areas (see Chap. 23).

The presence of mice and rats is probably as old as human civilization (Auffray et al. 1990). Following people on their trade routes, these commensal invasive species travelled by ships among goods, establishing in harbours before spreading further into the countryside of new areas. Brown Rat (*Rattus norvegicus*) and Black Rat (*Rattus rattus*) both occur in UAE, although their respective status and distribution is not well known. The Black Rat or House Rat is probably the most widespread, living in cities, gardens, parks, farms, where they eat from human food waste, crops, seeds and fruit. The Brown Rat, or Norwegian Rat is a larger

Fig. 14.18 Northern Palm Squirrel (*Funambulus pennantii*). Photo credit: Jacky Judas

species, more heavily built, that might prefer wide open spaces, such as labour camps or most frequented picnic areas. The House Mouse (*Mus musculus*) is present in nearly all human settlements, from city centres to villages and isolated farms, but can also be found in wilder habitats, such as scrublands and desert edges.

How the Northern Palm Squirrel (*Funambulus pennantii*, Fig. 14.18) made its way to UAE from its native range of western Asia (India, Nepal, Pakistan) is unknown. We might guess that it has been imported in the pet trade, where some individuals managed to escape or may even have been intentionally released (Judas and Hellyer 2016). The first known record of this squirrel in the UAE comes from Al Hamrania farms (Ras-Al Khaimah) in January 2011, and few months later from Fujairah near a housing complex. Since then, records have multiplied, coming from a growing number of locations. The species is now widespread all over UAE, with records from all emirates in farmlands, parks, and gardens.

On the other hand, few individuals of Persian Squirrel (*Sciurus anomalus*), presumably originating from the pet trade, have subsisted in parks and gardens of Abu Dhabi between 1999 and 2003, before they appear to have disappeared (Hellyer and Aspinall 2005).

A very healthy colony of Indian Desert Jird (*Meriones hurrianae*) was reported between 2008 and 2011 from farms in Ajban area, presumably these were escapees from local pet markets. This species, available in pet shops in the UAE, naturally occurs in Pakistan and northwest India in desert habitats. Being adapted to similar environmental conditions, the risk exists that they might extend their range and eventually compete with native Jirds.

Fig. 14.19 Patagonian mara (*Dolichotis patagonum*). Photo credit: Jacky Judas

More recently, another exotic species, the Patagonian mara (*Dolichotis patagonum*, Fig. 14.19), of South American origin, the second largest known rodent after the Capybara (*Hydrochoerus hydrochaeris*), made its appearance in Abu Dhabi and Dubai. This large rodent is a common species in zoological collections and undoubtedly found its way out from captivity. They can regularly be seen sleeping or eating grass in the middle of round-abouts at Al Qudra (Dubai Emirate). This species is not adapted to live in arid environment, although in the absence of his usual predators, like pumas, it can possibly survive in highly modified habitats with tree plantations, lawns and ponds.

The Indian Grey Mongoose, *Herpestes edwardsii*, was recorded in the northern emirates in the 1980s and two thought to have been this species were observed in Abu Dhabi in 1985 and 1988, although the lack of recent records may indicate that the species has failed to establish a viable self-sustaining population.

The Rock Hyrax *Procavia capensis* was introduced on Jebel Hafit (Al Ain, Abu Dhabi) in the 1990s, and a small population has been persisting until today around a water source. The species is also well represented on Sir Bani Yas.

Barbary Sheep or Aoudad (*Ammotragus lervia*) is endemic to mountains across North Africa. It is kept in captivity in several private collections in the UAE, and some individuals have been released or escaped in Hatta area (Dubai). The species has also been reported from Jebel Hafit, Wadi Kub (Fujairah), and Wadi Shawka (Ras Al Khaimah). This species, well-adapted to live in arid mountains, might well survive in the Hajar Mountains, and become a competitor and threat to the native Arabian Tahr.

Fig. 14.20 Feral Goat (*Capra aegagrus hircus*). Photo credit: Jacky Judas

Feral species are another category of non-native species present in UAE. These species were once domesticated either for their meat, used to carry people and material, or as pets. Goats (Fig. 14.20) have been kept by villagers for centuries. Following rain, when the dry slopes of the Hajar Mountains turn green, it is not rare for shepherds to let their livestock pasture freely for several days or weeks. This practise might have been entertained for a long time, and it is unsurprising that some goats might have escaped into the wild. Feral populations have settled well, and are now widespread all over the Hajar Mountains.

Another feral group, donkeys (Fig. 14.21), used to carry goods and material on steep paths in wadis, although they became less useful when motorized vehicles appeared in the UAE. Some have probably been abandoned, left to their sad fate. They learned to survive in the wild and are now widespread through the Hajar Mountains. Unlike goats, less agile, they can’t access the steepest parts of the mountains, and limit their movements to lower elevation, or areas relatively easy to access. Among other vegetal material they consume, donkeys eat the bark of some native trees (*Moringa peregrina* for instance), seriously damaging them, and compromising their growth and survival.

Camels have for a long time been left to free-range and feed in desert areas. Although this practise is increasingly controlled and regulated, they have largely contributed to overgrazing in most areas of the country. Camels are presumed to be

Fig. 14.21 Feral Donkey (*Equus asinus*). Photo credit: Jacky Judas

native to Arabia (Thompson 2015), although wild populations no longer exist; neither are there any feral populations—all camels encountered are domestic animals.

Cats and dogs have also established feral populations throughout UAE, presumably as abandoned, lost, or escaped pets. Dogs mainly remain in proximity of human settlements where they can find or beg for food. They often live in small clans of a dozen or more individuals and are particularly attracted by landfills. They do not venture far into natural habitats. On the contrary, feral cats are solitary, and although well represented in and around cities and villages, they also venture quite deep in natural habitats, being sometimes observed kilometres away from the nearest habitations, deep in the desert or in mountain wadis. Feral cats have important negative effects on the native fauna, predating on small rodents, birds and reptiles.

14.2.7 Potential Species

A few new species may remain yet to be discovered in the UAE, most likely among the most cryptic or less surveyed taxonomic groups. There are certainly two or three more bats that wait to be discovered. During surveys conducted by Emirates Nature-WWF, the echolocation calls of at least two species were recorded that could not be allocated to the species' already known. These are presumed to be the Egyptian Free-tailed Bat (*Tadarida aegyptiaca*), and a small Pipistrelle, possibly Rüppel's Pipistrelle (*Vansonia rueppellii*). Without capturing them, their identity can only be assumed. The Blasius Horseshoe Bat (*Rhinolophus blasius*) and the Arabian Pipistrelle (*Hypsugo arabicus*), known from the Hajar Mountains in Oman are other potential candidates. The Arabian White-toothed Shrew (*Crocidura arabica*), known from Dhofar and Mussandam in Oman, and the House Shrew (*Suncus murinus*), which were recorded in various other regions of the Arabian Peninsula, are two other potential candidates.

14.3 Adaptations to Arid Environment

Living in the arid environment of UAE, being able to survive long periods of drought and cope with temperatures often raising above 45 °C during summer, which is at the limit of physiological limit of tolerance for many animals, requires specific adaptations from organisms, mainly to regulate water exchange and control body temperature (Lindsay Maclean 1996; Asres and Amha 2014). Native mammal species that have evolved in these harsh conditions have developed morphological, physiological, or behavioural adaptations.

Most UAE mammals have adopted nocturnal or crepuscular habits to forage and feed, avoiding the peak daily temperature period. During the day, they hide in burrows or caves. Bats generally emerge from their roosts in rock cracks, old buildings, caves, or trees very shortly after sunset, stay active all night, and end their hunt shortly before sunrise. This is also the case for carnivores and rodents, who hunt or forage at night and retreat in their burrows at night. By feeding at night, rodents are also able to make use of the dew on plants as a source of water. The Cheesman's Gerbil is known to carry damp vegetation to its burrow, which raises the humidity level inside. The burrow entrance is often at the base of a shrubby plant, and the gerbil closes the entrance when it enters by flicking sand across with its tail. Some species, like the Red Fox, become seasonally more active during daylight in early morning or late afternoon, in spring when food resources are more abundant and when they are raising their cubs. Diurnal species, like Gazelles and Oryx, spend the hottest hours under the shade of trees, and are mainly active at dawn or dusk.

Physiological responses to cope with thermal challenges involve neural and hormonal mechanisms, such as adapted sweat gland flow that regulates heat production (Tattersall et al. 2012). Mammals use evaporative cooling that allows them to maintain a balance between thermoregulation and water balance (be it through panting or through sweat). Water scarcity often constrains these species to obtain much or all their water from the food they consume. The reduced water intake is partially balanced through lower volumes of fluids in concentrated urine and dry faeces.

Morphological adaptations also help mammals to maintain their heat and water balance, allowing them to survive the arid and hot environmental conditions. Desert Hares have hyper-enlarged hears that increase the surface area for exchange between the body and the air, and contribute to dissipate their corporal heat and control their body temperature. Fur density of camels greatly increases their skin and body insulation, allowing them to stay cool even in direct summer sun; the fat deposit that makes up their 'hump' also provides insulation on their highly exposed upper-back. Several species like the Cheesman's Gerbil have their soles covered with hairs allowing them to step and to run on hot sand.

14.4 Main Threats to Mammals

Most factors that threaten biodiversity worldwide also occur in UAE. One of the most important, and still on-going, threats is certainly the degradation, fragmentation, and loss of habitats. The rapid growth of UAE economy in the last 60 years, following oil discovery in 1958, has resulted in a rapid human population growth and expansion of cities and industrial areas, mainly on coastal areas (Fig. 14.22), and encroachment into natural habitats (see Chap. 23). These lost and degraded habitats

Fig. 14.22 Coastal development in Khor Fakkan (Sharjah Emirate). Photo credit: Jacky Judas

Fig. 14.23 Highway crossing the Hajar mountains. Photo credit: Jacky Judas

are in many areas unsuitable for native mammals, as such reducing their overall populations.

An important network of roads has been, and is still being, developed across the Emirates (Fig. 14.23). Although this eases the time required to travel and transport goods from town to town, these roads—and more recently railways—are fragmenting once-extensive habitats into smaller and smaller areas. Such linear infrastructure creates barriers that animals avoid or hesitate to cross. In some places in the Hajar mountains, long concrete walls in the middle of the roads are used for separating traffic, and while certainly useful for security reasons represent barriers for mammals that attempt to cross roadways, and end-up impacted by vehicles. The ubiquitous road-side fences pose similar issues for larger mammal species. In addition, the noise generated by the traffic can be heard kilometres away, keeping the shyest species at distance.

Large areas that haven't yet been developed nevertheless have become unsuitable for many species. The repeated passages of off-road motor vehicles created tracks coming from all directions through the desert often degrade vegetation cover, crushing perennial plants that typically need years to grow and recover. Overgrazing by domestic livestock (camels, goats and sheep) in the interior sand and gravel desert or in the mountains also decreases vegetation cover, changes the composition of plants communities and decreases the floral diversity—often to the benefit of invasive and/or non-palatable species—and decreases food availability for

Fig. 14.24 Sheep grazing in the mountains of Fujairah Emirate. Photo credit: Jacky Judas

herbivores (see Chap. 5). Grazing and nomadic pastoralism has been practised in this region for millennia, long before the discovery of oil. The number and size of livestock herds were historically limited by the availability of pasture and rainfall. With economic development, access to water, transport, purchase of fodder during drought and natural food shortage became far easier. As a result, more livestock could be maintained (Fig. 14.24), increasing grazing pressure and competing with wild herbivores.

Over-hunting or poaching have been responsible for the local extinction of important populations, reducing many game species such as the Arabian and Sand gazelles, Arabian Oryx, Arabian Tahr, Cape Hare. In the last decades, hunting became more of a leisure than a means to obtain food, as it was in the past. Trivialization of the use of vehicles and firearms have worsened the situation, allowing more animals to be killed off in less time, farther into the wilderness. Predators, like Arabian Leopard, Arabian Wolf and Striped Hyaena, were persecuted and driven to local extinction because of past human/wildlife conflicts when these predators would regularly predate domestic livestock due to degradation of their natural habitats and loss of natural food sources.

The threat posed by non-native invasive or feral species, introduced above, adds to the pressure on native species. The numerous feral cats and dogs wandering in the UAE's environment are additional predators of rodents, bats, and other small

Fig. 14.25 Artificial lights at night in Bidiyah (Fujairah Emirate). Photo credit: Jacky Judas

mammals. Dogs have been seen chasing the endangered Arabian Tahr on Jebel Hafit.

Recent human population growth has resulted in increased frequentation of natural habitats by city-dwelling resident who are seeking connection with nature, but this too has led to conflicts with wildlife due to the incredible pressure that 'attractive' and interesting sites receive. Promotion of ecotourism, with the creation of hiking trails or camping sites, if not properly managed, raise the level of disturbance in natural habitats and can impact mammals populations. The time spent by mammals on alert or hidden reduces the time they can allocate for feeding (Schnidrig-Petrig and Ingold 2021), and can decrease the size of the areas in which they forage, ultimately impacting their body condition, reproduction success, or survival.

Artificial lights at night (Fig. 14.25) have spread everywhere through the country, in towns and along an important network of roads (see Chap. 23). Their impact has not been studied in UAE, but it is known from other nations in Europe and America to have important negative effects on wildlife (Beier 2006), including attracting insects and contributing to their decrease (Owens and Lewis 2018). Impacts to insects, being at the basis of the food chain for many animals, affects the whole ecosystem by decreasing food resources for insectivorous species. Bat populations are particularly sensitive to the effects of light and its ramifications on the insect communities on which they feed (Seewagen and Adams 2021).

14.5 Relations with Humans

Humans have occupied the region, now known as UAE, for millennia, first as hunter-gatherers with a nomadic lifestyle, before progressively shifting to sheep-herders and villagers. Their relations with wild mammals changed accordingly. Hunting large herbivores for food, or killing predators—perceived as competitors or to protect themselves—were probably the most ancient relations they might have with wild mammals. Progressively, humans started domesticating goats, sheep, and camels from wild animals that were caught in natural habitats, herding them to pastures (when more humid times were common, see Chap. 4) and slowly beginning the process of domestication. Where water was more reliably available, like in mountains (Fig. 14.26), man started to cultivate crops and fruits, settling down in permanent villages. The time of domestication likely saw an increase in human-wildlife conflicts, as larger carnivores likely predated on the easy-to-target prey that were domestic animals. Animal domestication likely started in modern day Iraq, and

Fig. 14.26 Oasis in wadi Shees (Sharjah Emirate). Photo credit: Jacky Judas

the practise exported later to southeast Arabia through human population movements and trade networks.

Nowadays, livestock breeding is still common practise, although much less vital than in the past since most food supplies, including meats of mammals and other vertebrates, are imported. Hunting of wild mammals is strictly regulated, and mostly forbidden.

Beside the direct benefits some mammals provide to man, all species have their role to play in ecosystems functioning by providing ecosystems services that indirectly benefit human populations. We have already mentioned some of them, like seed dispersal by rodents, pest control by bats that eat mosquitoes and other harmful insects, and predation by small carnivores (foxes, mongoose) that control rodents' populations (mice and rats). Bats also contribute by dispersing nutrients through the surrounding ecosystems.

Much must still be learned of the specific adaptations that mammals have acquired during their long evolution in arid environment and by studying the biological characteristics of species living in UAE. Several species are already used as animal models for human medicine (Gaire et al. 2021). Species of *Acomys* (Spiny-Mouse) have gained attention for their unique ability among mammals for tissue regeneration, and as a result have become more widely used in animal laboratories to understand the specific biological mechanisms. Moreover, this species has small litter size, and a relatively long gestation (42 days). Most organ development occurs in utero, resulting in precocial neonates. Unlike mouse and rats, *Acomys* might be a good model for studying the events of late human pregnancy due to the relatively advanced state of their foetus relative to many other mammals. Bats have good capacity in maintaining high blood glucoses levels, and glucose homeostasis, and to lower blood glucose levels through insulin. These physiological features suggest that bats might be good models for understanding lifestyle and genetic factors regulating glucose metabolism and studying diabetes mechanisms in humans. Bats are less sensitive to cancer than many other mammal species; they are also known to carry high virus loads without being affected. These characteristics also open doors to future research that can open avenues for potential applications in human medicine.

14.6 Management and Conservation

The IUCN Red List is the authoritative reference to assess and rank the level of threats on wildlife species. These lists can be assessed at the global, national, or local levels. According to the IUCN Red Data List, 20% of the 44 native mammal species present in UAE are threatened at the global scale (Table 14.1 and Fig. 14.27a). This percentage raised to 41% at the national level (Fig. 14.27b), excluding the 11 species listed as Data Deficient (i.e. insufficient information for experts to make a judgement on status, Mallon et al. 2019). Not enough is known on the status of these latter species to even assess if they range closer to the optimal 'Least Concern' status

Table 14.1 Number of mammal species per IUCN red list categories at the global and national levels

Red List status	Global		National
	Native	Non-native	Native
RE	1		6
CR	1		4
EN	1		3
VU	4	1	3
NT	2	1	2
LC	35	8	13
DD	0		11
N.E.	0	4	2
Total	44	14	44

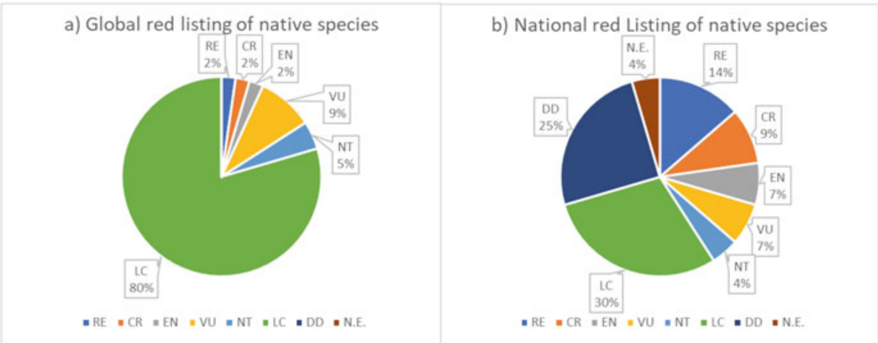


Fig. 14.27 Distribution of UAE native mammal species according to their IUCN red list status (**a**) at the global level and (**b**) at the National level. RE, regionally extinct; CR, critically endangered; EN, endangered; VU, vulnerable; NT, near threatened; LC, least concerned; DD, data deficient; NE, not evaluated

versus the highly concerning ‘Critically Endangered’ status. Data deficient species are mainly among bats (7 species out of 11), the others being the Baluchistan Gerbil, the Arabian Jird, the Honey Badger and the Savi’s Pygmy Shrew. Interestingly, two non-native species that were recently introduced in UAE, the Patagonian Mara and the Barbary Sheep, are considered ‘Near Threatened’ and ‘Vulnerable’, respectively, in their native ranges. More attention might be given to local populations of these species in the UAE—despite being introduced—by perhaps integrating them in local captive breeding programmes so that the UAE can contribute to global conservation initiatives.

The conservation status of some mammal species has been improving in the last few decades, mainly the ungulates, thanks to conservation efforts engaged by local environmental authorities. However, the status of many other species is poorly known and continues to deteriorate, due in large part to habitat loss. Population trends and status in the UAE are largely based on best-guess and assumptions of experts, rather than on supportive empirical data. At the initiative of the Breeding Centre of Endangered Arabian Wildlife (BCEAW) of Sharjah, workshops evaluating the status of different taxonomic groups, including mammals, have been annually conducted for the past 20 years. These workshops regularly reunite regional experts to produced number of region-focused conservation strategies for the most emblematic and endangered species, such as the Arabian Tahr and Arabian Leopard.

Captive-breeding and reintroduction programmes, mainly focusing on ungulates (Arabian Oryx, Arabian Mountain Gazelle and Arabian Sand Gazelle), but also on Arabian Hare, have contributed to partially restore their populations. Populations of Arabian Oryx were hunted to extinction from their wild habitats of Arabia in 1972. The species was only surviving captive in zoos or private collections (IUCN 2017). Thanks to captive-breeding and reintroduction programme initiated by the Phoenix and San Diego zoos, the species has been reintroduced to the wild in Oman, Saudi Arabia, Jordan and UAE. The last census recorded more than 7000 Arabian Oryx living in UAE, most in captivity or semi-captivity. The Environment Agency of Abu Dhabi has been managing a reintroduction programme in Umm Al Zummul since 2011, in the southeast of Abu Dhabi's western region at the border of the Rub Al-Khali, where more than 800 Oryx are now free-ranging. The species also successfully bred at the Dubai Desert Conservation Reserve, although the area is entirely fenced-in and has limited carrying capacity to support larger populations; they are provided supplemental feed and water to maintain their populations here. Al Marmoum Protected Area (Dubai Emirate) artificially maintains a population in semi-free conditions, also with water and feeding stations. Both Gazelle species have also been heavily managed, bred in captivity, maintained in private enclosure, translocated, and released. They are now well-present in several protected areas in the Emirates. The Arabian Tahr is bred in captivity in Al Ain by the Management for Nature Conservation, under HH Sheikh Khalifa bin Zayed Al Nahyan's private collection, with several hundred animals currently present. A dozen individuals were transferred to Fujairah to initiate another captive breeding for future reintroduction to Wadi Wurayah National Park.

The number and size of protected areas have been substantially increased over the last few decades and cover most habitats, from sand desert to gravel plains and mountains, offering protection for their mammal inhabitants. Wadi Wurayah National Park was declared as the first Mountain Protected Area in the UAE in 2008, designated as a Ramsar wetlands site in 2010 (Judas 2016), and as Man and Biosphere Reserve by UNESCO in 2018. Its management plan was developed by Emirates Nature-WWF in 2012–2015, and handed-over to Fujairah Municipality for further implementation. The reintroduction and conservation of the Arabian Tahr is one of the priority goals, as well as the conservation of the wider mammal community that include nationally endangered species such as Caracal, Blanford's Fox and Indian Crested Porcupine. Other Mountains Protected Areas have been designated by the Environment and Protected Areas Authority of Sharjah (EPAA) in subsequent years, in Wadi Helo and Kalba. Abu Dhabi has designated more than ten protected areas, mostly in the western region, including Al Bida'a, Al Dilfaweya, Al Ramlah, Qasr Al Sarab, Umm Al Zummul or Arabian Oryx Protected Area, Al Ghada, Al

Wathba Wetland reserve, Jebel Hafit, Yaw Al Dibsa, Badaa Hazza, Barqa Al Suqoor, Al Tawi, Baynunah mignas or Houbara Protected Area. All these areas offer protection for desert specialized mammals.

14.7 The Future of Mammals' Research and Conservation in UAE

As highlighted through this chapter, important gaps in our knowledge on mammal status, abundance, distribution, population trends, ecology still need to be fulfilled. It's only armed with such knowledge that successful conservation programmes can be implemented. The needs for additional research and populations monitoring, relying on sustainable governmental and financial supports, are important.

A number of methods can be used for mammal studies that vary according to the taxonomic groups. Except few large diurnal species that can be relatively easily seen, or their tracks found in the sand, most species are nocturnal and elusive and require more elaborate field surveys techniques.

Camera trapping is one such non-invasive method, which use has exploded since camera traps shifted from film to digital images in recent decades (Wearn and Glover-Kapfer 2017). Camera traps deployed in various habitats, left alone for several weeks or months, allow recording of the presence of many species of medium to large sizes that pass in their detection range up to 20–30 m; many include infrared capacity that allow the cameras to 'see' mammals at night as well. Smaller mammals, like rodents, might eventually be recorded too, but are often difficult to identify from pictures. Systematic deployment of camera traps can provide numerous information on species diversity, distribution, relative abundance, detection probability, density. The use of helicopters or drones, coupled with high-resolution imageries or video cameras is also increasingly used to survey larger mammals, such as ungulates in areas difficult to access, allowing to assess numbers and distribution. Large amount of data generated by these techniques can be facilitated by the development of deep learning algorithms and Artificial Intelligence (Zualkernan et al. 2022).

Other methods are more invasive and require trapping and capturing the animals to take their measurements, genetic samples, tag them with rings, or ear tags, equip them with loggers or transmitters, and monitor their movements and activities by radio- or satellite-tracking. Each species requires different trapping techniques, adapted to their morphology, behaviour and activities. Rodents are generally caught with special rodent traps (model Sherman or Tomahawk), larger mammals with larger cage traps or foot snares, while bats are caught in flight with mistnets or harps.

Field surveys to study bats have been carried out in recent years in several Arabian countries (Yemen, Lebanon, Jordan, Saudi Arabia), but to date, very few have been performed in UAE. Living at night, hidden in places difficult to access during the day, study of bats is challenging. One of the classical approaches to study

Fig. 14.28 Deployment of mistnet to capture bats in wadi Abadilah (Fujairah Emirate—March 2018). Photo credit: Jeremy Dechartre

them requires to identify areas where they fly, such as at the exit of their roosts and near a ponds where they drink or areas where they feed, and to deploy mistnets (Fig. 14.28) in an attempt to catch them (Mitchell-Jones and McLeish 2004). This technique, although efficient in the way it allows researchers to handle bats by hand to take their measurements (Fig. 14.29) and identify them from morphological criteria, remain very time consuming and has other practical limits. Not all species will get trapped in mistnets; many will detect the nets with their echolocation calls and avoid them, while others fly too high to get caught. Moreover, the number of sites that can be surveyed is limited by the time and effort required. In the last decades, the use of acoustic-based bat detectors (Fig. 14.30) has spread first among professional researchers and with the decrease of prices and multiplication of models available on the market to the wider naturalists' community (Brigham et al. 2002). These bat detectors transform the bats' ultrasound echolocation calls into audible sounds that can be recorded and digitized using specific sound analysis software for

Fig. 14.29 Bats specialists at work. Photo credit: Jacky Judas

species identification. While references describing echolocation calls of European or North American species are available, they are still scarce for the species encountered in UAE. Identifying bats from their echolocation call is not straightforward. While a few species have very specific calls and frequency characteristics, this is largely overlapping for many other species. Unlike birds, which often have stereotyped calls and songs that they use for communication, bats use their calls to navigate in the dark and locate their prey. Their calls vary according to the habitats in which they occur, the environmental conditions, or to interactions amongst members of the same species. Determining the frequencies and characteristics of the calls under different circumstances for each species thus requires capturing individuals for identification by hand and their release with a luminescent tag temporarily glued on their back. This tag allows researchers to visually follow them in darkness and associate specific individuals with specific echolocation calls. This work has been initiated by Emirates Nature-WWF in 2018–2020 to build a reference echolocation calls library, but it remains under development.

Radio or satellite transmitters deployed on mammals provides different information than camera trapping, and allows determination of activity rhythms, movement, home ranges and survival (Millspaugh and Marzluff 2001). An important limiting

Fig. 14.30 Bat detector model D1000X from Pettersson Electronik. Photo credit: Jacky Judas

factor for such approaches is the weight of the species under study as, in practise, the weight of the transmitter should not exceed 5% of the body weight. For instance, for a species weighing 5 kg, like a small red fox, the transmitter should not exceed 250 g. Most of the weight of the transmitter are from its batteries, which dictates its life expectancy and the volume of information that can be transmitted. For large species, the life expectancy of transmitters can often last a year or more, but for smaller species, like rodents or bats, transmitters of a few grams will last only a few weeks. Radio-tracking or satellite-tracking has only been conducted on few species in the UAE, mainly on Gazelles and Arabian Oryx, and for limited time periods on Blanford's fox.

In term of mammal conservation, the increasing number of protected areas and the percentage of terrestrial land under protection, which includes a diverse array of habitat types, is enhancing their chances of survival. However, improvements are required to develop and implement protected area management plans. Smaller species, those that do not need large home ranges, will benefit from this network of protected areas, as long as degraded habitats are restored and rewilded. Larger species that require larger home ranges can, in most cases, only be maintained as managed semi-captive populations. With development, habitat loss and fragmentation, network of roads and highways through the mountains, a lack of suitable prey species, and increasing human disturbance in natural habitats, the amount of suitable area for habitation has shrunk considerably, leaving little space for entirely free-ranging large mammals. The reintroduction of the Arabian Leopard in UAE, which might have been considered earlier, is probably impossible now, at least with the objective to restore a viable self-sustaining population. At best, a few individuals might be maintained in semi-captivity in large enclosures, where prey are managed and released for these individuals to prey upon.

14.8 Conclusions

In the current context of global biodiversity loss, and increasing impacts of climate change, it is becoming critically urgent to take further actions to protect UAE natural environment, create and efficiently manage protected areas to strengthen ecosystems resilience, stop habitat losses, eliminate or reduce as much as possible all threats. The country holds a captivating mammals' diversity highly adapted to the harsh environmental conditions, including several species endemic to Arabia. However, much remains to be learnt on their status and ecology. Several species have already vanished, others are critically endangered or data deficient. It's only by increasing knowledge on these species, that efficient conservation measures can be implemented, and their populations securely protected for the benefit of future generation.

14.9 Recommended Reading

For readers interested in learning more about the mammal communities of the UAE written towards a general audience, see Hellyer and Aspinall (2005). More information on species biology and conservation and research techniques in animals' ecology can consult Campbell (1993) and Boitani and Fuller (2000), respectively.

Appendix

Taxonomic list of Mammalian species recorded in the United Arab Emirates, according to their taxonomic order and family, with indications on their origin and current status.

Taxonomy—scientific names	English names	Status UAE	Listed in 2005	IUCN Red List Global	IUCN Red List National
Order Chiroptera					
Family Emballonuridae					
Taphozous nudiventris	Naked bellied Tomb Bat	Confirmed	Yes	LC	VU
Taphozous perforatus	Egyptian Tomb Bat	Confirmed		LC	DD
Family Hipposideridae					
Asellia tridens	Geoffroy's Trident Leaf-nosed Bat	Confirmed	Yes	LC	DD
Triaenops persicus	Persian Leaf-nosed Bat	Confirmed	Yes	LC	DD
Family Pteropodidae					
Rousettus aegyptiacus	Egyptian Fruit Bat	Confirmed	Yes	LC	LC
Family Rhinopomatidae					
Rhinopoma muscatellum	Muscat Mouse-tailed Bat	Confirmed	Yes	LC	LC
Family Vespertilionidae					
Eptesicus bottae	Botta's Serotine Bat	Confirmed		LC	DD
Myotis emarginatus	Geoffroy's Bat	Confirmed		LC	DD
Otonycteris hemprichii	Hemprich's Long-eared bat	Confirmed	Yes	LC	DD
Pipistrellus kuhlii	Kuhl's Pipistrelle	Confirmed	Yes	LC	LC
Pipistrellus pipistrellus	Common Pipistrelle	Confirmed		LC	N.E.
Rhyneptesicus nasutus	Sind Serotine Bat	Confirmed	Yes	LC	LC
Vespertilio murinus	Parti-coloured Bat	Confirmed		LC	DD
Order Insectivora					
Family Erinaceidae					
Paraechinus aethiopicus	Ethiopian Hedgehog	Confirmed	Yes	LC	LC
Paraechinus hypomelas	Brandt's Hedgehog	Confirmed	Yes	LC	LC
Family Soricidae					
Suncus etruscus	Savi's Pygmy Shrew	Confirmed	Yes	LC	DD

(continued)

Taxonomy—scientific names	English names	Status UAE	Listed in 2005	IUCN Red List Global	IUCN Red List National
Order Carnivora					
Family Canidae					
Canis lupus arabicus	Arabian Wolf	Extinct	Yes	LC	RE
Vulpes vulpes	Red Fox	Confirmed	Yes	LC	LC
Vulpes rueppellii	Ruppell's Sand Fox	Confirmed	Yes	LC	CR
Vulpes cana	Blanford's Fox	Confirmed	Yes	LC	VU
Canis familiaris	Feral Dog	Feral		N.E.	N.A.
Family Mustelidae					
Mellivora capensis	Honey Badger	Confirmed	Yes	LC	DD
Family Viverridae					
Ichneumia albicauda	White-tailed Mongoose	Confirmed	Yes	LC	EN
Herpestes edwardsii	Indian Grey Mongoose	Introduced	Yes	LC	N.A.
Family Hyaenidae					
Hyaena hyaena	Striped Hyena	Extinct	Yes	NT	RE
Family Felidae					
Felis libyca	Wild Cat	Confirmed	Yes	LC	EN
Felis margarita	Sand Cat	Confirmed	Yes	LC	EN
Caracal caracal	Caracal	Confirmed	Yes	LC	CR
Panthera pardus nimr	Arabian Leopard	Extinct	Yes	VU	RE
Felis catus	Feral Cat	Feral		N.E.	N.A.
Order Hyracoidea					
Family Procaviidae					
Procavia capensis	Hyrax	Introduced	Yes	LC	N.A.
Order Artiodactyla					
Family Bovidae					
Hemitragus jayakari	Arabian Tahr	Confirmed	Yes	EN	CR
Oryx leucoryx	Arabian Oryx	Confirmed	Yes	VU	VU
Gazella arabica	Arabian Gazelle	Confirmed	Yes	VU	LC
Gazella marica	Arabian Sand Gazelle	Confirmed	Yes	VU	LC
Capra aegagrus	Wild Goat	Extinct	Yes	NT	RE
Capra aegagrus hircus	Feral Goat	Feral		N.A.	N.A.
Capra nubiana	Nubian Ibex	Extinct	Yes	VU	RE
Ammotragus lervia	Barbary Sheep or Aoudad	Introduced		VU	N.A.
Ovis arabica	Arabian Wild Sheep	Extinct	Yes	Ex	EX

(continued)

Taxonomy—scientific names	English names	Status UAE	Listed in 2005	IUCN Red List Global	IUCN Red List National
Order Perrisodactyla					
Family Equiidae					
Equus asinus	Feral Donkey	Feral		N.E.	N.A.
Order Lagomorpha					
Family Leporidae					
Lepus capensis	Cape Hare	Confirmed	Yes	LC	LC
Order Rodentia					
Family Caviidae					
Dolichotis patagonum	Patagonian Mara	Introduced		NT	N.A.
Family Sciuridae					
Funambulus pennantii	Northern Palm Squirrel	Introduced		LC	N.A.
Sciurus anomalus	Persian Squirrel	Introduced and extinct	Yes	LC	N.A.
Family Hystricidae					
Hystrix indica	Indian Crested Porcupine	Confirmed		LC	CR
Family Dipodidae					
Jaculus jaculus	Lesser Jerboa	Confirmed	Yes	LC	NT
Family Muridae					
Rattus rattus	Black Rat	Introduced	Yes	LC	N.A.
Rattus norvegicus	Brown Rat	Introduced	Yes	LC	N.A.
Mus musculus	House Mouse	Introduced	Yes	LC	N.A.
Acomys dimidiatus	Arabian Spiny Mouse	Confirmed	Yes	LC	NT
Family Muridae—subfamily Gerbillinae					
Gerbillus nanus	Baluchistan Gerbil	Confirmed	Yes	LC	DD
Gerbillus dasyurus	Wagner's Gerbil	Confirmed	Yes	LC	LC
Gerbillus cheesmani	Cheesman's Gerbil	Confirmed	Yes	LC	LC
Meriones arimalius	Arabian Jird	Confirmed	Yes	LC	DD
Meriones crassus	Sundevall's Jird	Confirmed	Yes	LC	LC
Meriones hurrianae	Indian Desert Jird	Introduced		LC	N.A.
Psammomys obesus	Fat Jird	Confirmed		LC	N.E.

Notes:
Endemic refers to species only found in the Arabian Peninsula. Species are listed as Near endemic, when most of their distribution is in Arabia, but some populations are also known in few neighbouring countries. LC, least concerned; VU, vulnerable; EN, endangered; CR, critically endangered; RE, regionally extinct; EX, extinct; N.A., not applicable; N.E., not evaluated

References

Al Dhaheri S, Gubiani RE, Al Zaabi R, Al Hammadi E, Ahmed S, Soorae P (2018) Range expansion of the Indian Crested Porcupine (*Hystrix indica*) with the first confirmed record in Abu Dhabi Emirates, United Arab Emirates. Tribulus 26:59–64

Anthony SJ, Johnson CK, Greig DJ, Kramer S, Che X et al (2017) Global patterns in coronavirus diversity. Virus Evol 3(1)

Aspinall S, Hellyer P (eds) (2004) Jebel Hafit: a natural History. ENHG, Abu Dhabi, UAE. 220 pp

Asres A, Amha N (2014) Physiological adaptation of animals to the change of Environment: a review. J Biol Agric Healthc 4(25):146–151

Auffray JC, Vanlerberghe F, Britton-Davidian J (1990) The house Mouse progression in Eurasia: a palaeontological and archaeozoological approach. Biol J Linnean Soc 41:13–25

Beier P (2006) Effects of artificial night lighting on terrestrial mammals. In: Rich C, Longcore T (eds) Ecological consequences of artificial night lighting. Island Press, Washington, DC, pp 19–42

Bhattacharyya T, Srinivasulu C, Molur S (2016) *Paraechinus hypomelas*. The IUCN Red List of Threatened Species 2016: e.T40610A115174910. https://doi.org/10.2305/IUCN.UK.2016-3.RLTS.T40610A22326573.en

Boitani L, Fuller TK (2000) Research techniques in animal ecology—controversies and consequences. Columbia University Press, New York, p 442

Brigham RM, Kalko EKV, Jones G, Parsons S, Limpens HJGA (2002) Bat Echolocation research: tools, techniques and analysis. Bat Conservation International, Austin. 167 pp

Burgin CJ, Colella JP, Kahn PL, Upham NS (2018) How many species of mammals are there? J Mammal 99(1):1–14

Campbell NA (1993) Biology. Benjamin/Cummings, San Francisco, 1190 pp

Cassola F (2016) *Meriones arimalius*. The IUCN Red List of Threatened Species 2016: e.T13159A115109703. https://doi.org/10.2305/IUCN.UK.2016-3.RLTS.T13159A22434113.en

Chan JFW, To KKW, Tse H, Jin DY, Yuen KY (2013) Interspecies transmission and emergence of novel viruses: lessons from bats and birds. Trends Microbiol 21(10):544–555

Chreiki MK, Steer MD, Majeed SU, Kakembo S, Ross S (2018) A first confirmed record of the Indian Crested Porcupine *Hystrix indica* (Mammalia: Rodentia: Hystricidae) in the United Arab Emirates. J Threatened Taxa 10(7):11928–11933

Cunningham PL (2004) Checklist and status of the terrestrial mammals from the United Arab Emirates. Zool Middle East 33(1):7–20

Drew CR, Tourenq C (2005) The Red List of terrestrial Mammal species of the Abu Dhabi Emirate. EAD unpublished report. 28 pp

EAD (2021) Arabian Caracal. https://www.ead.gov.ae/en/discover-our-biodiversity/mammals/arabian-caracal. Accessed 22/07/2022

Gaire J, Varholick JA, Rana S, Sunshine MD, Doré S, Barbazuk WB, Fuller DD, Maden M, Simmons CS (2021) Spiny mouse (*Acomys*): an emerging research organism for regenerative medicine with applications beyond the skin. Regen Med 6:1. https://doi.org/10.1038/s41536-020-00111-1

Harrison DL (1955) CIV.—On a collection of mammals from Oman, Arabia. With the description of two new bats. Ann Mag Nat Hist Ser 12 8(96):897–910. https://doi.org/10.1080/00222935508655710

Harrison DL, Bates PJJ (1991) The mammals of Arabia, 2nd edn. Harrison Zoological Museum, Kent

Hellyer P, Aspinall S (eds) (2005) The Emirates: a natural history. Trident, Abu Dhabi, UAE. 428 pp

Hornby R (1996) Red list of mammals for the United Arab Emirates. Tribulus 6(1):13–14

IUCN SSC Antelope Specialist Group (2017) Oryx leucoryx. The IUCN Red List of Threatened Species 2017: e.T15569A50191626. https://doi.org/10.2305/IUCN.UK.2017-2.RLTS.T15569A50191626.en

Jongbloed M, Llewellyn R, Sawaf M (2002) Wild about mammals. A field guide to the terrestrial mammals of the UAE. Arabian Leopard Trust, UAE. 70 pp

Judas J (2016) Wadi Wurayah National Park—Scientific Research Report 2013–2015. EWS-WWF Internal report. 120 pp

Judas J, Hellyer P (2016) Five-striped palm squirrel, *Funambulus pennantii* (Wroughton, 1905)—a new addition to the UAE's exotic fauna. Tribulus 24:126–129

Judas J, Csorba G, Benda P (2018) The Bat Fauna (Mammalia: Chiroptera) of the United Arab Emirates: a review of published records and museum specimens with conservation notes. J Threatened Taxa 10(3):11379–11390

Kalka MB, Smith AR, Kalko EK (2008) Bats limit arthropods and herbivory in a tropical forest. Science 320:71–71. https://doi.org/10.1126/science.1153352

Kelm DH, Wiesner KR, von Helversen O (2008) Effect of artificial roosts for Frugivorous bats on seed dispersal in a Neotropical forest pasture mosaic. Conserv Biol 22:733–741. https://doi.org/10.1111/j.1523-1739.2008.00925.x

Leelapaibul W, Bumrungsri S, Pattanawiboon A (2005) Diet of wrinkle lipped free-tail bat (*Tadarida plicata* Buchannan, 1800) in central Thailand: insectivorous bats potentially act as biological pest control agents. Acta Chiropterol 7:111–119. https://doi.org/10.3161/1733-5329(2005)7[111:DOWFBT]2.0.CO

Lerp H, Wronski T, Platha M, Schröter A, Pfenninger M (2013) Phylogenetic and population genetic analyses suggest a potential species boundary between Mountain (*Gazella gazella*) and Arabian Gazelles (*G. arabica*) in the Levant. Mammal Biol 78:383–386

Lindsay Maclean G (1996) Ecophysiology of desert birds. Adaptations of desert organisms series. Springer, Berlin. 181 pp

Mallon D, Hillton-Taylor C, Allen D, Harding K (2019) UAE National Red List of Mammals: Marine and Terrestrial. April 2019. A report to the Ministry of Climate Change and Environment, United Arab Emirates. MOCCAE, 75 pp

Markotter W, Coertse J, De Vries L, Geldenhuys M, Mortlock M (2020) Bat-borne viruses in Africa: a critical review. J Zool. https://doi.org/10.1111/jzo.12769

Melville H, Chaber AL (2016) Altitudinal variations in the diversity and structure of the desert rodent community from Jebel Jais, United Arab Emirates. Zool Middle East 62(3):200–205

Millspaugh JJ, Marzluff JM (eds) (2001) Radio-tracking and animal populations. Academic, San Diego. 474 pp

Mitchell-Jones AJ, McLeish AP (eds) (2004) Bat workers manual, 3rd edn. Joint Nature Conservation Committee, Peterborough

Monadjem A, Joubert C, Richards L, Nielsen IB, Nielsen M, Kjartansdottir KR, Bohmann K, Mourier T, Hansen AJ (2016) First record of *Vespertilio murinus* from the Arabian Peninsula. Vespertilio 18:79–89

Munton PN (1985) The ecology of the Arabian Tahr (*Hemitragus jayakari* Thomas 1894) and a strategy for the conservation of the species. J Oman Stud 8:11–48

Owens ACS, Lewis SM (2018) The impact of artificial light at night on nocturnal insects: a review and synthesis. Ecol Evol 8:11337–11358

Randi E, Pierpaoli M, Beaumont M, Ragni B, Sforzi A (2001) Genetic identification of wild and domestic cats (*Felis silvestris*) and their hybrids using Bayesian clustering methods. Mol Biol Evol 18(9):1679–1693

Schnidrig-Petrig R, Ingold P (2021) Effects of paragliding on Alpine Chamois *Rucicapra rucicapra*. Wild Biol 7(4):285–294

Seewagen CL, Adams AM (2021) Turning to the dark side: LED light at night alters the activity and species composition of a foraging bat assemblage in the northeastern United States. Ecol Evol 11(10):5635–5645

Smith M, Budd KJ, Gross C (2003) The distribution of Blanford's fox (*Vulpes cana* Blanford, 1877) in the United Arab Emirates. J Arid Environ 54(1):55–60

Tattersall GJ, Sinclair B, Withers P, Fields P, Seebacher F, Cooper C, Maloney SK (2012) Coping with Thermal challenges: physiological adaptations to environmental temperatures. Compr Physiol 2:2151–2202

Thompson K (2015) Where do camels belong? The story and science of Invasive species. Profile Books, London. 262 pp

Tuttle MD (2017) Fear of bats and its consequences. J Bats Res Conserv 10(1)

Tuttle MD (2020) A viral witch hunt. Issues in science & technology. 27 March 2020. https://issues.org/a-viral-witch-hunt-bats/

Wacher T, Wronski T, Hammond RL, Winney B, Blacket MJ, Hundertmark KJ, Mohammed OB, Omer SA, Macasero W, Lerp H, Plath M, Belidorn C (2010) Phylogenetic analysis of mitochondrial DNA sequences reveals polyphyly in the goitred gazelle (*Gazella subgutturosa*). Conserv Genet 12(3):827–831. https://doi.org/10.1007/s10592-010-0169-6

Wearn OR, Glover-Kapfer P (2017) Camera trapping for conservation: A guide to best practices. WWF Conservation Technology Series 1(1). WWF-UK, Woking, UK

Whittaker RJ, Jones SH (1994) The role of frugivorous Bats and Birds in the rebuilding of a Tropical Forest Ecosystem, Krakatau, Indonesia. J Biogeogr 21(3):245–258

Woo PCY, Lau SKP (2019) Viruses and bats. Viruses 11:884. https://doi.org/10.3390/v11100884

Zualkernan I, Dhou S, Judas J, Sajun AR, Gomez BR, Hussain LA (2022) An IoT system using deep learning to classify camera trap images on the edge. Computers 11(1):13. https://doi.org/10.3390/computers11010013

Chapter 15
An Introduction to the Birds of the United Arab Emirates

Oscar Campbell

15.1 Introduction

The avifauna of the United Arab Emirates (UAE) is of interest for a multitude of reasons, belying the country's small size and inhospitably hot, arid environment. It is surprisingly varied and constantly evolving, in response to both anthropogenic landscape modifications and longer term climatic changes. Lying at the juxtaposition of four great biogeographic realms, the bird communities of the UAE represent a melting pot of species, whilst its position on the edge of the great intercontinental stepping stone that is the Arabian peninsula guarantees the biannual through passage of millions of birds of some 140 species, on journeys that span from western Europe, the Siberian Arctic and Eastern China to India, southern Africa, and all points between. Birds, being predominately diurnal, relatively large and hence conspicuous have been well-studied over many years in the UAE. This chapter will outline the composition of the country's avifauna, discuss a selection of species that characterize important habitats, discuss adaptations exhibited by resident species in response to the challenging environmental conditions prevalent and summarize aspects of migration through the country. Finally, conservation issues are considered and selected recent discoveries showcased.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-031-37397-8_15.

O. Campbell (✉)
Nautica Environmental Associates LLC, Abu Dhabi, UAE

British School Al Khubairat, Abu Dhabi, UAE
e-mail: oscar@nea.ae

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_15

15.2 Biogeographical Aspects of the UAE's Avifauna

The list of birds recorded in the UAE as wild (including those with established populations originating from escapes or releases) is currently 468 species, of which over a fifth, 102 species, typically breed annually. Of the regular breeders, 83% are of native origin (Pedersen et al. 2022). Many breeding species (including all those introduced) are resident (i.e. present all year) but a small proportion of species migrate to the UAE to breed, then depart to spend the non-breeding season elsewhere (usually Africa). The UAE's much larger community of non-breeding species primarily comprises passage migrants (usually en-route from Eurasia to Africa, or, in a few cases, India) or winter visitors. Within a given species, some individuals may occur in the UAE as migrants only, whilst others remain the entire non-breeding season, some of which may remain year-round without attempting to breed. This occurs particularly amongst shorebirds and herons and usually involves individuals that are too young to breed.

The UAE's avifaunal diversity, measured as numbers of species recorded and/or breeding, compares favorably to other Arabian peninsula countries (Fig. 15.1), reflecting a diverse range of habitats (see Chap. 2) in a comparatively small area. Most important, compared to similarly sized Qatar and Kuwait, are the Hajar mountains and Jebel Hafit, both exceeding 1000 m elevation, and 60 km of coastline on the Gulf of Oman. Breeding species diversity is greatest in the north east, declining westwards and, particularly, southwards into the desert interior. Aspinall (2010) maps the distribution of the UAE's breeding birds by 50 × 50 km^2 and provides totals for each square. In the three most north-easterly squares, 60–65 species have been recorded as breeding (or likely breeding) but this declines to 18 in the most westerly square on the Arabian Gulf coast, and a maximum of ten on the northern fringes of the Rub Al-Khali (Empty Quarter). An analysis of 167 species (breeding, migrant and wintering) produced a similar pattern (Burfield et al. 2021). This cline reflects landscape and habitat availability, including diverse anthropogenic habitats, but also matches national climate trends, in particular that for

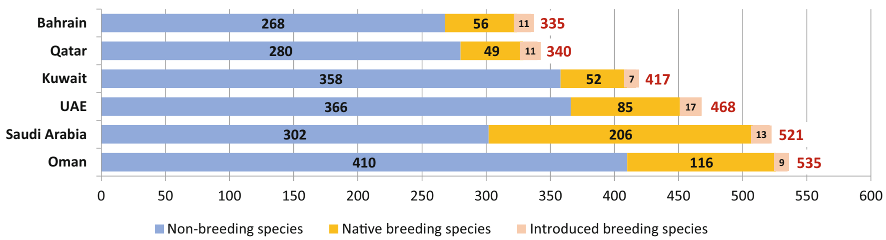


Fig. 15.1 Numbers of native non-breeding and breeding species, and non-native species (all of which breed) recorded in the UAE and five neighbouring Arabian countries. Data sources: Pedersen et al. (2022); Eriksen and Victor (2013), J Eriksen in litt; Qatar Birds Records Committee (www.qatarbirds.org/); H King in litt; Pope and Zogaris (2012), A Al-Sirhan in litt; Boland and Alsuhaibany (2020), J Babbington in litt

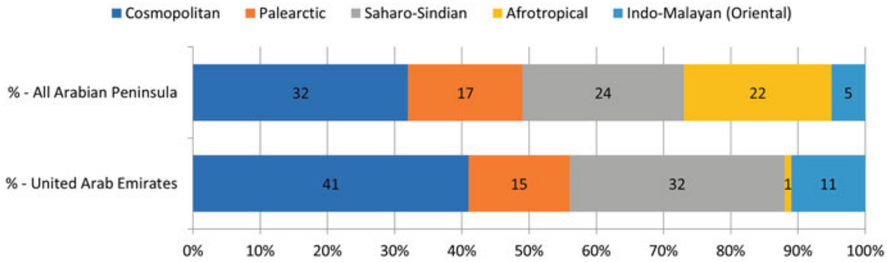


Fig. 15.2 Biogeographic affinity of regularly breeding species in the UAE (85 species) and the Arabian Peninsula as a whole (273 species) based on their breeding distribution out with the Arabian peninsula. Data source: Jennings (2010) for Arabian Peninsula data. *Cosmopolitan* refers to species occurring widely in two or more biogeographic zones; for terrestrial birds breeding in the UAE this is mainly Palearctic/Indo-Malayan or African/Indo-Malayan. A few species have a much wider distribution. *Palearctic* refers to species whose main breeding distribution encompasses some or all of the temperate zone of the Old World (i.e Eurasia, excluding south and south east Asia). *Saharan-Sindian* refers to species' whose main breeding distribution encompasses the general Saharan region (North Africa, Arabia, Iran to north western India) or some part thereof. It is also termed *Eremic* and is of relatively recent geological origin (dating from late Miocene, 5–10 million years ago). Species included may have distributions that extend marginally into arid East Africa or central Asia. *Afro-tropical* refers to species whose main breeding distribution encompasses some or all of sub-Saharan Africa. *Indo-Malayan (Oriental)* refers to species whose main breeding distribution encompasses some or all of tropical Asia

precipitation (see Chap. 3). Urban areas have noticeably greater diversity than surrounding hinterlands, reflecting increased habitat variety and availability of food and water sources on local scales. Thus, the square incorporating Abu Dhabi island has 47 breeding species, compared to 9–12 species for the three squares immediately south (Aspinall 2010).

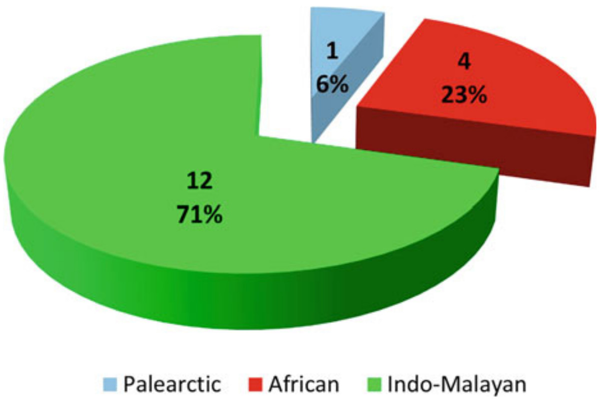
The biogeographical affinities of the 85 species regularly breeding in the UAE are presented in Fig. 15.2, with four selected examples illustrated in Fig 15.3. This excludes 17 naturalized species now well established. Of regular breeding species, 55% have fairly wide-ranging UAE distributions (although in some cases at very low densities); the remainder are extremely local (generally restricted to very few sites). In terms of biogeography, 41% species breeding in the UAE are widespread across two or more biogeographical regions. A significant proportion of these are large species such as raptors, herons and certain seabirds. Of the remainder, perhaps most interesting are the 32% classified as Saharo-Sindian. Being species whose main distribution lies between western Sahara and north western India, they are highly adapted to extreme heat and aridity and include four (of five) of the UAE's regularly breeding larks. Almost half of Saharo-Sindian species occurring in the UAE have a mainly Arabian distribution and are endemic, or nearly so, to the Arabian peninsula. Given geographical proximity, Indo-Malayan species are poorly represented; the Arabian distribution of this group generally only encompasses the far north and east of the peninsula, although several (e.g. Red-wattled Lapwing *Vanellus indicus*, Indian Roller *Coracias benghalensis*, Purple Sunbird *Cinnyris asiaticus*) are

Fig. 15.3 Species breeding in the UAE with different biogeographical affinities. Clockwise from top left: Bridled Tern (*Onychoprion anaethetus*, Cosmopolitan), Blue-cheeked Bee-eater (*Merops superciliosus*, Palearctic), Pharoah Eagle-Owl (*Bubo ascalaphus*, Saharo-Sindian), Indian Roller (*Coracias benghalensis*, Indo-Malayan). Photographer: Oscar Campbell

conspicuously common and have spread widely across the UAE in recent decades, concomitant with the country's greening. The Empty Quarter is clearly an effective barrier to African species characteristic of south west Arabia and Dhofar (southern Oman); only one UAE breeding bird, Namaqua Dove (*Oena capensis*), is of Afrotropical origin. Unrecorded until 1988, this species first bred in 1997 as part of a general spread across the Arabian peninsula from its core range in the south west (Jennings 2010). The foregoing data are not dissimilar to a recent biogeographical analysis on the butterfly fauna of the UAE (Feulner et al. 2021).Jennings (2010) presents a comparable analysis for breeding birds of the Arabian peninsula which, as a whole, has a much greater proportion of Afrotropical species but a somewhat smaller proportion of Saharo-Sindian and Indo-Malayan species.

The biogeographic origin of 17 naturalized species is summarized in Fig. 15.4. These species mainly originate from deliberate releases, although accidental introductions have also occurred. Such species constitute a greater proportion of the UAE's breeding avifauna than in neighbouring countries (Fig. 15.1). Although naturalized species concentrate in urban areas, they have spread relatively further

Fig. 15.4 The biogeographic origin of 17 species now naturalized and breeding annually in the UAE



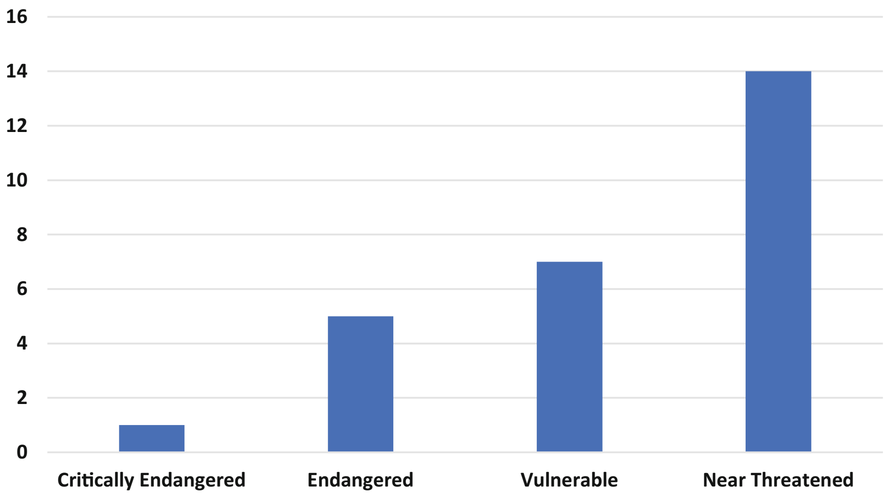


Fig. 15.5 The threat status of 27 globally threatened and Near Threatened bird species that occur in the UAE. Data source: BirdLife International (2022a)

in the UAE than elsewhere regionally (Jennings 2010). Unsurprisingly given geographical proximity and historical ties over millennia, the majority originate in southern Asia, especially Pakistan and India. Half have spread spectacularly since introduction and several (e.g. Grey Francolin *Francolinus pondicerianus*, White-eared Bulbul *Pycnonotus leucotis*, Common Myna *Acridotheres tristis*) are now amongst the UAE's most abundant and conspicuous species.

Twenty-seven species occurring in the UAE are of global conservation concern with 13 classified as globally threatened (Fig. 15.5; see also SOM Tables 15.1 and 15.2), including one Critically Endangered (Sociable Lapwing *Vanellus gregarius*) and five that are Endangered (BirdLife International 2022a). A further fourteen are Near Threatened. Seven globally threatened species occur in winter or on migration

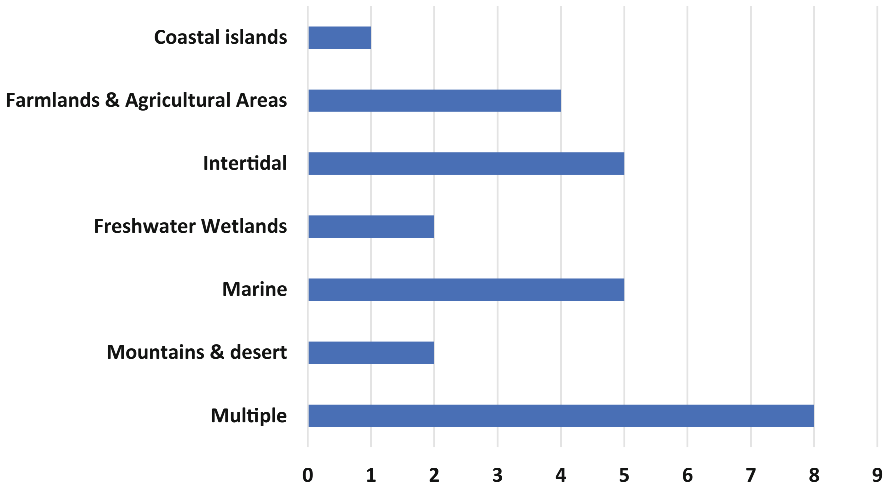


Fig. 15.6 Main habitat usage of 27 globally threatened and Near Threatened bird species that occur in the UAE. Data source: BirdLife International (2022a)

and habitats used include intertidal mudflats and extensive agricultural areas. Five species have bred, although only two (European Turtle Dove *Streptopelia turtur*, Socotra Cormorant *Phalacrocorax nigrogularis*) are widespread or numerous. Broad habitat preferences in the UAE for all 23 globally threatened and Near Threatened species are summarized in Fig. 15.6.

A number of other species, whilst not of global conservation concern, are particularly significant from a local perspective, in that the UAE is amongst the easiest countries in the world to observe them. Such species are globally range-restricted or breed in remote parts of countries were tourism is underdeveloped. These species are of great interest to visiting birdwatchers and include Ménétries's Warbler (*Sylvia mystacea;* common migrant; breeding Turkey to south-central Asia), Hypocolius (*Hypocolius ampelinus*; uncommon passage migrant and winter visitor to coastal lowlands of the Arabian Gulf, mainly breeding Iraq) and four species characteristic of the UAE's mountains and adjacent plains: Hume's Wheat-ear (*Oenanthe albonigra*, common resident breeder, otherwise mainly breeding Iran) and Variable Wheatear (*O. picata)*, Persian Wheatear (*O. chrysopygia)* and Plain Leaf Warbler (*Phylloscopus neglectus*), all locally common short-distance winter visitors from south-central Asia. Figure 15.7 depicts four species occurring in the UAE that are either globally threatened or range-restricted. Also notable are two seabirds that are Arabian breeding endemics: Jouanin's Petrel (*Bulweria fallax)* and Persian Shearwater (*Puffinus persicus*), breeding Socotra Island and along the south Arabian coast respectively. They both occur as non-breeding visitors to UAE waters of the Gulf of Oman.

Fig. 15.7 Globally threatened and restricted-range species. Clockwise from top left: Eastern Imperial Eagle (*Aquila heliaca*, Vulnerable), Great Knot (*Calidris tenuirostris*, Endangered), Hypocolious (*Hypocolius ampelinus*, range-restricted) and European Turtle Dove (*Streptopelia turtur*, Vulnerable). Photographer: Oscar Campbell

15.3 A Survey of the UAE's Key Bird Habitats

The present section considers characteristic bird species of seven broad habitats, from natural to wholly anthropogenic, ranging from mountains and deserts to intertidal shorelines and the offshore islands of the Arabian Gulf. Species discussed have been selected to give a flavour of those more characteristic or interesting, put into a regional context. Five natural habitats are discussed first, followed by two that owe their existence to human activities. The avifauna of urban areas is discussed in Chap. 23; that occurring in the offshore waters of the Gulf of Oman in Box 15.1.

15.3.1 Natural Habitats

15.3.1.1 Mountains and Adjacent Stony Plains

Despite occupying a small portion of the country, montane regions significantly boost the UAE's avian diversity, although not to the same extent as they do for floral and invertebrate diversity (Chaps. 13 and 17). Both breeding and wintering bird communities in the UAE mountains are moderately distinctive and represent a somewhat impoverished subset of communities found in the more extensive Zagros chain of Iran. Elevations are not high enough, nor available land at such altitudes extensive enough, to support contrasting vegetation zones with distinctive avifaunal communities, as occur at the greater elevations of Jebel Shams, Oman, or Asir, Saudi Arabia. Thus, UAE montane bird diversity shows no clear altitudinal gradient. Although densities are often low (as in all natural terrestrial habitats of the UAE), certain species occur exclusively in montane habitats e.g. Hume's Wheatear and Lichtenstein's Sandgrouse (*Pterocles lichtensteinii*). Habitat destruction and disturbance, often in the form of road-building, quarrying and rock-crushing operations continues to threaten areas locally, but there are still extensive areas of relatively undisturbed habitat. Localities to observe species characteristic of UAE montane habitats include Wadi Wurayah National Park and the nearby Masafi area (both Fujairah), the mountains of Ras al Khaimah (e.g. Wadi Bih) and, of course, the outlying inselberg of Jebel Hafit (Abu Dhabi). Typical resident species include White-spectacled Bulbul (*Pycnonotus xanthopygos*), an Arabian near-endemic, Striolated Bunting (*Emberiza striolata*), easy to hear but often hard to locate when singing motionless from small promontories, the poorly named Desert Lark (*Ammomanes deserti*; in the UAE found almost exclusively in rocky montane areas) and the strikingly pied Hume's Wheatear, a globally range-restricted species easily found when singing in the early mornings from November to March.

Equally characteristic and widespread, but much less numerous and conspicuous are the cryptic Sand Partridge (*Ammoperdix heyi*) and virtually nocturnal but exquisitely patterned Lichtenstein's Sandgrouse. The latter, difficult to find during day, is commonly heard after sunset as small groups fly to drinking pools. Box 15.2 illustrates that there is still much to learn about birds occurring in the Hajar Mountains, not least at night.

From October to March, resident species are complemented by others arriving to overwinter in the Emirates. Notable are the widespread Persian Wheatear and Plain Leaf Warbler (in rocky wadis with some vegetation, particular *Acacia* and *Euphorbia larica*) and the extremely localized Variable Wheatear, a species with a preference for *Acacia*-dominated gravel plains on the flanks of the northern Hajars. All three are united by their remote and desolate breeding habitat, mainly in Iran and Afghanistan. Figure 15.8 illustrates four species typical of mountains and adjacent stony plains.

All species occurring in the main Hajar chain extend their ranges south into Oman and, via the Ruus al Jibal of the Musandam peninsula, almost all range north into Iran. The majority are also found on the geologically distinct outlying massif of Jebel

Fig. 15.8 Species characteristic of mountains and adjacent stony plains; all featured species are range-restricted in a global context. Clockwise from top left: Hume's Wheatear (*Oenanthe albonigra*), White-spectacled Bulbul (*Pycnonotus xanthopygos*), Persian Wheatear (*Oenanthe chrysopygia*), Plain Leaf Warbler (*Phylloscopus neglectus*). Photographer: Oscar Campbell

Hafit, which lies 30 km off the main Hajar range. A notable exception is Streaked Scrub-Warbler (*Scotocerca inquieta*), a unique small warbler with no close relatives in the UAE, most reliably found in the Masafi area of the Hajars but never reported from well-studied Jebel Hafit.

15.3.1.2 Coastal Deserts

Descending westwards from the Hajars, one traverses gravel outwash plains which soon merge into the sandy, rolling desert of the coastal plain. This broadens southwards into interior deserts (see below) on the western side of the country but on the eastern side the narrow gravel plain soon reaches the Gulf of Oman. As elsewhere in Arabia (e.g. Kuwait; Brown 2009), many areas have been degraded by severe over-grazing, off-road driving and rampant development, particularly on the coastal fringes. However Al-Marmoom (Qudra) and Dubai Desert Conservation Reserve (both Dubai) are good localities to experience this habitat. Bird

Fig. 15.9 Species characteristic of coastal deserts. Clockwise from top left: Black-crowned Sparrow Lark (*Eremopterix nigriceps*), Cream-coloured Courser (*Cursorius cursor*), Egyptian Nightjar (*Caprimulgus aegyptius*). Photographer: Oscar Campbell

communities are less diverse than those of montane areas but nevertheless hold interesting species. These include Greater Hoopoe-Lark (*Alaemon alaudipes*) and Black-crowned Sparrow-Lark (*Eremopterix nigriceps*), both of which have adapted to the lack of song posts with display flights given in early spring. That of the former makes Greater Hoopoe-Lark one of the most spectacular denizens of the Arabian desert—a near vertical rise from a low perch followed by an abrupt plummet, accompanied by the purest of whistles and a vivid flash of black and white wings and tail that are otherwise concealed. Other Saharo-Sindian species such as Chestnut-bellied Sandgrouse (*Pterocles exustus*) and Cream-colored Courser (*Cursorius cursor*), both representatives of two classic arid landscape families, are typical of sandy coastal deserts, although densities of all aforementioned resident species are greatest in the vicinity of agricultural areas (see below). It has recently been established that Egyptian Nightjar (*Caprimulgus aegyptius*) breeds annually in the UAE (Campbell and Smiles 2018) with a population that may number many tens of pairs. Elsewhere in Arabia, this species is currently known to breed only in Bahrain. Figure 15.9 presents three species typical of coastal deserts.

In winter, areas of coastal desert with sufficient scrub support wintering Desert Wheatears (*O. deserti*), which perch prominently on low bushes. They are often accompanied by the much less conspicuous Asian Desert Warbler (*Sylvia nana*) which assiduously follow the 'sentinel' wheatears, presumably to benefit from early warning of potential predators. What, if anything, the wheatear gains is not clear. Both species breed in the deserts of central Asia and occur in the UAE from October to March; their associative behavior has been noted widely across Arabia to north-west India (Shirihai et al. 2001).

15.3.1.3 Interior Deserts

Much of the southern UAE is covered in extensive sand sheets and, in places, large wind-blown dunes on the northern edge of the Empty Quarter. Examples of such habitat can be found south of the Liwa Crescent (Abu Dhabi). Reflecting sparse vegetation and limited foraging opportunities, bird diversity and densities are extremely low, even in winter. Certain species characteristic of coastal deserts (e.g. Cream-colored Courser) are scarce or absent. However, Greater Hoopoe-Lark remains widespread and the few breeding records of two rare raptors, Long-legged Buzzard (*Buteo rufinus*) and Golden Eagle (*Aquila chrysaetos*) are all from this area. Pharaoh Eagle-Owl (*Bubo ascalaphus*), which if undisturbed, can use the smallest of cliffs or sparsest of vegetation to nest, is widespread and probably greatly under-recorded. Recently established plantations, most obvious along the Abu Dhabi to Al Ain highway and in parts of the Western Region have doubtless assisted the spread of species such of as White-eared Bulbul, Delicate Prinia (*Prinia lepida*), Purple Sunbird and Shikra (*Accipiter badius*). The latter, a small predatory hawk, was until 2014 largely restricted to urban Dubai but since has expanded its range spectacularly (Campbell et al. 2022). Such plantations also support many of the UAE's breeding European Turtle Doves and Rufous-tailed Scrub-Robins (*Cercotrichas galactotes*), as well as doubtlessly being the difference between life and death for many an exhausted migrant.

15.3.1.4 Intertidal Areas

The shallow, low-energy environment of the southern Arabian Gulf is ideal for the development of intertidal mudflats and the varied network of low, fringing islands and shallow shoals ensure extensive intertidal habitat along the coastline from Abu Dhabi island westwards. Further north, intertidal areas are best developed in sheltered creeks, such as at Ras Al-Khor (Dubai) or where barrier islands provide additional shelter, such as Siniyah Island, sheltering the complex site of Khor al-Beida (Umm al Quwain) (see Chap. 8). Such areas are extremely important for large numbers of shorebirds, Greater Flamingoes (*Phoenicopterus roseus*), herons and gulls. Depending on species and time of year, birds present will be a combination of those remaining for the non-breeding season, others making temporary refueling stopovers during long migratory journeys, and a relatively small proportion present to breed. The vast, complex nature of such habitats makes assessing water-bird populations labor-intensive and logistically difficult, to the extent that there are no reliable estimates of populations, let alone monitoring of trends. Some early work was carried out in the mid-1990s, concentrating at Ras Al-Khor, Dubai, (Keijl et al. 1998) whilst Environment Agency–Abu Dhabi have organized January counts of various wetland sites, as part of the International Waterbird Census coordinated by Wetlands International. As well as the Endangered Great Knot (*Calidris tenuirostris*), of ten Near Threatened species occurring in the UAE, five (Eurasian Oystercatcher *Haematopus ostralegus*, Eurasian Curlew *Numenius arquata*, Black-tailed Godwit *Limosa limosa*, Bar-tailed Godwit *L. lapponica* and Curlew Sandpiper *C. ferruginea*) are migrant shorebirds almost wholly dependent on intertidal habitats. Regrettably, such habitat is under increasing threat in the UAE, as elsewhere, from development and reclamation (see Burt 2014).

In intertidal areas, shorebirds dominate in both variety and absolute numbers; over 20 species co-occur at the richest sites. Almost all nest from central Asia northwards to the Arctic Ocean and make long migratory journeys to reach the food-rich Arabian Gulf. These include the Great Knot, for which the Arabian Gulf constitutes the westernmost edge of its wintering range and, as indicated by a ringing recovery, reaches the UAE from Kamchatka, Russia (Dorofeev and Campbell 2017). This very localized species is best sought amongst extensive flocks of the more numerous Bar-tailed Godwit and Grey Plover (*Pluvialis squatarola*). Numerically most abundant are small sandpipers (e.g. Dunlin *C. alpina*) and plovers (particularly Kentish *Charadrius alexandrinus* and Tibetan Sand Plover *C. atrifrons*). Crab Plover (*Dromas ardeola*) and Kentish Plover represent rare examples of intertidal shorebirds that breed locally. The former has a number of unique characteristics for a shorebird, not least its striking, pied plumage and habit of excavating nesting burrows. It occupies its own monospecific family and is very much an Arabian breeding speciality. The 1400–1500 pairs that breed very locally in the UAE may represent over 30% of the Arabian population (Table 15.1; Javed et al. 2012). Kentish Plovers are much more widespread, breeding year round alongside saline shores, in areas where disturbance is limited.

Greater Flamingo occurs in many intertidal areas of the UAE, with the waters surrounding Abu Dhabi Island and Ras al-Khor particularly favored. Satellite tracking of UAE birds reveals that some summer as far north as Turkmenistan and move between multiple intertidal sites on the UAE coast (Javed and Khan 2007). Other characteristic species of intertidal habitats include the numerous Western Reef Heron (*Egretta gularis)* and the much less conspicuous Striated Heron (*Butorides striata*). Both require large stands of gray mangroves (*Avicennia marina*, see Chap. 7) for nesting. The globally Vulnerable Greater Spotted Eagle (*Clanga clanga*) also favors areas with extensive mangroves, where it roosts and forages on injured or sickly waterfowl. Winter concentrations of up to 20 individuals occur at Ras al-Khor, Dubai, providing a spectacular sight as the cool morning air warms and they soar on developing thermals, against a backdrop of city skyscrapers.

Table 15.1 Population estimates of eight breeding species characteristic of offshore islands in the Arabian Gulf

	Estimated UAE population, breeding pairs	Estimated Arabian Population, breeding pairs
Crab Plover *Dromas ardeola*	1400–1500 (Javed et al. 2012)	4000
Bridled Tern *Onychoprion anaethetus*	40,000–45,000 (Aspinall 2010)	300,000
White-cheeked Tern *Sterna repressa*	25,000 (Aspinall 2010)	75,000–80,000
Saunders's Tern *Sternula saundersi*	300–500 (Aspinall 2010)	4000
Sooty Gull *Ichthyaetus hemprichii*	2100 (Aspinall 2010)	28,000
Socotra Cormorant *Phalacrocorax nigrogularis*	60,000–70,000 (Khan et al. 2018)	110,000
Osprey *Pandion haliaetus*	72 (Khan et al. 2007)	850
Sooty Falcon *Falco concolor*	5–6 (Shah et al. 2008; Aspinall 2010)	500

Source: Jennings (2010); updated information for UAE populations as indicated

The high energy Gulf of Oman shoreline is almost bereft of extensive intertidal areas, with the notable exception of Khor Kalba (Sharjah). This site has evocative forests of old growth mangroves and is the only location in the UAE for Collared Kingfisher (*Todirhamphus chloris*), of endemic subspecies *kalbaensis*. This requires holes in old trees for nesting and recent surveys have revealed a population of over 100 birds. Kalba is further unique in UAE terms for supporting regular wintering Indian Pond Herons (*Ardeola grayii*) and a small resident population of Sykes's Warbler (*Iduna rama*), a species otherwise breeding mainly in inland central Asia. This important site is now fully protected as Al Qurm Nature Reserve and is open to the public for visiting. Figure 15.10 depicts four species typical of the intertidal areas of the UAE.

15.3.1.5 Offshore Coastal Islands of the Arabian Gulf

Small islands pepper the Arabian Gulf coastline, both inshore (particularly in the vicinity of Abu Dhabi) and further offshore. Some harbor internationally important populations of breeding seabirds, especially terns and Socotra Cormorants. Compared to terrestrial bird populations, these have been relatively well-studied. Population estimates for eight nationally important species, five of which are predominately Arabian in breeding distribution, are given in Table 15.1 and four characteristic species of this habitat are presented in Fig. 15.11. Most islands are distant from shore and thus inaccessible to the casual visitor, a remoteness vital for ground-nesting birds. However, many have been subject to development in recent decades, particularly for the petroleum industry. This causes increased disturbance at

Fig. 15.10 Species characteristic of intertidal areas. Clockwise from top left: Collared Kingfisher (*Todirhamphus chloris*), Greater Spotted Eagle (*Clanga clanga*), Bar-tailed Godwits (*Limosa lapponica*), Western Reef Heron (*Egretta gularis*). Photographer: Oscar Campbell

best and, in many cases, extensive habitat destruction and the introduction of mammalian predators such as feral cats.

Characteristic breeding species include five species of terns of which three, Saunders's (*Sternula saundersi*), White-cheeked (*Sterna repressa*) and Bridled Terns (*Onychoprion anaethetus*) are conspicuous in inshore waters around Abu Dhabi island during the breeding season. Saunders's Tern breeds at low densities but the other two may occur in large colonies. Saunders's Terns nest earliest and often have juveniles fledged by mid to late May; as with White-cheeked Tern it nests in bare scrapes above the high tide line. Bridled Terns do not return until late April and nest later, generally under the protection of shrubs or rock crevices. All three winter in the Indian Ocean and are generally absent from the Arabian Gulf when not breeding. An important species, nesting in very dense colonies, is the Arabian endemic Socotra Cormorant. This globally Vulnerable species, which makes spectacular early morning mass feeding flights, has undergone a recent population increase nationally; the UAE may now hold almost half the world population (Khan et al. 2018). A colony at Siniyah Island (Umm al Quwain) has been intensively studied (e.g. Muzaffar et al. 2017) but to date has no formal protection.

Fig. 15.11 Species characteristic of offshore coastal islands of the Arabian Gulf. Clockwise from top left: Socotra Cormorant (*Phalacrocorax nigrogularis*), White-cheeked Tern (*Sterna repressa*), Osprey (*Pandion haliaetus*), Sooty Falcon (*Falco concolor*). Photographer: Oscar Campbell

One species of shorebird and two raptors are characteristic of Arabian Gulf islands. Crab Plover is an Arabian near-endemic breeder, confined to two colonies in the UAE, with Abu Al Abyad (Abu Dhabi) holding the vast majority. The population here is well-protected, in contrast to some of the sites used by non-breeding birds (Javed et al. 2012, and references therein). Birds from Abu Al Abyad have been satellite-tracked to the Seychelles. The cosmopolitan Western Osprey (*Pandion haliaetus*) occurs at high densities in the vicinity of Abu Dhabi Island where it is conspicuous, readily using artificially provided nesting platforms, as well as natural outcrops on low headlands. Nests are reused annually, resulting in vast, bulky structures. In contrast, the globally Vulnerable and nationally extremely rare Sooty Falcon (*Falco concolor*) is now restricted to breeding sites in the far west of the Abu Dhabi emirate and, having undergone a severe decline (five pairs in 2007; two or three pairs since then; Shah et al. 2008; Javed et al. 2020) faces a bleak outlook.

Box 15.1: Seabirds in UAE Waters of the Gulf of Oman

A concerted effort to survey the UAE's deeper offshore waters was initiated in 2010, when local birdwatchers initiated trips out from Kalba, Sharjah, on the UAE's east coast. The results to 2016 were summarized by Campbell et al. (2017) and resulted in revision of the known UAE status of eleven species, including two species recorded for the first time. The waters off the Omani coast are extremely rich biologically, due primarily to an upwelling of cold, nutrient rich water from May to October as south westerly winds of the Indian monsoon blow warm surface water offshore (Chap. 4). Although the main upwelling does not reach UAE waters, many seabird species that breed or move into Omani waters as a result of the foraging opportunities offered overspill into UAE waters, at least occasionally. As most occur some way offshore (in excess of 40 km), land-based observations could never establish the true status of such species. Those occurring include four Near Threatened seabirds, three of which make remarkable journeys to reach UAE waters. The diminutive Swinhoe's Storm-Petrel (*Hydrobates monorhis*) breeds only in islands in the Korean archipelago yet occurs regularly throughout the North Indian Ocean. Large numbers of Flesh-footed Shearwaters (*Ardenna carneipes*), presumably from colonies on St Paul Island, southern Indian Ocean and western Australia migrate to the Gulf of Oman to spend the non-breeding season and use the rich feeding opportunities presented by the monsoon to moult. Sooty Shearwaters (*A. griseus*) come from even further afield; UAE birds likely originate in New Zealand but have migrated north west through the Indian Ocean, instead of the Pacific Ocean, so reaching the UAE instead of Japan, where they normally spend the early summer. All three species occur annually in small numbers in UAE waters. The fourth species, Jouanin's Petrel (*Bulweria fallax*) is rather different; known to breed only on Socotra Island, Yemen, it occurs erratically in UAE waters, mainly autumn and early winter. Over 600 have been counted on occasion. With a world population estimated at less than 10,000 (BirdLife International 2022c), local offshore waters are clearly of global significance for this poorly known species.

Other notable seabirds occurring in UAE waters of the Gulf of Oman include the Arabian breeding endemic Persian Shearwater (sometimes common, close inshore), Wilson's Petrel (*Oceanites oceanicus*, a common non-breeding visitor, from Antarctic islands), large numbers of the Arctic-breeding Red-necked Phalarope (*Phalaropus lobatus*, which stage in UAE waters mainly in spring and early autumn; wintering further offshore) and Arctic Skuas (*Stercorarius parasiticus*) which winter in and migrate through UAE waters, before making high altitude overland flights from the Iranian coastline, to breeding grounds on the Siberian tundra.

15.3.2 Anthropogenic Habitats

The growth of anthropogenic habitats, here broadly defined as those whose existence is more or less wholly due to human activities e.g. agricultural areas, wetlands associated with treated water discharge, has been responsible for large changes in the UAE's avifauna in modern times. Whilst such habitats generally attract widespread generalist species, they nevertheless support a high diversity, often at densities exceptional in natural terrestrial habitats. Some species using such areas, particularly extensive fodder fields, may be of high conservation value (see SOM Tables 15.1 and 15.2) and even Saharo-Sindian specialists use such habitats for part of the year, concentrating in numbers unknown elsewhere. It is a striking fact that, of the ten sites with the longest bird species lists in the UAE, all are almost wholly anthropogenic (eBird 2022). This clearly constitutes part of what Callaghan et al. (2018) term 'unnatural history' and which Cowan (2018) further discusses, based on avian observations from the Arabian Peninsula.

15.3.2.1 Farms and Agricultural Areas

Agricultural areas, ranging from small-scale, relatively unmechanized farming plots to vast, industrial-scale grasslands, support more bird species, at higher densities, than any other UAE habitat. Figure 15.12 illustrates four characteristic species of such habitats. Particularly important are areas of extensive fodder fields, cultivating species such as Lucerne (*Medicago sativa*) and watered by large, rotating irrigation booms. Sites with fields in a variety of tillage states, where native vegetation such as *Leptadenia pyrotechnica* is allowed to grow on the fringes, and with adjacent wetland areas (from released water associated with agricultural operations) are particularly rich, supporting abundant breeding and wintering species, numbers of which may rise rapidly after establishment (Campbell and Smiles 2019). Virtually all the UAE's breeding Collared Pratincoles (*Glareola pratincola*), Common Starlings (*Sturnus vulgaris*) and Western Yellow Wagtails (*Motacilla flava*) breed at such sites which have also facilitated the recent, rapid status change of Black-winged Kite (*Elanus caeruleus*) from vagrant to breeding resident (Campbell et al. 2022). These species are typical of warm temperate climates; their occurrence as Arabian breeders is reliant on sites providing a comparatively humid, sheltered microclimate. However, even quintessential desert dwellers, such as Cream-colored Courser, Egyptian Nightjar and Greater Hoopoe-Lark breed on the fringes, or more distantly, from such sites but then concentrate at them during the hottest months of the year, dispersing back into the desert in late autumn as temperatures ameliorate. Another desert denizen, Chestnut-bellied Sandgrouse, uses ephemeral pools in such areas for drinking, making conspicuous flights mid-morning. Wintering species include large numbers of shrikes, stonechats, wagtails, pipits and larks from breeding areas across much of central and northern Asia. Multiple species in each group are represented, but more significant still are several shorebirds which favour bare, tilled

Fig. 15.12 Species characteristic of farms and agricultural areas. Clockwise from top left: Black-winged Kite (*Elanus caeruleus*), Arabian Babbler (*Argya squamiceps*), Collared Pratincole (*Glareola pratincola*), Sociable Lapwing (*Vanellus gregarius*). Photographer: Oscar Campbell

ground. These include the high Arctic breeding Pacific Golden Plover (*Pluvialis fulva*), which in the UAE is at the western extremity of its regular wintering range, and the Sociable Lapwing, the UAE's only regularly occurring Critically Endangered species. Now restricted to nesting in small areas of Kazakhstan, and subject to severe declines caused by changes to agricultural practice on its steppe breeding grounds and hunting pressures on migration and wintering grounds, small numbers of Sociable Lapwing migrate through and winter annually in the UAE. Recent observations suggest that increasing numbers now remain each winter, as noted elsewhere in Arabia (Babbington and Roberts 2017). A record flock of 34 were discovered at one agricultural site in Abu Dhabi Emirate in February 2021, and almost 80 individuals were recorded at five sites during winter 2022-23.

High densities of prey and, doubtless, limited disturbance due to restricted access, attract wintering and migrant predators. The UAE's most extensive agricultural areas regularly support up to three species of harrier and both Greater Spotted and Eastern Imperial Eagles (*Aquila heliaca*). Pallid Harrier (*Circus macrourus*) and both eagles are species of global conservation concern.

In the late 1990s, areas of small-scale farming amidst mature Ghaf (*Prosopis cinerea*) woodland in Ras al-Khaimah, in the far north of the UAE, temporarily hosted a number of breeding species unique in a UAE and Arabian context (Aspinall 2010). These included small populations of three species typical of warm temperate latitudes: European Roller (*Coracias garrulus*), European Bee-eater (*Merops apiaster*) and Spanish Sparrow (*Passer hispaniolensis*), all of which no longer occur as breeding species in the UAE. The attractive wooded, farmland landscape they inhabited is still present, as are previously documented co-occurring species such as Arabian Babbler (*Argya squamiceps*) and Common Starling. It is possible that climatic changes account for the loss of such species, all of which were at the southern extremity of their global breeding range in the northernmost UAE (see Chap. 3).

15.3.2.2 Freshwater Wetlands

Non-saline wetlands of any type are very infrequent in the UAE and are thus of prime importance for a number of species, many of which are, by definition, highly localized nationally (although often with very extensive global ranges). The origin of such wetlands is often linked to agricultural operations or discharge of treated waste water. Many are ephemeral, perhaps the consequence of a flash flood or accidental leakage. They are also prone to rapid succession, becoming choked in vegetation and drying out, particularly by the rapidly colonizing reed *Phragmites australis*. However, even temporary shallow pools, if not hypersaline, rapidly attract at least small numbers of shorebirds and waterfowl, some of which, such as Black-winged Stilt (*Himantopus himantopus*) and Kentish Plover, may remain to breed. The presence of early successional fringing vegetation, providing additional cover and microhabitat variety, soon draws in Little Grebe (*Tachybaptus ruficollis*), Common Moorhen (*Gallinula chloropus*) and Clamorous Reed Warbler (*Acrocephalus stentoreus*), all of which have greatly increased ranges and populations in the UAE in recent decades. The most permanent and extensive sites, such as Al Wathba Wetland Reserve, Abu Dhabi, (which results from the release of treated waste water eutrophicating a naturally saline, shallow waterbody) hold large numbers of wintering wildfowl and shorebirds (e.g. Northern Shoveler *Anas clypeata*, Eurasian Teal *Anas crecca* and Little Stint *Calidris minuta*). Wintering Western Marsh Harriers (*Circus aeruginosus*) may congregate to roost in groups of up to 50, although most disperse into the surrounding desert and plantations to hunt during the day. Two species worthy of particular mention are the very uncommon, breeding White-tailed Lapwing (*Vanellus leucurus*) and the Near Threatened, wintering Ferruginous Duck (*Aythya nyroca*). Unlike the superficially similar but much more generalist Red-wattled Lapwing, the former is restricted to shallow wetland fringes, and despite colonizing the UAE from 1996 onwards (Aspinall 2010), has remained extremely localized in its distribution. Ferruginous Duck is reliant on wetlands with extensive fringing vegetation and may occur in small flocks at favored sites; over-summering has occurred but breeding not yet been confirmed. Four species

Fig. 15.13 Species characteristic of freshwater wetlands. Clockwise from top left: Western Marsh Harrier (*Circus aeruginosus*), Ferruginous Duck (*Aythya nyroca*), White-tailed Lapwing (*Vanellus leucurus*), Little Grebe (*Tachybaptus ruficollis*). Photographer: Oscar Campbell

typical of freshwater wetlands are depicted in Fig. 15.13. In additional to their intrinsic worth for biodiversity, freshwater wetlands are extremely significant for their great educational value, an opportunity currently being effectively realized at Al Wathba Wetland Reserve and Al Wasit, Sharjah. Despite promising signs in the early stages, one similar opportunity that was spectacularly missed was at Al Warsan Lakes, Dubai, which has now been lost to development.

15.4 Adaptations

The UAE's resident and migratory birds must be able to survive the climatological extremes prevalent for much of the year; only the small proportion that are solely winter visitors, occurring November to early March, will avoid these extremes. Intense solar radiation and high ambient temperatures exacerbated by high humidity levels make maintaining a safe body temperature challenging and increase water demand at a time of year when freshwater availability is particularly limited. Severe wind conditions such as the well-known 'Shamal' storm events are less of a threat, although they may add to general desiccation and resulting dust storms may disorientate migrants. This section discusses adaptations, both behavioral and physiological, of resident breeding birds to the climate of the UAE.

15.4.1 Behavioural Adaptations

An obvious general strategy, employed by many desert organisms, is avoidance of temperature extremes. Most are active at dawn and prior to dusk; in between, activity is reduced to a minimum, with most birds resting in shade where possible. Whilst sparse desert vegetation offers limited shade, solid objects such as rocks or buildings offer more; various larks and even Cream-colored Courser have been observed seeking shade from vehicles and even animals (Jennings 2010). Sheltering underground, characteristic of mammals and reptiles (see Chaps. 14 and 16, respectively) is less typical of birds, although Williams et al. (1999) recorded four species of larks, mainly Greater Hoopoe-Lark, using burrows of the Spiny-tailed Lizard (*Uromastyx aegypticus*). This behavior was routinely observed 11:00–16:00 hrs and birds remained underground for much of that period, reducing water loss by as much as 81%. The burrow-nesting Crab Plover (Fig. 15.14) is another example, although not quite for the same reasons as the Greater Hoopoe-Lark. A study in Eritrea (De Marchi et al. 2008) revealed the relatively constant temperature (35 °C) and humidity

Fig. 15.14 Crab Plover (*Dromas ardeola*), a taxonomically unique burrow-nesting shorebird. This species forages in extensive areas of intertidal mud but requires undisturbed sandy islands for breeding. Photographer: Oscar Campbell

(60%) of two burrows studied would be near-optimum for embryo development and permitted very low incubation attendance of adults.

In the absence of shade, various larks aid thermoregulation by prostrating themselves into depressions, particularly where the ground is moist or covered with vegetation such as the mat-forming, large-leaved Desert gourd (*Citrullus colocynthis*) (Cowan and Brown 2001; Brown 2009). Birds remained prostrate for long periods, despite being fully exposed to the sun. Prostrating has also been observed by Greater Hoopoe-Larks within burrows, where it was interpreted as an attempt to conduct heat away from the body that would otherwise require evaporative water loss (Williams et al. 1999). Evaporative water loss by panting is frequently observed in birds during the hotter months. However, it seems to be mainly performed by temperate zone species migrating through the UAE, or those resident in relatively moist habitats (where such water may be easily replaced), rather than by true desert specialists.

Many species breed early in spring, so particularly sensitive stages of the life-cycle (eggs or chicks which cannot thermoregulate effectively) are fledged before the highest temperatures arrive. These include species from a wide variety of habitats (e.g. montane Hume's Wheatear, the widespread Great Grey Shrike (*Lanius excubitor*), reedbed-haunting Clamorous Reed Warbler and the coastal Saunders's Tern) but also Saharo-Sindian species of sandy deserts, such as Cream-colored Courser, Greater Hoopoe-Lark and Brown-necked Raven (*Corvus ruficollis*), all of which may have young fledged by April. Some then change habitat post-breeding, concentrating in comparatively moist agricultural areas until September/October, before dispersing back into the surrounding desert (see Farms and Agricultural areas, above). Rather than switching habitats within a discrete area, species such as Black-crowned Sparrow-Lark and the Bar-tailed Lark (*Ammomanes cinctura*) vacate large areas for extended periods. Although nomadism is inevitable for birds that feed on profusely seeding plants that grow rapidly but irregularly (Dean 2004), such nomadism is less frequent in Arabia, where seasonal distinctions are well-defined, than it is in, for example, interior Australia. Many nomadic species in Arabia are granivorous, have minimal reliance on water sources and typically occupy sandy plains, avoiding montane areas where they are likely outcompeted by sedentary species (Jennings 2010). They may appear suddenly in areas subject to good rainfall to take advantage of the glut of seeds available for several months and then vanish for years as conditions deteriorate. Two further species, the uncommon resident Trumpeter Finch (*Rhodopechys githaginea*) and the migratory Pale Rock Sparrow (*Carpospiza brachydactyla*) are interesting in that they occur, albeit highly erratically, in rocky areas including both rocky outcrops in sandy deserts and in true montane regions. The former is likely nomadic yet highly dependent on regular access to water; the latter certainly is nomadic and highly unpredictable in both distribution and numbers both as a migrant and breeder.

A few species take adjustment to timing of breeding further still, restricting nesting to winter. Osprey and Socotra Cormorant share this strategy, the latter also having chicks covered in white down, improving thermoregulation by enhanced reflection of radiation. However others, e.g. Chestnut-bellied Sandgrouse and White-cheeked Tern habitually nest on bare ground from late spring to summer fully exposed to the full intensity of the sun and elevated ground temperatures, where shading by adults is critical to avoid eggs and chicks over-heating. Necessity of shade and cooling extends to when chicks start moving after hatching. It can be attained by standing over nests or chicks but also by adults wetting their belly feathers, a behavior observed in Chestnut-bellied Sandgrouse, Kentish Plover, Red-wattled Lapwing and Bridled Tern (Jennings 2010). Sandgrouse, three species of which breed in the UAE, are well-known for their ability to transport water to nests over long distances using modified belly feathers that are ultra-absorbent due to a unique barbule structure. In a study of the breeding ecology of Kentish Plovers at Al Wathba Wetland Reserve, Abu Dhabi, Kosztolányi et al. (2009) found that frequency of biparental care and site fidelity was greater than populations of the same species breeding in temperate latitudes, suggesting biparental care was likely selected for by the harsh local environment, where egg and chick survival is highly dependent on shade provision by parents.

Most Saharo-Sindian species seem not to require regular drinking, although some take advantage as the opportunity arises. Species such as Greater Hoopoe-Lark appear to drink rarely and presumably satisfy their water needs from dew or food. Others, some of which are highly sedentary in rocky, montane habitats such as Sand Partridge, Hume's Wheatear and Streaked Scrub-Warbler readily drink when possible but survive long periods when free water is unavailable. However, a third, much larger group of species must drink regularly and their UAE distributions reflects this need. This includes all non Saharo-Sindian species, but also Chestnut-bellied and Lichtenstein's Sandgrouse, both of which make daily flights to drink.

15.4.2 Physiological Adaptations

Williams and Tieleman (2005) review studies outlining evidence for physiological adaptions to extreme heat and aridity in desert birds. Such traits are less obvious than behavioral adaptions and are poorly studied in birds generally, compared to taxonomic groups such as insects or reptiles. However, they have been clearly demonstrated in Greater Hoopoe-Lark (Fig. 15.15) and are likely present in other Saharo-Sindian species. Such adaptions equate to significant overall distinctions in a species' life-history, compared to related species inhabiting more temperate, less arid environments. A lower rate of metabolism has been demonstrated both in the laboratory and the field for desert birds compared to non-desert species, and within a family (Larks) along an increasing aridity gradient from Western Europe to Arabia. Lower metabolism translates into a lower energy requirement and reduced food intake, an unsurprising adaptation of species living in environments such as deserts with low primary productivity.

Water balance is another critical issue for desert-dwelling organisms, in particular birds which are largely diurnal and, with a few exceptions, don't burrow. Desert-dwelling birds overall have lower total evaporative water loss than species from

Fig. 15.15 Greater Hoopoe-Lark (*Alaemon alaudipes*), a species highly adapted to life in Arabia, but which regularly forages and as seen here, collects nesting material, at anthropogenic sites. Photographer: Oscar Campbell

more moist environments, and this loss decreases within various species of larks along a gradient of increasing aridity (Williams and Tieleman 2005). A reduction of water loss through the skin rather than via respiration may be the reason for this overall reduction. It has been demonstrated that three species of Arabian larks, compared to two from the Netherlands, have subtly different combinations of lipids and cholesterol within the upper skin epidermis, thus reducing the movement of water vapor through the skin.

Other adaptations to living in extreme aridity include generalist diets that may shift opportunistically, smaller clutch sizes, fewer clutches per breeding season and relatively slow rates of nestling growth, meaning that adults do not risk having to continually forage (Dean and Williams 2004). Nestling fitness is also reduced, and this implies higher adult survival and greater longevity. In some especially dry years desert birds avoid breeding completely; this implies greater longevity, with birds only attempting to breed when conditions present little risk, compared to temperate zone species which breed annually. However, in response to sufficient rainfall, breeding attempts are then made very rapidly.

Box 15.2: Montane Owls

Perhaps the most remarkable discoveries concerning the UAE avifauna in the last decade have concerned the realization that two rare and little-known owl species are breeding residents of the Hajar mountains. Omani Owl (*Strix butleri*) a species missing since description of the first specimen in 1878 and

(continued)

Box 15.2 (continued)
long conflated with a very similar species resident in western Arabia, was rediscovered in northern Oman in 2013 and found in the UAE in 2015 (Judas et al. 2015), although with hindsight may have been recorded as early as 2006 (Tourenq et al. 2009). It is still known from only a single location but field studies are hindered by its quiet vocalizations and the remote terrain it favors. It may yet prove to be somewhat more widespread.

In 2017, two territories of Arabian Spotted Eagle Owl *Bubo milesi* were discovered in an area of the Hajars near Masafi (Fujairah). This Arabian endemic, most numerous in southern Oman and Yemen, is rare in northern Oman but was hitherto unrecorded, and unsuspected, in the UAE. Subsequent concerted survey work has detected a minimum of ten territories (J Judas pers comm) with birds even observed in and around village date plantations. The species is probably widespread at low densities throughout much of the Hajar mountains.

15.5 Bird Migration through the UAE

As a natural link between the vast, diverse breeding grounds of Eurasia and the food-rich wintering grounds of Africa, the entire Middle East is a superlative location to observe bird migration. Arid landscapes, leading lines formed by mountain chains, and avoidance of extended ocean crossings cause migrants to concentrate in certain locations where migration intensity can be globally exceptional. Radar-based studies, conducted nocturnally in Israel, suggest approximately four million migrant birds per 100 km per night, and overall some 4–5 billion individuals moving south each autumn (Bruderer 1996; Newton 2010). Smaller numbers (40–65%, due to mortality during migration and on wintering grounds) return northwards in spring. Density of migration declines eastwards across Arabia, so absolute numbers passing through UAE airspace, where quantification has never been attempted, are likely significantly lower. However, as the UAE lies within both the Central Asia and East Asia/East Africa flyways, but also on the eastern margin of the Mediterranean/Black Sea flyway (see BirdLife International 2010), species diversity is high. The vast majority of migratory birds transit on a north-south axis, but the Central Asia flyway includes species such as Yellow-throated Sparrow (*Gymnoris xanthocollis*) and Red-breasted Flycatcher (*Ficedula parva*), which breed in the Middle East and Eastern Europe respectively and winter in India, so transiting the UAE on an east-west axis.

With the extremes of spring passage spanning late January to late May, and that of autumn from late June to November, migration is ongoing throughout the UAE for much of the year. Indeed, as the latest winterers arrive in December, and sudden cold snaps in Iran force birds south across the Arabian Gulf in January, new arrivals may occur any month of the year. However, the vast majority of migration occurs March to mid-May and mid-August to October.

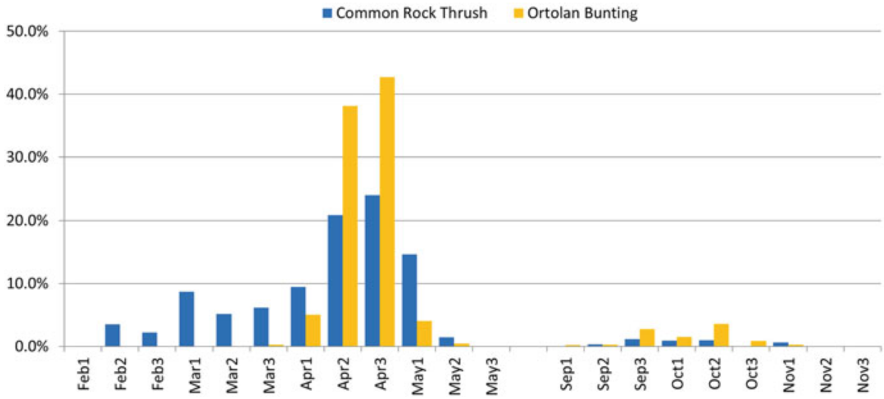


Fig. 15.16 Phenology and relative abundance of Ortolan Bunting (*Emberiza hortulana*) and Common Rock Thrush (*Monticola saxatilis*) through the UAE, expressed as percentage of total passage occurring in 10-day intervals. Sample sizes are 1539 bird-days (Ortolan Bunting) and 376 bird-days (Common Rock Thrush). Data from: Campbell and Smiles (2021). Ortolan Bunting is an example of a species in which spring migration is concentrated in a particularly narrow time period (mid to late April) whereas Common Rock Thrush has an unusually wide passage period. This may be explicable by breeding sites, whilst at comparatively low latitudes, encompassing a wide range of elevations and hence climates, from foothills in Iran to montane regions of Mongolia. Both species are much more frequent in spring (Ortolan Bunting 91% of passage occurring then; Common Rock Thrush 96%) than autumn. The two species discussed here are depicted in Fig. 15.19

In the UAE, the majority of migrants are active flyers which migrate nocturnally to avoid over-heating and dehydration. Diurnal migrants that are dependent on thermals for energy-efficient soaring (e.g. storks, eagles) tend to concentrate through the Levant and Kuwait rather than cross the Arabian Gulf directly, where the absence of thermals prevents passive soaring. The Straits of Hormuz are a surprisingly effective barrier to such species. Tracking data (e.g. McGrady et al. 2019) indicate marked detours to avoid crossing the Arabian Gulf, even in spring when the Hajar Mountains and Ruus al Jibal form a leading line of elevated land for north-bound birds. However, active flyers (e.g. songbirds, rollers, bee-eaters, shorebirds) are not deterred, and thus constitute the bulk of migrants using UAE airspace. Such nocturnal migrants must descend and pause migration soon after sunrise, when they may be forced to accept the first shelter available; such species are at risk of disorientation and collision in highly illuminated urban areas, especially if low-level mist is encountered. Some 140 species of birds regularly transit the UAE; Campbell and Moran (2016) and Campbell and Smiles (2021) provide phenological data and discussion on the more numerous species.

Whilst passage periods overall are prolonged, many species pass within a rather narrow time period and the date of peak passage is, in the absence of anomalous weather, rather constant from year to year (e.g. Ortolan Bunting *Emberiza hortulana*, Fig. 15.16). This is consistent with results from other well-studied migration hotspots in the Middle East (e.g. Shirihai 1996). Certain species show broader

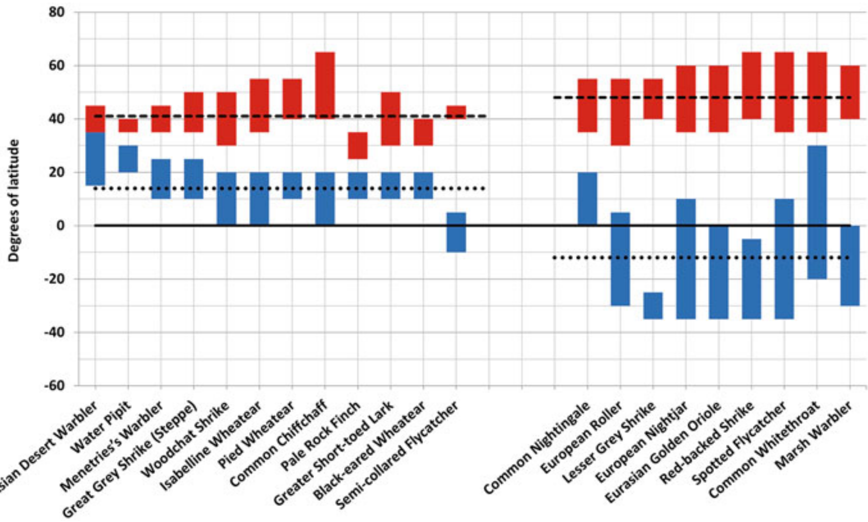


Fig. 15.17 Latitudinal ranges of breeding range (red bars) and wintering ranges (blue) for 21 migrant species that pass through the UAE, categorized as *Early* (main passage period mid-February–March; 12 species on left) or *Late* (main passage period late April–May; 9 species on right). Data sources: Birdguides (2008); Campbell and Smiles (2021); see data in SOM, Table 15.3 where scientific names for all species analysed are given. Dashed lines indicate the mean wintering and breeding latitude for each group of species

passage periods, presumably related to different populations migrating to breeding grounds which become hospitable at different times during the spring (e.g. Common Rock Thrush *Monticola saxatilis*, Fig. 15.16). This is further exemplified by Western Yellow Wagtail (*Motacilla flava*), four subspecies of which are readily distinguishable by male head pattern. The most southerly subspecies (breeding to 40°N) has peak passage early to mid-March whilst the latest, (breeding at 60–70°N) migrates through the UAE in early May. Migrants in late March and April mainly comprise two subspecies breeding at 50–60°N.

Another generality is that species with spring migration that peaks early (mid February–March) breed at lower average latitudes than those with spring migration peaking later (late April–May). Even more strikingly, early migrants tend to winter further north (generally north of the equator) than late migrants (Fig. 15.17; see also SOM Table 15.3), which may reach as far south as 35°S in southern Africa. This analysis, conducted for 21 UAE species, closely matches results for 132 species from a study in southern England (Newton et al. 2010).

As evident in Fig. 15.16 and further illustrated in Fig. 15.18, many species exhibit markedly different abundances in spring compared to autumn. Campbell and Smiles (2021), analyzing migration timing and relative seasonal scale of passage through the UAE, found that of 77 species studied, 40% were more frequent in spring (defined as 65% or more of total passage occurring in that season). These included

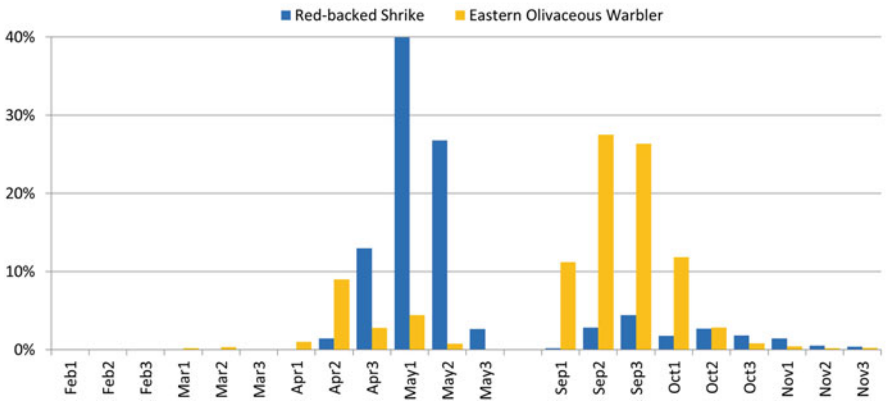


Fig. 15.18 Phenology and relative abundance in spring vs autumn of Red-backed Shrike (*Lanius collurio*) and Eastern Olivaceous Warbler (*Iduna pallida*) through the UAE expressed as percentage of total passage occurring in 10-day intervals. Sample sizes are 752 bird-days (Red-backed Shrike) and 487 bird-days (Eastern Olivaceous Warbler). Data source: Campbell and Smiles (2021). Red-backed Shrike is an example of a species in which spring migration is concentrated in a particularly narrow time period (May) and which is much more frequent then (85% of passage) than autumn. In contrast, Eastern Olivaceous Warbler is much more frequent in autumn (77% of passage) than spring. The two species discussed here are depicted in Fig. 15.19.

nine species that occurred almost exclusively in spring (defined as at least 98% of passage occurring then). Only 29% of species were more frequent in autumn, with only one species occurring almost exclusively then. Greater numbers of grounded migrants in spring than autumn (despite smaller total populations in the former season) has been demonstrated elsewhere in the Middle East and North Africa (e.g. Shirihai 1996; Newton 2010). Reasons are multiple and complex. One is a greater need for recuperation and refueling immediately following an arduous desert crossing in spring (whereas in autumn birds lay down sufficient fuel stores in food-rich regions to the north to permit overflying, and then refuel again in southern Arabia or the sub-Saharan Sahel region, both of which experience late summer rainfall). Further, the UAE and central Asian deserts are more hospitable in spring than autumn due to cooler temperatures and winter rains. Avoidance of central Asian deserts in autumn for species breeding in the steppe and forest zones of the Asian Palearctic necessitates an initial westward migration at relatively high latitudes, before turning south well north-west of the UAE. The overall effect is a loop migration, with many species taking a more easterly route in spring, as demonstrated by ringing studies (e.g. Marsh Warbler *Acrocephalus palustris*; Birdguides 2008) and satellite-tracking (e.g. Red-backed Shrike *Lanius collurio*; Tøttrup et al. 2011).

Within a population, males migrate on average earlier than females, to reach the breeding grounds earlier and claim a better quality territory (Newton 2010). Data from Abu Dhabi Island (Campbell and Moran 2016) demonstrates this for Pied Wheatear, a species with strong sexual dimorphism (Figs. 15.20 and 15.21).

Fig. 15.19 Migrant species occurring in the UAE. Clockwise from top right: Common Rock Thrush (*Monticola saxatilis*), Ortolan Bunting (*Emberiza hortulana*), Eastern Olivaceous Warbler (*Iduna pallida*) and Red-backed Shrike (*Lanius collurio*). Photographer: Oscar Campbell

Although routine in that it is undertaken by billions of birds of hundreds of species annually, migration through deserts is one of the most extreme endurance feats undertaken by birds. Some of the adaptations for making this journey, both behavioral and physiological, are discussed by Newton (2010) who notes that each year the journey is taking longer to complete, due to desertification of the African Sahel. However, in the UAE it is likely the journey has become somewhat easier in recent decades, as formation of anthropogenic habitats, from urban gardens and parks to large scale agricultural areas, has yielded mesic, food-rich shelter that did not previously exist. Conversely, increased artificial illumination of urban and industrial areas, the latter particularly if associated with the oil industry in remote desert or offshore locations, have negative impacts on survival. As well as dehydration, and to a lesser extent starvation, migrating birds in the Middle East run the gauntlet of illegal, indiscriminate hunting, although this is a minor issue in the UAE compared to surrounding countries (Brochet et al. 2019). Disorientation due to sand and dust storms are another hazard and may precipitate remarkable fall-outs of birds, forced to temporarily pause their journeys. Such severe conditions are exceptional, however, and most individuals quickly re-orientate, often departing the following night if conditions allow.

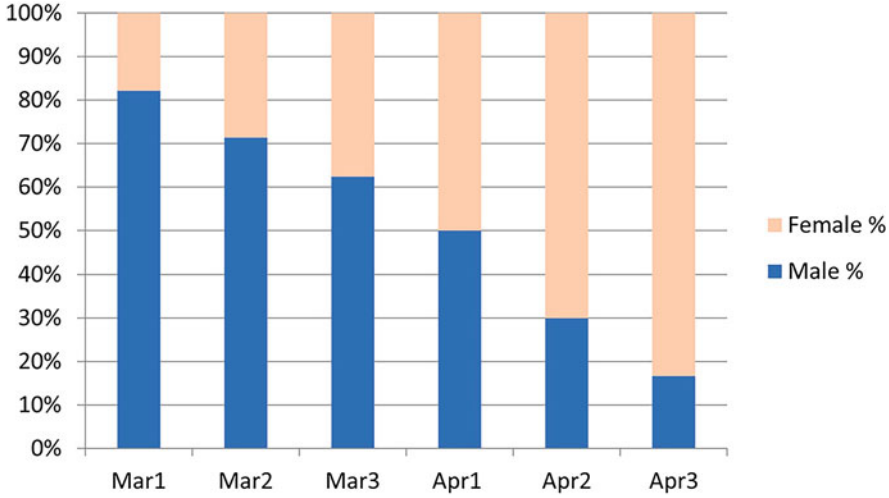


Fig. 15.20 Sex ratio data for Pied Wheatears (*Oenanthe pleschanka;* sample size 642 bird-days) migrating through Abu Dhabi Island on spring migration. Data are expressed as a percentage of male and female birds recorded in each 10 day period from 1 March to 31 April 2007–2014. Data source: Campbell and Moran (2016)

Fig. 15.21 Pied Wheatear male (*Oenanthe pleschanka*). Males of this species are easily distinguished from females, allowing relative timing of spring migration between sexes to be studied. Photographer: Oscar Campbell

15.6 Conservation

Although there has been welcome, much-needed progress in recent decades, efforts to conserve the UAE's avifauna still do not match its intrinsic interest and significance. Federal laws to prevent the hunting of birds have been in place since 1983 (Aspinall 2010) and, coupled with a limited hunting culture and the difficulty of obtaining firearms, have been broadly effective, although many species that occur seasonally are threatened by such activities outside the UAE (Burfield et al. 2021). However, threats to birds come from many sources other than direct persecution. Threats identified by Aspinall (2010), namely land-use changes (development, reclamation and agriculture), human disturbance, chronic over-grazing, over-abstraction of ground-water, pollution (including oil-related incidents), and introduction, inadvertent or otherwise, of mammalian predators (particularly to offshore islands) and exotic species, are still ongoing (Burfield et al. 2021). Establishment of government agencies, most notably the Environmental Research and Wildlife Development Agency (ERWDA; forerunner to the Environment Agency–Abu Dhabi) in 1996 (and with similar authorities in other Emirates) was a key step in the conservation of birds, their habitats and ecosystems generally in the UAE. Exercising regulatory powers, monitoring biodiversity and status of protected areas and ensuring compliance with various international conventions that the UAE is signatory to are amongst the critical roles undertaken.

One approach to conservation is to categorize species on the level of threat within a country, taking into account regional and global distribution and trends. This highlights priority species towards which funding, research, and action plans can then be targeted. Hornby and Aspinall (1997) identified 13 species or subspecies of global conservation interest, and a further 29 species which are either threatened or rare in the UAE and hence important in terms of national biodiversity. A similar list by EAD for the Emirate of Abu Dhabi only (Khan et al. 2020) assessed 49 species, of which 33 were classified as threatened. However, many species discussed therein were always likely to be extremely local and/or rare in the UAE, based on their dependence on naturally very rare habitats (particularly freshwater wetlands) whilst certain nationally declining or globally range-restricted resident species, such as Chestnut-bellied Sandgrouse, Arabian Babbler and White-spectacled Bulbul were puzzling omissions.

A more comprehensive analysis (Burfield et al. 2021) for the entire UAE assessed 167 regularly occurring species. In total over half (53%) were classified as nationally threatened and a further 14% Near Threatened. This extent of threat is a greater proportion for birds than for mammals or amphibians and reptiles. It is also a somewhat greater proportion of threatened species than the global average, although the situation for birds is deemed to have improved slightly based on retrospective estimations generated for 1996. Raptors, owls, shorebirds, terns and larks are particularly frequent amongst nationally threatened species. Some are threatened in the UAE due to naturally small ranges but others have undergone serious population declines. Most threatened species occur in areas where bird species diversity is highest, particularly the northern and eastern coastlines and mountains, reflecting rapid, widespread land-use change due to development (residential and commercial) being the greatest risk to many species. Biodiversity loss due to development is unintentional and inevitable, at least to some extent, in all countries with developing economies but other major threats, such as invasive species and human intrusion and disturbance are readily soluble by recognition of the problem and then education, if necessary backed up by enforced legislation.

Another approach to bird conservation is identification of Important Bird Areas (IBAs). IBAs offer better protection to species that naturally concentrate (e.g. breeding terns, wintering shorebirds) rather than to wide-ranging, low density resident species (e.g. Arabian Babbler). However, an effective network of IBAs can go a long way to preserve national biodiversity and, as birds represent well-studied indicator species, habitat protection for them benefits many other taxa too. Twenty IBAs were first defined in the early 1990s, predominately islands in the Arabian Gulf and coastal wetlands (Evans 1994). Progress to protect such areas was evaluated by Aspinall and Hellyer (2006), who noted only faltering protection efforts, based mainly on ruling decree at an individual Emirate level and that, as effective protection for most important areas had not been achieved, some had suffered serious environmental degradation. An updated assessment of IBAs was released in 2018, representing the first official governmental-level evaluation of the IBA network (MoCCaE 2018). This upheld 14 of the original IBAs and announced the confirmation of 16 (out of a proposed 20) additional locations. The resultant 30 IBAs occupy 4200 km^2, 5% of the land area of the UAE. Most are coastal but also include several significant areas of interior desert and Fujairah's Wadi Wurayah National Park, the last, relatively untouched extensive portion of the Hajar Mountains in the UAE. Wadi Wurayah has also been recognised as a UNESCO Man and Biosphere Reserve. However, of the six IBAs identified in 1994 that subsequently lost their status, four were delisted as they no longer met the criteria for inclusion, so seriously had they been degraded. Further, 11 of the current 30 IBAs are unprotected in any way and some, including very significant locations for birds (such as Umm al Quwain's Khor al Beida and the adjoining Siniyah Island) face multiple threats. Even formally protected IBAs may face varying degrees of threat, including severe; in 2017 the condition of nine locations was deemed unfavourable or very unfavourable. Of the 30 IBAs, 19 were judged to be under medium to very high pressure, mainly from development, disturbance and invasive species. Such threats are still on-going.

For example, Jebel Hafit, a remarkable montane landscape amidst interior desert on the outskirts of Al Ain and holding important numbers of the globally Endangered Egyptian Vulture (Fig. 15.22), despite being decreed a National Park in 2017, is currently being subjected to tree planting at densities far beyond natural levels, as well as the deliberate release of large numbers of non-natives such as Arabian Partridge (*Alectoris melanocephala*). The proposed release of non-native ungulates has the potential to devastate the fragile vegetation and, hence the basis of the food chain. Ras Al-Khor, a remarkable 'green lung' in the heart of Dubai, has seen its important shorebirds populations decline due to misguided planting of mangroves (which replace highly productive mudflat areas) and currently is undergoing major

Fig. 15.22 Egyptian Vulture (*Neophron percnopterus*). This spectacular, globally Endangered species is present in the UAE only at Jebel Hafit, where it was finally confirmed to breed in 2017 (Williams et al. 2023). Its future at Jebel Hafit, despite the site having National Park status, remains uncertain. Photographer: Oscar Campbell

development on its immediate margins. In addition to the demise of their intrinsic conservation value, both sites represent missed opportunities in showcasing spectacular UAE natural history to large urban populations living in close proximity and to eco-tourists who visit for birdwatching. The admirable and highly successful efforts at sites such as Al Wathba Wetland Reserve (Abu Dhabi) and Khor Kalba, Wasit Nature Reserve and Wadi Shees (all Sharjah) notwithstanding, environmental education, both explicitly and by allowing people to simply visit and appreciate IBAs, is still a greatly underplayed aspect of conservation in the UAE.

To some extent, it is inevitable that the UAE faces major conservation challenges. The rapid increase in population, from less than 500,000 in 1971 to nearly 10 million in 2022 (Anon 2022a), has occurred overwhelmingly in coastal areas. The consequent impact on fragile coastal and island ecosystems and their birdlife has been enormous, and while somewhat ameliorated by the creation of new anthropogenic bird habitats, has been particularly challenging for specialist species whose native habitats have been degraded. At the same time, however, an understanding of the importance of conservation has become accepted as a key element of Government planning, at both the federal and local (Emirate) levels.

Although there is much work still to do, there are signs that things are moving in a positive direction. The national Red List Index generated by Burfield et al. (2021) indicates that, overall, there has been a slight improvement since 1996, which bucks the global trend and reflects the fact that there are 27 species whose status seems to have genuinely improved in the UAE between 1996 and 2019, compared to 18 species whose species has deteriorated. With regard to IBAs, overall the development-related pressure that they are under has declined slightly since 2006, partly caused by significantly increased conservation planning and action. Consequently, overall IBA state has improved somewhat (MoCCaE 2018).

Other welcome developments include announcements in early 2022 concerning the establishment of formal structures to protect and manage Umm Al Quwain's Khor al Beida and Siniyah Island and creation of an independent Fujairah Environment Authority, with a dedicated mandate. This suggests that significant progress in terms of conservation continues to be made. The Convention of Wetlands ('Ramsar Convention') is one example of a number of important conservation treaties to which the UAE has become signatory in recent years and the country now has ten Ramsar sites, six designated since 2017 (Anon 2022b). Abu Dhabi's hosting of the Conservation of Migratory Species Secretariat since 2009 and BirdLife International's Global Flyway's Summit in 2018 are just two further examples of how the UAE is increasingly taking conservation in general, and that of birds in particular, increasingly seriously.

15.7 Further Reading

A readable early summary of the UAE's avifauna is provided by Richardson (1990), updated by Pedersen and Aspinall (2010) and Pedersen et al. (2022). Data on breeding bird distribution and ecology was summarized by Aspinall (2010); Jennings (2010) eloquently and comprehensively puts the UAE's breeding avifauna into a regional context. Dean and Williams (2004) summarize bird adaptations to life in deserts, particularly larks, with examples from research undertaken in Saudi Arabia.

Acknowledgements The data and ideas outlined have been discussed over many years with many UAE birdwatchers, too numerous to mention. However, I gratefully acknowledge the contributions of Simon Lloyd, Tommy Pedersen and Mark Smiles. The latter, and the late Peter Hellyer, read drafts of this chapter and made many helpful suggestions. In addition, Mark Smiles assisted greatly with presentation of data.

References

Anon (2022a) CIA World Factbook—United Arab Emirates. https://www.cia.gov/the-world-factbook/countries/united-arab-emirates/. Accessed 1 June 2022

Anon (2022b) Ramsar—United Arab Emirates. https://www.ramsar.org/wetland/united-arab-emirates. Accessed 15 Mar 2022

Aspinall S (2010) Breeding birds of the United Arab Emirates. Environment Agency–Abu Dhabi, Abu Dhabi

Aspinall S, Hellyer P (2006) Important bird areas of the United Arab Emirates. Br Birds 99:546–561

Babbington J, Roberts P (2017) An update on the wintering status of Sociable Lapwings *Vanellus gregarius* in Saudi Arabia with a new wintering location in the Eastern province. Sandgrouse 39(2):172–176

Birdguides (2008) Birds of the Western Palearctic Interactive. DVD Version 2.1. Birdguides & Oxford University Press, UK

BirdLife International (2010) Spotlight on flyways. http://datazone.birdlife.org/sowb/spotFlyway. Accessed 15 Mar 2022

BirdLife International (2022a) http://datazone.birdlife.org/country/united-arab-emirates. Accessed 12 May 2022

BirdLife International (2022b) IUCN Red List for birds. http://www.birdlife.org. Accessed 12 May 2022

BirdLife International (2022c) Species factsheet: *Bulweria fallax*. http://www.birdlife.org. Accessed 12 May 2022

Boland C, Alsuhaibany A (2020) The birds of Saudi Arabia. Saudi Aramco & Motivate Media, Dubai

Brochet AL, Sharif J, Sheldon RD, Porter R, Jones VR, Al Fazari W, Al Saghier O, Alkhuzai S, Al-obeidi LA, Angwin R, Ararat K, Pope M, Shobrak MY, Willson MS, Zadegan SS, Butchart SHM (2019) A preliminary assessment of the scope and scale of illegal killing and taking of wild birds in the Arabian peninsula, Iran and Iraq. Sandgrouse 41:154–175

Brown GM (2009) Observations on the cooling behavior and associated habitat of four desert lark species (Alaudidae) in two areas of Kuwait. Sandgrouse 31(1):6–14

Bruderer B (1996) Nocturnal bird migration in Israel. In: Shirihai H (ed) The birds of Israel. Academic, London, pp 58–60

Burfield IJ, Westrip J, Sheldon RD, Hermes C, Wheatley H, Smith D, Harding KA, Allen DJ, Alshamsi O (2021) UAE National Red List of Birds. Ministry of Climate Change and Environment, Dubai, United Arab Emirates

Burt J (2014) The environmental costs of coastal urbanization in the Arabian Gulf. City Anal Urban Trends Cult Theory Policy Action 18:760–770. https://doi.org/10.1080/13604813.2014.962889

Callaghan CT, Martin JM, Kingsford RT, Brooks DM (2018) Unnatural history: is a paradigm shift of natural history in the 21st century ornithology needed? Ibis 160:475–480

Campbell O, Moran N (2016) Phenology of spring landbird migration through Abu Dhabi island, United Arab Emirates, 2007–2014. Sandgrouse 38:38–70

Campbell O, Smiles M (2018) Breeding Egyptian Nightjars in the UAE. British Birds 111:196–210

Campbell O, Smiles M (2019) Notable breeding records from a recently established anthropogenic, agricultural site in the United Arab Emirates. Sandgrouse 41(1):18–31

Campbell O, Smiles M (2021) A phenological analysis of spring and autumn bird migration through the United Arab Emirates. Sandgrouse 43(1):43–89

Campbell O, Smiles M, Roberts H, Judas J, Pedersen T (2017) Gulf of Oman: analysis of seabird records of boat trips from the east coast of the United Arab Emirates 2010–2016. Sandgrouse 39: 139–165

Campbell O, Al-Ali A, AlMazrouie M (2022) Significant breeding bird records from the United Arab Emirates from 2020 and 2021, including the first confirmed breeding record of Barn Swallow *Hirundo rustica*. Sandgrouse 44(1):175–185

Cowan PJ (2018) The unnatural history of desert birds in the Arabian peninsula. A review. Sandgrouse Suppl 4:113–117

Cowan PJ, Brown GM (2001) Prostrate desert gourd plants as apparent cooling sites for larks in the heat of the day. Sandgrouse 23:59–60

Dean WRJ (2004) Nomadic desert birds. Adaptations of desert. Organisms series. Springer, Berlin. 185 pp

Dean WRJ, Williams JB (2004) Adaptations of birds for life in deserts with particular reference to Larks (Alaudidae). Trans Roy Soc S Afr 59(2):79–91

De Marchi G, Chiozzi G, Fasola M (2008) Solar incubation cuts down parental care in a burrow nesting tropical shorebird, the Crab Plover *Dromas ardeola*. J Avian Biol 39(5):484–486

Dorofeev D, Campbell O (2017) From Russia with Love (or at least a ring): Kamchatka Great Knot reaches the Arabian Gulf! https://osme.org/2017/02/from-russia-with-love-or-at-least-a-ring-kamchatka-great-knot-reaches-the-arabian-gulf/. Accessed 12 May 2022

eBird (2022) United Arab Emirates. https://ebird.org/region/AE/hotspots. Accessed 12 May 2022

Eriksen J, Victor R (2013) Oman bird list edition 7. Centre for Environmental Studies and Research, Sultan Qaboos University, Muscat

Evans MI (ed) (1994) Important bird areas in the Middle East. BirdLife conservation series 2. BirdLife, Cambridge

Feulner GR, Roobas B, Hutchings V, Otto HHH, Campbell O, Roberts HGB, Hornby RJ, Howarth B (2021) Butterflies of the United Arab Emirates and Northern Oman. Motivate Media, Dubai

Hornby R, Aspinall S (1997) A Red Data List for the birds of the United Arab Emirates. Sandgrouse 19(2):102–110

Javed S, Khan S (2007) Satellite-tracking of Greater Flamingoes from the UAE. Phoenix 23:7

Javed S, Khan SB, Tourenq C, Launay F, Merrit J (2012) Nesting, distribution and conservation of the Crab Plover, *Dromas ardeola*, in the United Arab Emirates. Z Middle East 56(1):9–19

Javed S, García-Rawlins AM, Rodríguez RP, Sakkir S, Dhaheri SS (eds) (2020) The Abu Dhabi Red List of Species: An assessment of the conservation status of mammals, birds, reptiles, invertebrates and plants in Abu Dhabi Emirate. Environment Agency-Abu Dhabi, Provita and IUCN Species Survival Commission

Jennings M (2010) Atlas of breeding birds of Arabia. Fauna Arabia 25

Judas J, Robb MS, Miller E (2015) Omani owl at Wadi Wurayah, United Arab Emirates, in March 2015. Dutch Birding 37:334–336

Keijl GO, Ruiters PS, van der Have TM, bij de Vaate A, Marteijn ECL, Noordhuis R (1998) Waders and other waterbirds in the United Arab Emirates—autumn 1994 and spring 1995. WIWO-report 62, Foundation Working Group International Waterbird and Wetland Research, The Netherlands

Khan S, Javed S, Nazeer J (2007) Survey of breeding Osprey *Pandion haliaetus* in Abu Dhabi Emirate. Tribulus 17:77–79

Khan SB, Javed S, Ahmed S, Al Hammadi EA, Al Hammadi AA, Al Dhaheri S (2018) Does a recent surge in Socotra Cormorant *Phalacrocorax nigrogularis* nesting population and establishment of new breeding colonies ensure long term conservation? Pragmatic assessment of recent augmentation in Abu Dhabi Emirate, UAE. Bird Conserv Int 29(3):361–369

Khan SB, Ahmed S, Javed S (2020) Conservation status of birds in Abu Dhabi Emirate. In: Javed S et al (eds) The Abu Dhabi Red List of Species, an assessment of the conservation status of mammals, birds, reptiles, invertebrates and plants in Abu Dhabi Emirate. Environment Agency-Abu Dhabi, Provita and IUCN Species Survival Commission

Kosztolányi A, Javed S, Küpper C, Cuthill IC, Al Shamsi A, Székely T (2009) Breeding ecology of Kentish Plover *Charadrius alexandrinus* in an extremely hot environment. Bird Study 56(2): 244–252

McGrady M, Al Lamki F, Meyberg B, Spalton A (2019) Steppe eagles in Oman. http://steppeeaglesoman.blogspot.com/2019/03/migration-is-well-underway.html. Accessed 1 Feb 2022

MoCCaE (2018) Status of important bird areas (IBAs) in the UAE. Ministry of Climate Change and the Environment, Dubai, United Arab Emirates. https://www.moccae.gov.ae/assets/download/e6b95627/2018_Birds_IBS%20Report.pdf.aspx?view=true. Accessed 15 Mar 2022

Muzaffar SB, Whelan R, Clarke C, Gubiani R, Benjamin S (2017) Breeding population biology in Socotra cormorants (*Phalacrocorax nigrogularis*) in the United Arab Emirates. Waterbirds 40(1):1–10

Newton I (2010) Bird migration. Collins, London

Newton I, Ekner A, Walker D, Sparks TH (2010) The migration seasons of birds as recorded at Dungeness Bird Observatory in south east England. Ring Migrat 25:71–87

Pedersen T, Aspinall S (2010) Checklist of the Birds of the United Arab Emirates. Sandgrouse Suppl 3

Pedersen T, Aspinall SJ, Campbell OJ, Smiles MC (comp) (2022) EBRC Annotated Checklist of the birds of the United Arab Emirates. https://www.uaebirding.com/bird-checklists. Accessed 25 July 2023

Pope M, Zogaris S (eds) (2012) Birds of Kuwait—a comprehensive visual guide. KUFPEC & Biodiversity East, Cyprus

Richardson C (1990) The birds of the United Arab Emirates. Hobby, Warrington, UK

Shah JN, Khan SB, Ahmed S, Javed S, Hammadi A (2008) Sooty Falcon in the United Arab Emirates. Falco 32:16–19

Shirihai H (1996) The birds of Israel. Academic, London

Shirihai H, Gargallo G, Helbig A (2001) Sylvia Warblers. Christopher Helm & AC Black, London

Tøttrup AP, Klaassen RHG, Strandberg R, Thorup K, Kristensen MW, Jørgensen PS, Fox J, Afanasyev V, Rahbek C, Alerstam T (2011) The annual cycle of a trans-equatorial Eurasian–African passerine migrant: different spatio-temporal strategies for autumn and spring migration. Proc R Soc B 279:1008–1016

Tourenq C, Khassim A, Sawaf M, Shuriqi MK, Smart E, Ziolkowski M, Brook M, Selwan R, Perry L (2009) Characterisation of the Wadi Wurayah Catchment Basin, the first Mountain Protected Area in the United Arab Emirates. Int J Ecol Environ Sci 35:289–311

Williams JB, Tieleman BI (2005) Physiological adaptation in desert birds. BioScience 55(5): 416–425

Williams JB, Tieleman BI, Shobrak M (1999) Lizard burrows provide thermal refugia for larks in the Arabian desert. Condor 101:714–717

Williams NP, Quade S, Campbell O, Arras P (2023) The first confirmed nesting of Egyptian Vulture *Neophron percnopterus* in the United Arab Emirates. Sandgrouse 45(1):94–101

Chapter 16
Terrestrial Reptiles and Amphibians of the United Arab Emirates

Johannes Els, Salvador Carranza, and Andrew Gardner

16.1 Diversity and Distribution of Terrestrial Reptiles

With an estimated 11,940 reptile species globally (Uetz 2022), the Arabian Peninsula is home to 178 described species (Cox et al. 2012; Šmíd et al. 2021a, b). Within the UAE, 60 species of terrestrial reptiles have been recorded of which 57 are native, 3 introduced (alien species) and 1 is endemic to the country (Burriel-Carranza et al. 2019). Reptiles can be found in all habitat types of the UAE, with the highest diversity in the northeast of the country (Fig. 16.1). The Hajar Mountains in the UAE have 14 endemic species whose extent of occurrence is restricted to this mountain range that is shared between Oman and the UAE (Burriel-Carranza et al. 2022). Reptile species from the UAE are in the Order Squamata and comprise 14 families, including the Agamas (Agamidae), Typical Geckos (Gekkonidae), Leaf-toed Geckos (Phyllodactylidae), Semaphore Geckos (Sphaerodactylidae), Lizards (Lacertidae), Desert Worm Lizards (Trogonophidae), Skinks (Scincidae), Varanids (Varanidae), Boas (Boidae), Colubrid Snakes (Colubridae), Sand Snakes (Psammophiidae), Thread Snakes (Leptotyphlopidae), Blind Snakes (Typhlopidae), and Vipers (Viperidae). The agamas have six species from four genera, Typical Geckos eleven species from seven genera, Leaf-toed Geckos six species from two genera, Semaphore Geckos five species from two genera, Lizards ten species from three genera, Skinks six species from five genera, Colubrid Snakes five species from

J. Els (✉)
Environment and Protected Areas Authority, Breeding Centre for Endangered Arabian Wildlife, Sharjah, United Arab Emirates

S. Carranza
Institute of Evolutionary Biology (CSIC-Universitat Pompeu Fabra), Passeig Marítim de la Barceloneta, Barcelona, Spain

A. Gardner
Emirates Nature WWF, Dubai, United Arab Emirates

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_16

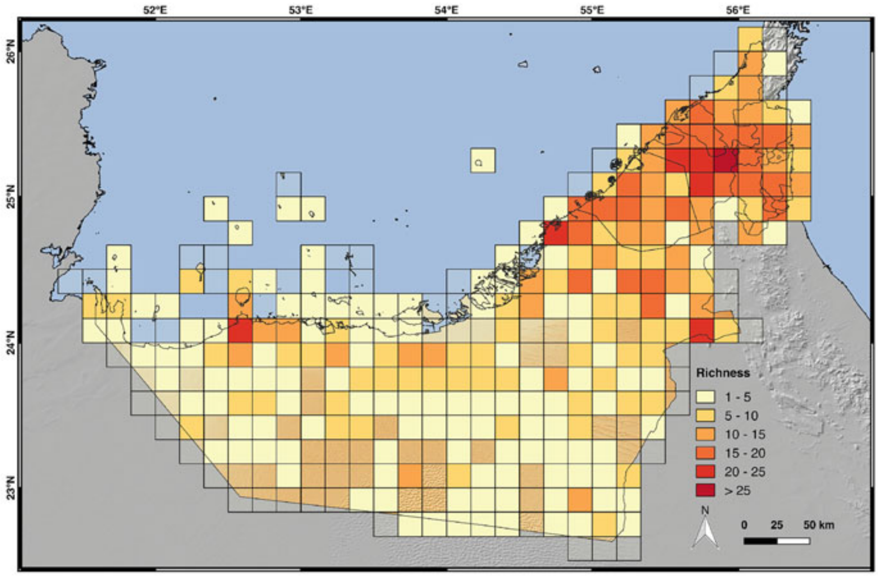


Fig. 16.1 UAE terrestrial reptile species richness by 10 arc-minutes grid cells inferred with occurrence point data Map source: Modified from Burriel-Carranza et al. (2019), reproduced under Creative Commons license (CC BY-SA-4.0)

four genera, Sand Snakes two species from two genera and Vipers four species from three genera. The families of Desert Worm Lizards, Varanids, Boas, Thread Snakes and Blind Snakes are comprised of one species each. All of the terrestrial reptile species within the UAE are harmless with the exception of the four venomous snakes, all vipers, which are of medical importance (Russell and Campbell 2015; Burriel-Carranza et al. 2019).

16.1.1 Agamas

There are six species from the family Agamidae in the UAE. All of the agama species are diurnal and occupy a wide range of habitats from coastal deserts, through the sandy interior deserts to the rocky Hajar Mountains and their surrounding gravel plains. They range in body size from 6–50 cm, from the small Toad-headed Agamas to the large and bulky Spiny-tailed Lizards. The Arabian Toad-headed Agama (*Phrynocephalus arabicus*) and Long-tailed Toad-head Agama (*Phrynocephalus longicaudatus*) are widely distributed in the arid areas of the UAE along both the coastal and inland deserts up to 300 m in elevation (Gardner 2013; Burriel-Carranza et al. 2019). Arabian Toad-headed Agamas (Fig. 16.2a) prefer habitats with soft desert sand and, as a defense mechanism, they will vibrate the body into the sand to conceal it from sight. Long-tailed Toad-headed Agamas are

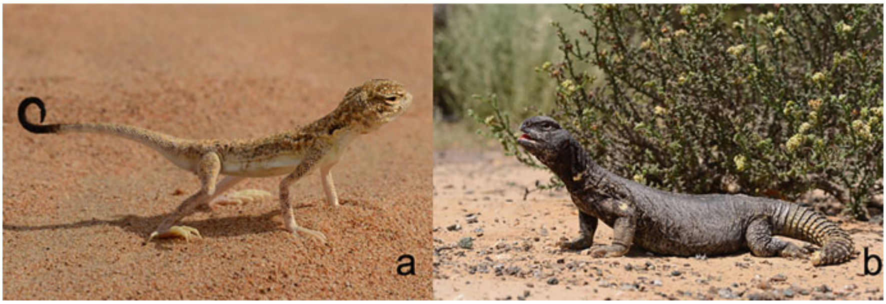


Fig. 16.2 (**a**) Arabian Toad-headed Agama; (**b**) Leptien's Spiny-tailed Lizard. Photo credit: Johannes Els (**a**, **b**)

found in habitats with more compact soil types in comparison with the Arabian Toad-headed Agamas, and rely on camouflage to avoid potential threats. Both species of Toad-headed Agamas have no external ear openings, the nostrils are positioned upwards and the eyes are encircled with large scales which function as a shield against the sand. Both species of Toad-headed Agamas feed on small insects and will lay 2–3 eggs per clutch during the summer.

The larger Yellow-spotted Agama (*Trapelus flavimaculatus*) is an Arabian endemic with a wide distribution across Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, UAE and Yemen (Sindaco and Jeremčenko 2008; Gardner 2013; Burriel-Carranza et al. 2019; Carranza et al. 2018, 2021). Yellow-spotted Agamas are less specialized than the Toad-head Agamas and occupy a variety of habitat types from the coast to inland sandy and gravel plains up to 400 m in elevation (Burriel-Carranza et al. 2019). Adults are brightly colored especially males with a blue head, throat and body covered in white spots and the tail is orange with dark bands. Contrasting to the adults, the hatchlings and juveniles are brown with white spots which most likely aid in camouflage from predators. Yellow-spotted Agamas feed on insects and other arthropods.

Among this group of agamas, the largest and bulkiest are the two subspecies of Spiny-tailed Lizards (*Uromastyx aegyptia*), known locally as '*dhub*', which have non-overlapping distributions (allopatric) and have different ecological preferences. Both of these subspecies can be found in bare areas with sand, but the Leptien's Spiny-tailed Lizard (*Uromastyx aegyptia leptieni*) is restricted to the northeast of the country from sea level up to 400 m in elevation in areas where annual precipitation is higher, while the Small-scaled Spiny-tailed Lizard (*Uromastyx aegyptia microlepis*) lives in the southwest of the country from sea level up to 200 m, tolerates higher temperatures, and lives in more arid areas (Burriel-Carranza et al. 2019). An Arabian endemic, Leptien's Spiny-tailed Lizard (Fig. 16.2b) is distributed across the north-eastern UAE, parts of the Hajar Mountains and the Batinah Plain in Oman (Gardner 2013; Burriel-Carranza et al. 2019, 2022; Carranza et al. 2018, 2021). The Small-scaled Spiny-tailed Lizard has a wide distribution across Arabia into Iraq, Jordan, Syria and coastal Iran (Gardner 2013; Sindaco and Jeremčenko 2008). Both subspecies of Spiny-tailed Lizard are herbivorous, feeding on a variety of plant species, but young individuals may consume invertebrates. Spiny-tailed Lizards have a thick tail covered with hard spiny scales which provide some protection from predators.

A rock habitat specialist, the Hajar Rock Agama (*Pseudotrapelus jensvindumi*) is restricted to the Hajar Mountains and surrounding gravel plains from sea level up to 1000 m in elevation in the UAE (Burriel-Carranza et al. 2019). This species is endemic to the Hajar Mountains which are shared between Oman and UAE, from Ras Al Hadd in the southeast of Oman to the Musandam Peninsula in the north (Tamar et al. 2016a, b, 2019; Carranza et al. 2021). Hajar Rock Agamas are abundant throughout their range, and both males and females are territorial. During the breeding season, mature males have a distinctive blue head and body, while the females have a brownish body with several orange or red spots. Hajar Rock Agamas feed on insects and can be active during the hottest periods of the day; when the surface of the rocks is too warm they will use their long thin legs to elevate the body off the surface to cool down, and if that fails they will retreat into the shade of rock crevices.

16.1.2 Geckos

Geckos in the UAE are the most diverse group of terrestrial reptiles, with 21 species from three families: Typical Geckos (Gekkonidae), Leaf-toed Geckos (Phyllodactylidae) and Semaphore Geckos (Sphaerodactylidae). All of the species are nocturnal with the exception of the Semaphore Geckos (*Pristurus*) which are mainly diurnal or both diurnal and nocturnal. Gecko species range in body size from the Small Semaphore Gecko (*Pristurus minimus*) of 3 cm to the large and robust 11-cm Wonder Gecko (*Teratoscincus keyserlingii*). Geckos are found throughout the UAE in both natural and man-made habitats (anthropogenic). The Baluch Ground Gecko (*Bunopus tuberculatus*), Rough Bent-toed Gecko (*Cyrtopodion scabrum*), Persian Gecko (*Hemidactylus persicus*), Red Sea House Gecko (*Hemidactylus robustus*), Arabian Web-footed Sand Gecko (*Trigonodactylus arabicus*), Dune Sand Gecko (*Stenodactylus doriae*), Eastern Sand Gecko (*Stenodactylus leptocosymbotes*) and Slevin's Sand Gecko (*Stenodactylus slevini*) are widespread in arid desert areas from sea level to 400 m in elevation (Gardner 2013; Burriel-Carranza et al. 2019). Yellow-bellied House Geckos (*Hemidactylus flaviviridis*) are an introduced (alien) species which is confined to urban areas and is widely distributed throughout the UAE (Burriel-Carranza et al. 2019), with its distribution expanding along with urban development (see Chap. 23). Rough Bent-toed Geckos (*Cyrtopodion scabrum*) and Red Sea House Geckos (*Hemidactylus robustus*) are also often associated with man-made habitats, where they can be more abundant than in their natural habitats.

The Hajar Banded Ground Gecko (*Trachydactylus hajarensis*), Leaf-toed Geckos (*Asaccus*), Fan-footed Geckos (*Ptyodactylus*) and Semaphore Geckos (*Pristurus*) are found at higher elevations with more precipitation in a wide spectrum of habitats, from vegetated to bare areas with gravel rock (Burriel-Carranza et al. 2019). The exception is the Small Semaphore Gecko (*Pristurus minimus*), which occupies both vegetated sandy and gravel rock habitats from sea level to 300 m in elevation (Gardner 2013; Burriel-Carranza et al. 2019). Rock Semaphore Geckos (*Pristurus rupestris*) and other members of this group are naturally found in the Hajar Mountains (Garcia-Porta et al. 2017), but the distribution of the Rock Semaphore Gecko has expanded beyond its natural range due to human intervention and they have colonized several coastal and inland urban areas over the last few decades (Burriel-Carranza et al. 2019).

Geckos in the UAE from the family Gekkonidae include the Baluch Ground Gecko (*Bunopus tuberculatus*), Rough Bent-toed Gecko (*Cyrtopodion scabrum*), Yellow-bellied House Gecko (*Hemidactylus flaviviridis*), Persian Gecko (*Hemidactylus persicus*), Red Sea House Gecko (*Hemidactylus robustus*), Gulf Sand Gecko (*Pseudoceramodactylus khobarensis*), Arabian Web-footed Sand Gecko (*Trigonodactylus arabicus*), Dune Sand Gecko (*Stenodactylus doriae*), Eastern Sand Gecko (*Stenodactylus leptocosymbotes*), Slevin's Sand Gecko (*Stenodactylus slevini*) and Hajar Banded Ground Gecko (*Trachydactylus hajarensis*).

The Baluch Ground Gecko, Rough Bent-toed Gecko, Dune Sand Gecko, Eastern Sand Gecko, Slevin's Sand Gecko and the Hajar Banded Ground Gecko are all ground-living species with slender toes without toepads. Most of the species are found in sandy habitats, with the exception of the Eastern Sand Gecko, which prefers compact soil types such as interdune gravel plain and those bordering the Hajar Mountains. Gulf Sand Geckos are found on moist, salt-impregnated to solid, salt-encrusted flats (sabkhas) and are often the only reptile species occupying such habitats (Gardner 2013; Metallinou et al. 2014; Carranza et al. 2018, 2021). To aid mobility in these moist and salt-encrusted habitats, the species is slender in comparison with the Dune Sand Gecko, and has long thin legs with 10–15 rows of sharply pointed scales beneath the toes. Endemic to the Hajar Mountains of Oman and UAE, the Hajar Banded Ground Gecko occupies rocky habitats with or without vegetation (de Pous et al. 2016a, b; Burriel-Carranza et al. 2019). All the other species in the UAE from this family are widely distributed across Arabia and are abundant within suitable habitats. The toes of the Yellow-bellied House Gecko, Persian Gecko and Red Sea House Gecko have adhesive pads (lamellae) which facilitate surface traction and enable them to climb; thus, they are not restricted within their habitats to the ground for sourcing food or reproduction, which can be beneficial for their survival. The smallest species in this family of geckos is the Arabian Web-footed Sand Gecko (Fig. 16.3a) which is widely distributed across the country, throughout most of Arabia and into Jordan (Pola et al. 2021), in soft sandy areas with dunes and scattered vegetation. Well adapted to its environment this small and slender gecko has webbing between its fingers on the forelimbs and fringes of pointed scales beneath toes of the hindlimbs which allows it to move with ease on the soft sand.

The gecko family Phyllodactylidae in the UAE consist of six species with restricted distribution ranges and all of which are endemic to the Hajar Mountains

Fig. 16.3 (**a**) Arabian Web-footed Sand Gecko, illustrating the webbing between the toes of this sand dweller; (**b**) Emirati Leaf-toed Gecko, the only endemic vertebrate of the UAE. Photo credit: Johannes Els (**a**, **b**)

of the UAE and Oman. This family includes the Leaf-toed Geckos (*Asaccus*), which have a pair of adhesive toe pads on each toe, and Fan-footed Geckos (*Ptyodactylus*) with a fan of numerous lamellae, and all are agile climbers moving with ease in rocky habitats. Females of the Leaf-toed Geckos have only one oviduct, and therefore always lay a single egg, although they can produce several eggs throughout the year. Fan-footed Geckos lay two eggs and communal nesting between individuals at the same location over a period of time is not uncommon. Both Leaf-toed Geckos and Fan-footed Geckos are nocturnal, but Fan-footed Geckos may also be encountered during the day in the shade of rock crevices. They feed on a variety of insect and other arthropod species.

The Emirati Leaf-toed Gecko (*Asaccus caudivolvulus*), Gallagher's Leaf-toed Gecko (*Asaccus gallagheri*), Gardner's Leaf-toed Gecko (*Asaccus gardneri*), Margarita's Leaf-toed Gecko (*Asaccus margaritae*), Orlov's Fan-footed Gecko (*Ptyodactylus orlovi*) and the Ruusaljibal Fan-footed Gecko (*Ptyodactylus ruusaljibalicus*) are all species within the family Phyllodactylidae. The only endemic vertebrate of the UAE is the Emirati Leaf-toed Gecko (Fig. 16.3b), which is found in isolated and fragmented coastal rocky habitats along the east coast at low elevations (Carranza et al. 2016; Burriel-Carranza et al. 2019; Carranza and Els 2021). This species is distinguished from all other Leaf-toed Geckos by the presence of tubercles on the upper arms. Gardner's Leaf-toed Gecko is widely distributed in the northern Hajar Mountains from around Harf Ghabi in the Musandam Peninsula, Oman, and further south into the UAE where it is frequently found at elevations between 100 and 600 m (Carranza et al. 2016; Burriel-Carranza et al. 2019). Margarita's Leaf-toed Gecko has isolated populations throughout the northern Hajar Mountains in the Musandam Peninsula, Oman, and further south to Wadi Al Helo in the UAE (Carranza et al. 2016; Burriel-Carranza et al. 2019). Further studies are required into the distribution of this species, but within the UAE it is known from lower elevation in the interior of mountains, and in the Musandam Peninsula it has been found at higher elevation between 1400 and 1500 m (Carranza et al. 2021). In all three species, (Emirati Leaf-toed Gecko, Gardner's Leaf-toed Gecko, Margarita's

Leaf-toed Gecko), the tail can be coiled and tip is laterally flattened and expanded vertically, and may be used to signal between individuals as a form of territorial display. Gallagher's Leaf-toed Gecko is the smallest species among the Leaf-toed Geckos, and these geckos are abundant and widespread throughout the Hajar Mountains, from Jebel Akhdar in Oman and further north through the UAE into the Musandam Peninsula (Carranza et al. 2018, 2021; Simó-Riudalbas et al. 2018). In the UAE, the Gallagher's Leaf-toed Geckos are found from sea level up to around 600 m in elevation (Burriel-Carranza et al. 2019). Gallagher's Leaf-toed Geckos is the only species of Leaf-toed Gecko in the UAE where there are visible differences between the males and females; males have a bright yellow tail with dark bands in comparison with white barred with black in females.

Orlov's Fan-footed Gecko is endemic to the Hajar Mountains of Oman and the UAE, but is absent from the Musandam mountains. In the UAE the species is found from sea level up to 1000 m in elevation. Ruusaljibal Fan-footed Gecko is endemic to the carbonate mountains of the Musandam Peninsula (Ruus Al Jibal) in Oman and its distribution extends south into the UAE towards Dibba (Simó-Riudalbas et al. 2017; Carranza et al. 2021). Within the UAE, the species has a limited distribution range and is frequently encountered from sea level up to 800 m in elevation (Burriel-Carranza et al. 2019). Orlov's Fan-footed Gecko and the Ruusaljibal Fan-footed Gecko are good examples of cryptic species (species morphologically very similar) well-differentiated genetically and geographically (present separated distributions).

The geckos of the family Sphaerodactylidae are the Carter's Semaphore Gecko (*Pristurus carteri*), Bar-tailed Semaphore Gecko (*Pristurus celerrimus*), Small Semaphore Gecko (*Pristurus minimus*), Rock Semaphore Gecko (*Pristurus rupestris*) and the Wonder Gecko (*Teratoscincus keyserlingii*). All of the species from this family within the UAE are diurnal, except for the Wonder Gecko which is strictly nocturnal, and are predominantly ground-dwelling with adhesive pads absent on the toes. As suggested by the name semaphore, these geckos use their tails as a form of visual communication between individuals of their own species by curling and waving it. Carter's Semaphore Geckos in the UAE are rarely encountered, and are restricted to a very small geographical area near the foothills of Jebel Hafeet which is divided by the political borders of Oman and UAE (Gardner 2013). The occurrence of the species in the UAE is considered the most northern distribution for this southern Arabian endemic, which is abundant and widely distributed in Oman with isolated populations in Yemen (Sindaco and Jeremčenko 2008; Carranza et al. 2021). Bar-tailed Semaphore Geckos are endemic to the Hajar Mountains, where their distribution extends from Jebel Akhdar, Oman, north through the UAE and into the Musandam Peninsula (Gardner 2013; Carranza et al. 2021; Burriel-Carranza et al. 2022). In the UAE the species is abundant throughout the Hajar Mountains and encountered from sea level up to 1400 m in elevation (Burriel-Carranza et al. 2019). Rock Semaphore Geckos (Fig. 16.4a) are widely distributed through the Hajar Mountains and surrounding lowland areas in Oman and UAE, with populations also on the southern coast of Iran (Garcia-Porta et al. 2017). Within the UAE, the distribution of the Rock Semaphore Geckos extends from the Hajar Mountains inland and along the Arabian Gulf coastline, including some of the

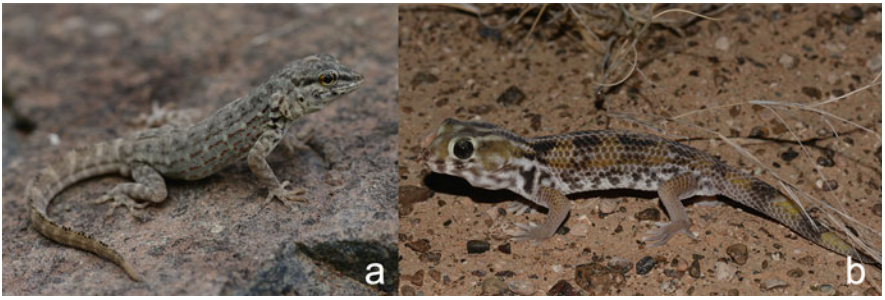


Fig. 16.4 (**a**) Rock Semaphore Gecko; (**b**) Wonder Gecko. Photo credit: Johannes Els (**a**, **b**)

offshore islands. It is abundant in both its natural rocky habitats within the Hajar Mountains, and in urban areas where it has colonized successfully. Rock Semaphore Geckos are encountered from sea level up to 1300 m in elevation (Burriel-Carranza et al. 2019).

The only Semaphore Gecko from the UAE which is absent from the Hajar Mountains is the Small Semaphore Gecko, which is found inland in sandy habitats with vegetation. Small Semaphore Geckos are less frequently encountered and are known to occur from sea level to up to 300 m in elevation (Burriel-Carranza et al. 2019). Its distribution extends from the UAE into Oman, Saudi Arabia and into eastern Yemen (Sindaco and Jeremčenko 2008; Carranza et al. 2021; Al Mutairi et al. 2023). Semaphore Geckos lay a single hard-shelled egg, with the exception of the much larger Carter's Semaphore Gecko which lays two eggs, and all species will reproduce multiple times throughout the year.

The largest species of the family Sphaerodactylidae is the Wonder Gecko (Fig. 16.4b), which is nocturnal and ground-dwelling, and within Arabia is known only from the UAE (Gardner 2013; Els et al. 2019a, b; Tamar et al. 2021). Wonder Geckos from the UAE are genetically similar to those populations found in coastal Iran from where the species distribution range extends further into Afghanistan and Pakistan (Tamar et al. 2021). Within the UAE, Wonder Geckos occur as isolated and severely fragmented populations due to urban development from Abu Dhabi northwards to Umm Al Quwain and inland towards Al Dhaid; they occur from sea level up to 200 m in elevation (Soorae et al. 2018; Burriel-Carranza et al. 2019; Els et al. 2019a, b). Wonder Geckos have been found in habitats with both sandy and compact soils with vegetation. It is a solitary species which takes refuge during the day in burrows. Females lay one or two large round eggs throughout the year. Wonder Geckos, as adults, are brightly colored, but as hatchlings and young animals are blackish with a less distinctive ground-color which may appear less conspicuous to predators and contribute to their survival.

16.1.3 Lizards

There are 11 species of lizards in the UAE, 10 species from the family Lacertidae and one species of desert worm lizards (family: Trogonophidae); the Zarudnyi's Worm Lizard (*Diplometopon zarudnyi*). The family Lacertidae include six species of Fringe-toed Lizards (*Acanthodactylus*), two species of Sand Lizards (*Mesalina*) and two species from the endemic genus *Omanosaura*. The Zarudnyi's Worm Lizard is widely distributed from sea level to 300 m in elevation through the interior dry and sandy deserts (Burriel-Carranza et al. 2019). In the UAE, Fringe-toed Lizard and Sand Lizard species are widely distributed in the dry deserts with sparse vegetation below elevation of 400 m. The Hajar Blue-tailed Lizard (*Omanosaura cyanura*) and Jayakar's Lizard (*Omanosaura jayakari*) are restricted to rocky habitats which are vegetated or poorly vegetated within the Hajar Mountains between 300 and 1200 m in elevation (Gardner 2013; Burriel-Carranza et al. 2019, 2022). In comparison with the Fringe-toed Lizards and Sand Lizards, both the Hajar Blue-tailed Lizard and Jayakar's Lizard occur in habitats that are cooler and wetter. All these lizard species are diurnal and ground-dwelling with females laying several eggs per clutch.

In the UAE, Blanford's Fringe-toed Lizard (*Acanthodactylus blanfordii*) is restricted to a small coastal habitat in Khor Kalba from sea level up to a 100 m in elevation (Burriel-Carranza et al. 2019). In Arabia, the species distribution extents from Khor Kalba in the UAE, south to Oman along the Batinah Plain around Muscat (Carranza et al. 2018, 2021). The species also occurs outside Arabia in Pakistan, southern Afghanistan and southeastern Iran (Sindaco and Jeremčenko 2008). Along the interior gravel plains on the southern slopes of the Hajar Mountains, Bosc's Fringe-toed Lizard (*Acanthodactylus boskianus*) occurs from 200 to 400 m in elevation in the UAE, and its distribution extends into Oman (Gardner 2013; Burriel-Carranza et al. 2019; Carranza et al. 2021). Bosc's Fringe-toed Lizards are found throughout Arabia, the Middle East into southwestern Iran and across most of North Africa (Sindaco and Jeremčenko 2008; Tamar et al. 2016a, b). Within the sandy interior habitats of the UAE, Saudi Fringe-toed Lizard (*Acanthodactylus gongrorhynchatus*) is widely distributed in scattered populations from the border of Saudi Arabia across to Abu Dhabi and Al Ain towards Dubai. Within the UAE, the Saudi Fringe-toed Lizard occur from sea level up to 400 m in elevation (Burriel-Carranza et al. 2019). It is an Arabian endemic, and the species distribution is only known from eastern Saudi Arabia and the UAE (Sindaco and Jeremčenko 2008). Haas's Fringe-toed Lizard (*Acanthodactylus haasi*) and the Snake-tailed Fringe-toed Lizard (*Acanthodactylus opheodurus*) are rare in the UAE, with very limited information available on their natural history and their extent of distribution is uncertain (Gardner 2013; Burriel-Carranza et al. 2019; Carranza et al. 2018, 2021). Haas's Fringe-toed Lizard is endemic to Arabia, and the Snake-tailed Fringe-toed Lizard is widely distributed across Arabia into Israel, Jordan and Iraq. The most abundant and widely distributed Fringe-toed Lizard in the UAE is Schmidt's Fringe-toed Lizard (*Acanthodactylus schmidti*), which occurs in almost all dry sandy habitats of the

Fig. 16.5 (**a**) Jayakar's Lizard, one of two species from the Hajar Mountains' of the endemic genus *Omanosaura*; (**b**) Zarudnyi's Worm Lizard, the only amphisbaenid species in the UAE. Photo credit: Johannes Els (**a**, **b**)

UAE. The species is not restricted to Arabia and the distribution extends into Jordan, southeast Iraq and southwestern Iran (Sindaco and Jeremčenko 2008). All of the Fringe-toed Lizards are distinguished from Sand Lizards by the presence of lateral fringes (a series of thin comb like scales) on the hind toes.

The Hadramaut Sand Lizard (*Mesalina adramitana*) is endemic to Arabia and is widely distributed across the UAE in sandy deserts and gravel plains, from sea level up to 400 m in elevation (Burriel-Carranza et al. 2019). The Short-snouted Sand Lizard (*Mesalina brevirostris*) is widely distributed within the UAE, but restricted to coastal habitats from sea level up to 200 m in elevation (Gardner 2013; Burriel-Carranza et al. 2019). Apart from the UAE, the species' distribution range extends across southeastern Saudi Arabia, Qatar, Kuwait into southwestern Iran (Šmíd et al. 2017).

Both the Hajar Blue-tailed Lizard (*Omanosaura cyanura*) and Jayakar's Lizard (*Omanosaura jayakari*) are endemic to the Hajar Mountains of Oman and UAE (Gardner 2013; Burriel-Carranza et al. 2019, 2022; Carranza et al. 2018, 2021). Recent genetic studies have shown that the Hajar Blue-tailed Lizards from the UAE and the Musandam Peninsula are very distinct from all the other populations, which suggests that they may represent a new cryptic species (Mendes et al. 2018). Jayakar's Lizards (Fig. 16.5a) are the largest species in the family Lacertidae in the UAE, with a body length of up to 20 cm. They feed mainly on insects, but Jayakar's Lizards are known to consume plant material and thus possibly aid seed dispersal.

The only amphisbaenid (a leg-less lizard) of the UAE is Zarudnyi's Worm Lizard (*Diplometopon zarudnyi*), a fossorial species which almost exclusively lives in soft sand, where they will surface at night for feeding or in search of a mate for breeding. Very little is known about the natural history of this relatively abundant species, which is distributed across the dry sandy desert habitats of the UAE. The species is widely distributed across Arabia, but absent from Yemen, and further northeast into Iraq and western Iran (Sindaco and Jeremčenko 2008; Gardner 2013; Burriel-Carranza et al. 2019; Carranza et al. 2021). Zarudnyi's Worm Lizards are adapted to their fossorial lifestyle with their undeveloped eyes protected beneath a colorless scale, and with an absence of external ear openings (Fig. 16.5b).

16.1.4 Skinks

There are six species of skinks from the family Scincidae: Asian Snake-eyed Skink (*Ablepharus pannonicus*), Ocellated Skink (*Chalcides ocellatus ocellatus*), Southern Grass Skink (*Heremites septemtaeniatus*), Arabian Sand Fish (*Scincus mitranus*), Blanford's Sand Skink (*Scincus conirostris*) and Tessellated Skink (*Trachylepis tessellata*). All of the UAE skink species are ground-dwelling and mainly diurnal, but during hot summer months it is not uncommon for them to exhibit activity for short periods after dusk. Asian Snake-eyed skink, Arabian Sand Skink and Tessellated skink lay small clutches of eggs (oviparous). Ocellated Skink (Fig. 16.6a) and Southern Grass Skink give birth to their young (viviparous). The Asian Snake-eyed Skink and Tessellated Skink are found in habitats with sparse vegetation and gravel rocks, from sea level to up a 1000 m in elevation in the Hajar Mountains (Gardner 2013; Burriel-Carranza et al. 2019). Endemic to southern Arabia, the distribution of the Tessellated Skink extends from the UAE across to Oman and into Yemen (Gardner 2013; Carranza et al. 2021). Ocellated Skinks are not native to the UAE and were introduced, presumably through activities related to horticulture; the origin of the Southern Grass Skink is questionable (Burriel-Carranza et al. 2019). Both species are associated with urban landscapes where the Ocellated Skink can be particularly abundant.

Abundant and widespread, the Arabian Sand Skink is found in dry sandy deserts at elevations below 400 m (Burriel-Carranza et al. 2019). The Arabian Sand Skink is endemic to Arabia, with its distribution range extending outside the UAE into Oman, Yemen, Saudi Arabia, Qatar, Kuwait and Bahrain (Šmíd et al. 2021a, b). Blanford's Sand Skink (Fig. 16.6b) is less abundant and prefers compact soils or gravel rock with sparse vegetation. Within the UAE, Blanford's Sand Skink is found along the Gulf of Oman coastline in Khor Fakkan and within several localities along the Arabian Gulf coastline, including on Sir Bani Yas Island (Gardner 2013; Burriel-

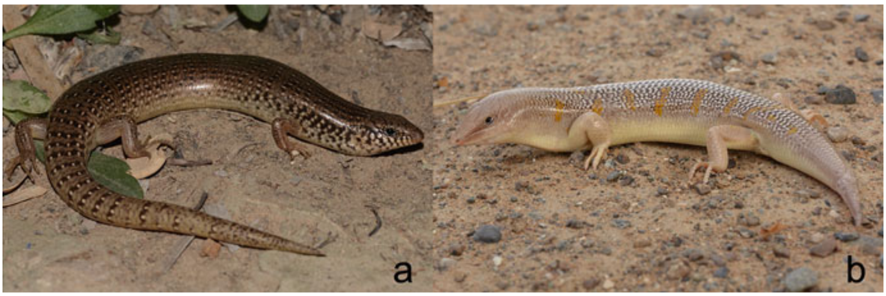


Fig. 16.6 (**a**) Ocellated Skink; (**b**) Blanford's Sand Skink. Photo credit: Johannes Els (**a**, **b**)

Carranza et al. 2019). Blanford's Sand Skinks were also recorded along the gravel plains bordering the Hajar Mountains with an increase in abundance from Al Dhaid southwards to Jebel Buhais. Due to their ability to dive into the sand and move with little effort, both species are collectively known as 'Sand Fish'.

16.1.5 Varanids

The Desert Monitor (*Varanus griseus*) is the only varanid species that occurs in the UAE, and it is widely distributed across most parts of the country in dry desert habitats below 300 m in elevation and where the annual precipitation is below 200 mm (Burriel-Carranza et al. 2019). The Desert Monitor (Fig. 16.7) is the largest lizard in the UAE with a body length of 56 cm with the tail up to 1.6 times longer than the body. A diurnal species which is mostly ground-dwelling, they can climb trees with ease using their powerful limbs and claws. They have a long-forked tongue which is used to detect prey, good vision and with the nostrils directed backwards towards the eyes. Desert Monitors are widely distributed across Arabia, through the Middle East and into North Africa, Central Asia and northern India (Geniez et al. 2004; Sindaco and Jeremčenko 2008; Gardner 2013). Arabia has two species of Varanids, the second being the endemic Yemen Monitor (*Varanus yemenensis*) from in southwestern Saudi Arabia and Yemen. Both species are taxonomically grouped within the Superfamily Anguimorpha and the family Varanidae.

Fig. 16.7 Desert Monitor. Photo credit: Johannes Els

16.1.6 Snakes

Within the UAE, snakes from the Suborder Serpentes are represented by 13 native species from 5 families, together with a single introduced species. These 14 species occupy a variety of habitats, but a few are specialists restricted to specific habitat types. The Arabian Sand Boa (*Eryx jayakari*), Crowned Leaf-nosed Snake (*Lytorhynchus diadema*) and Arabian Horned Viper (*Cerastes gasperettii gasperettii*) are adapted to live in sandy deserts and occupy areas with low annual rainfall. Others like the Hajar Saw-scaled Viper (*Echis omanensis*), Persian Horned Viper (*Pseudocerastes persicus*), Arabian Cat Snake (*Telescopus dhara*) and Wadi Racer (*Platyceps rhodorachis*) are restricted to the northeast of the country, including the Hajar Mountains, where they occupy rocky habitats with cooler temperatures and higher annual rainfall, and occur from sea level up to 1200 m. Hardwick's Racer (*Platyceps ventromaculatus*) is restricted to coastal areas on the offshore islands of the UAE. The introduced Brahminy Blind Snake (*Indotyphlops braminus*), is found only within urban areas. Schokari Sand Racer (*Psammophis schokari*) is a generalist that occupies coastal, interior sandy deserts and rocky mountain habitats.

Boas from the family Boidae are represented by two species in Arabia, the Arabian Sand Boa (*Eryx jayakari*) and Javelin Sand Boa (*Eryx jaculus*), but the former is the only species found within the UAE. The Arabian Sand Boa (Fig. 16.8a) is a small nocturnal and fossorial species reaching lengths of up to 62 cm. The nostrils and eyes of this fossorial species are positioned upwards, exposing only the eyes when in ambush. Arabian Sand Boas feed mainly on geckos and rodents, but are opportunistic and will predate on small birds feeding on the ground. Females lay a small clutch of eggs. It is widespread across the country from sea level up to 300 m in elevation in dry coastal and interior sandy desert habitats (Gardner 2013; Burriel-Carranza et al. 2019). Apart from the UAE, the distribution of the Arabian Sand Boa extends into Oman, Yemen, Saudi Arabia, Bahrain, Kuwait, and into southwest Khuzestan, Iran (Sindaco et al. 2013; Carranza et al. 2021).

The most species diverse group of snakes are within the family Colubridae, which includes the Crowned Leaf-nosed Snake (*Lytorhynchus diadema*), Wadi Racer (*Platyceps rhodorachis*), Hardwick's Racer (*Platyceps ventromaculatus*), Clifford's Diadem Snake (*Spalerosophis diadema cliffordii*) and Arabian Cat Snake (*Telescopus dhara*). Crowned-Leaf-nosed Snakes are abundant and widely distributed across the UAE in dry sandy deserts from sea level up to 300 m in elevation (Burriel-Carranza et al. 2019). In Arabia, the species is widely distributed with its distribution extending westwards throughout North Africa and eastwards to South and southwestern Iran (Sindaco et al. 2013; Carranza et al. 2021). It is a small, nocturnal and fossorial snake species that feeds mainly on geckos.

Wadi Racers are found throughout the Hajar Mountains, including the surrounding gravel plains from sea level up to 1200 m in elevation (Gardner 2013; Burriel-Carranza et al. 2019). A widely distributed species, its distribution range extends beyond Arabia into North Africa and Central Asia (Sindaco et al. 2013). It is a long and slender diurnal species, which feeds mainly on lizards, toads and fish, but as an

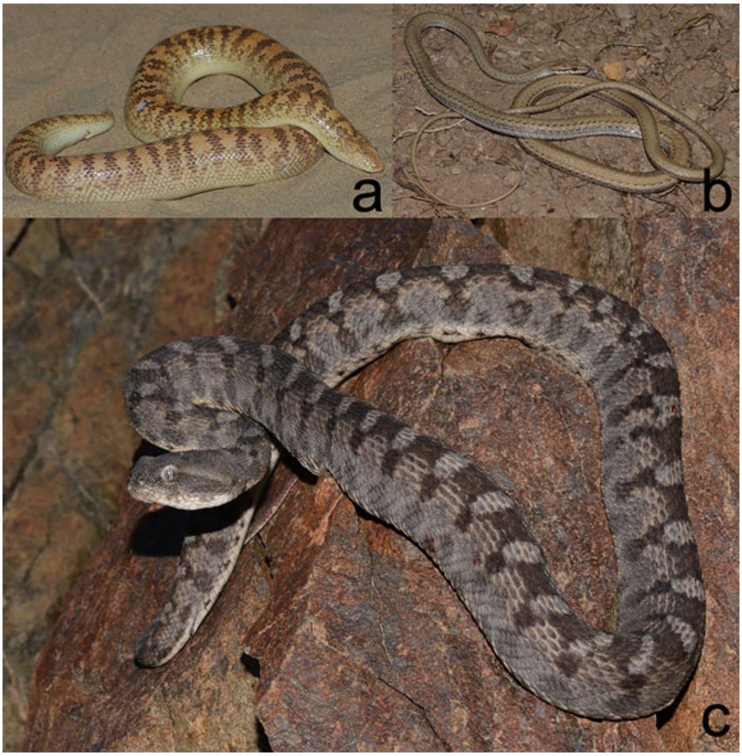


Fig. 16.8 (**a**) Arabian Sand Boa; (**b**) Schokari Sand Racer; (**c**) Hajar Saw-scaled Viper. Photo credit: Johannes Els (**a**–**c**)

opportunistic hunter, rodents and small birds are also taken. Hardwick's Racers were recorded only from the two small offshore islands located in the Arabian Gulf, Sir Bani Yas and Dalma (Gardner 2013). There are no records of the species on the mainland, although its distribution extends across Saudi Arabia, Bahrain, Kuwait, Iraq and Iran along the Arabian Gulf; and also known from Jordan, North India, Pakistan, Afghanistan and southeast Turkey (Whitaker and Captian 2007; Sindaco et al. 2013; Geniez 2018).

The largest member of this family is Clifford's Diadem Snake, a harmless species which is both diurnal and nocturnal. It occurs from sea level up to 500 m in elevation along the southern slopes of the Hajar Mountains and adjacent gravel plains, extending into sandy areas with compact soil (Gardner 2013; Burriel-Carranza et al. 2019). Widespread across Arabia, the species range extends into North Africa and into northwestern Iran. Within the UAE the species is frequently encountered around farms and cultivated areas where it preys on rodents and birds. A nocturnal species, the Arabian Cat Snake is found in rocky habitats at lower elevation throughout the Hajar Mountains, where it is less abundant in comparison with other areas of its distribution within Arabia (Gardner et al. 2010; Gardner 2013;

Burriel-Carranza et al. 2019; Carranza et al. 2021). Within Arabia the species is recorded from Oman, Yemen and Saudi Arabia; and northwards into western Jordan, Israel, Palestine and the Sinai Peninsula, Egypt. With a flat head, this species can climb and access rock crevices with ease to hunt geckos and lizards. Arabian Cat Snakes have rear grooved fangs and venom is injected while chewing on the prey. It is not considered dangerous to humans.

Both habitat generalists, the two species from the family Psammophiidae are the Schokari Sand Racer (*Psammophis schokari*) and Moila Snake (*Malpolon moilensis*). Schokari Sand Racers are widely distributed across the UAE from sea level up to 1000 m in elevation (Burriel-Carranza et al. 2019). Not restricted to Arabia, its distribution extends into North Africa and northwestern India (Gonçalves et al. 2018). This species occupies sandy deserts, gravel plains and rocky habitats with vegetation. Schokari Sand Racers (Fig. 16.8b) have also successfully occupied urban areas, with individuals often occupying an area for their entire life. Within these urban areas they will take advantage of the abundance of prey species such as the Ocellated Skinks, Yellow-bellied House Geckos, rodents and smaller bird species associated with human habitation. A diurnal species, Schokari Sand Racers are both ground-dwelling and arboreal (i.e. tree-dwelling), often using vegetation to thermoregulate by moving up or down within the vegetation. In the UAE, Moila Snakes were recorded from sea level up to 300 m in elevation within coastal and inland sandy deserts and the gravel plains bordering the Hajar Mountains, but the species is absent from the mountains and the Rub' al Khali sand desert (Burriel-Carranza et al. 2019). A widespread species, it is distributed across North Africa, into Arabia and eastwards into northwestern Iran (Sindaco et al. 2013). In comparison with the diurnal Schokari Sand Racer, the Moila Snake is active at dusk during the warmer seasons. Both species have venom to paralyze prey, which through a chewing motion are injected with grooved fangs position in the rear of the mouth. They are not considered dangerous to humans.

Slender Blind Snakes from the family Leptotyphlopidae have one species, Hooked Blind Snake (*Myriopholis macrorhyncha*), which is native to the UAE. The Brahminy Blind Snake (*Indotyphlops braminus*) from the family Typhlopidae is a global invader and restricted within the UAE to urban gardens. It is unusual in that all individuals are females, reproducing parthenogenetically. Both are harmless fossorial species, burrowing in the soil to re-surface during the night. The Hooked Blind Snake occurs from sea level up to 300 m in elevation in sandy deserts, and appears to be more abundant in the northeast of the country but may have been overlooked in surveys in the drier interior of the country (Burriel-Carranza et al. 2019). It is a widespread species ranging from East Africa across the Middle East into northwest Indian (Sindaco et al. 2013). A specialized feeder, it predates on termites and their eggs, as well as larvae and pupae from other insects. Similar to the Zarudnyi's Worm Lizard, this fossorial species has undeveloped eyes which are covered with a transparent scale.

The four species of medically important, terrestrial venomous snakes within the UAE are members of the family Viperidae. These are the Arabian Horned Viper (*Cerastes gasperettii gasperettii*), Sindh Saw-scaled Viper (*Echis carinatus* *sochureki*), Hajar Saw-scaled Viper (*Echis omanensis*) and Persian Horned Viper (*Pseudocerastes persicus*). All of these viper species, with the exception of the Persian Horned Viper which colonized the Hajar Mountains from Iran during the last glaciation (de Pous et al. 2016a, b), use their serrated scales on the side of the body to make a warning 'hiss' sound.

Arabian Horned Vipers are widely distributed across the nation in sandy habitats. Well adapted to arid environments, they also occupy areas with lower annual rainfall from which the Sindh Saw-scaled Viper is absent. It has been recorded throughout Arabia, into Jordan, Iraq and northwestern Iran (Sindaco et al. 2013; Carranza et al. 2021). The name is misleading as not all individuals of this species have a single-scale horn above each eye. The reasons why some individuals have horns and others not are still largely unknown. The Arabian Horned Viper is adapted to sandy deserts, through which it moves with ease using sidewinding movements, and it can burry itself into the sand to ambush prey such as rodents, geckos, lizards and birds. Exclusively a ground-dweller, it is a weak climber, thus the species will not be encountered higher up in vegetation. Arabian Sand Vipers are mainly nocturnal, but during the cooler season they are often active in the early mornings when they bask in the sun. Sindh Saw-scaled Vipers are found in vegetated sandy areas and gravel plains, and are particular abundant and successful colonizers of cultivated and urban gardens where they take advantage of the abundance of both prey and water. This species occurs in the northeast of the country at lower elevation with higher annual rainfall, but is absent in the Hajar Mountains (Burriel-Carranza et al. 2019, 2022). This Arabian subspecies is found only in Oman and UAE; outside of this range the species was also recorded from Iran, North India, Bangladesh, Pakistan, South Afghanistan, and Iraq (Sindaco et al. 2013). This viper is mainly active after dusk, and females give birth to 5–11 young. The young of Sindh Saw-scaled Vipers feed on invertebrates and as they mature, progress to larger prey such as geckos and rodents.

Endemic to the Hajar Mountains of Oman and UAE, the Hajar Saw-scaled Viper (Fig. 16.8c) is also known, in error, as the Oman Carpet Viper due to earlier misconception that the species distribution was restricted only to the mountains in Oman. In the UAE it is widely distributed throughout the Hajar Mountains, from sea level up to 1000 m in elevation (Burriel-Carranza et al. 2019). Within its rocky mountainous habitat this species is relatively abundant, especially around areas with permanent surface water. It is frequently encountered within the many cultivated areas found throughout its distribution range. Primarily nocturnal, it may also be seen in daylight hours during the cooler season. Hajar Saw-scaled Vipers feed on toads, which are in abundance within most of its distribution range, but being an opportunistic predator, it will also feed on lizards, rodents and birds. The Persian Horned Viper is both nocturnal and diurnal, and is found within the rocky habitats of the Hajar Mountains from sea level up to 1400 m within the UAE (Burriel-Carranza et al. 2019). In comparison with the Arabian Horned Viper, which have a single scale-horn above each eye, the Persian Horned Vipers have horns made from several scales. Variable in body color, individuals of this species matches the color of the surrounding rocks in their habitat. Unique to the Persian Horned Viper, females will lay clutches of 11–21 eggs in an advanced stage of development which hatch after 29–30 days (Phelps 2010), compared to the typical incubation period of 60–80 days in other egg laying snake species.

16.2 Diversity and Distribution of Amphibians

The only amphibians occurring in the UAE are the Arabian Toad (*Sclerophrys arabica*) and Dhofar Toad (*Duttaphrynus dhufarensis*) from the frog family Bufonidae (Gardner 2013; Soorae et al. 2013; Burriel-Carranza et al. 2022). Both species have restricted distribution ranges within the UAE, and are confined to the Hajar Mountains and surrounding gravel plains where surface water is available.

The Arabian Toad (Fig. 16.9) is endemic to Arabia, and is abundant throughout most of its distribution range. In areas with permanent water, the species can be found in large numbers and is active during both the day and night. Mostly nocturnal, the Dhofar Toad is well adapted to arid environments. Dhofar Toads may not be noticed during the drier seasons of the year, until the first rains when they congregate in large numbers to spawn in seasonal water bodies. During these dry periods, Dhofar Toads seek shelter deep within rock crevices or in burrows where the soil has higher moister content, and while in a state of inactivity (aestivation) their body is protected by a slimy coat to prevent dehydration. Outside of their natural distribution range, the Arabian Toad is found within agricultural areas, which have increased its distribution within the UAE. In surveys, the chytrid fungus which has caused declines in many amphibian populations globally, has not been detected in either species in the UAE (Soorae et al. 2013).

Fig. 16.9 Arabian Toad. Photo credit: Johannes Els

16.3 Importance of Reptiles and Amphibians in Ecosystems

Within the arid habitats of the UAE, where overall vertebrate species richness is relatively low, reptiles have adapted to these challenging environmental conditions through modifications in their physiology and behaviors. Their ability to adapt to their environment has resulted in reptiles being one of the most diverse vertebrate groups in these arid ecosystems. In addition to higher diversity, some species also have large populations, providing a vital role in the overall functioning of the ecosystem they occupy.

Semaphore Geckos, which are the most abundant terrestrial vertebrate in the Hajar Mountains, prey on small insects that may harm crops and, therefore, act as a natural source of pest control. Within urban areas, gecko species such as the Rough Bent-toed Gecko, Yellow-bellied House Gecko and Red Sea House Gecko are often noticed at night near lights preying on insects, which may also aid in controlling vector-borne diseases transmitted by mosquitos. Larger ground dwelling species, like the Dune Sand Gecko, predate grasshoppers which, depending on their abundance, can pose a threat to cultivated areas. Snakes such as the Arabian Horned Viper predate on rodent species (Fig. 16.10), aiding in controlling population numbers. Clifford's Diadem Snakes and Sand Racers are often found within human habitation and predate on feral rodents, which in cultivated areas can cause significant damage to crops. Apart from being predators in the food-web, they are also a source of food for smaller carnivores and birds.

The importance of reptiles in desert ecosystems is often overlooked. For example, the Spiny-tailed Lizards and Jayakar's Lizards which consume plant material and potentially contribute to seed dispersal in the absence of larger herbivores. Some studies have shown that seeds which pass through the guts of lizards had improved germination rates compared to seeds not consumed by lizards. Parasitic species also have an important function in many ecosystems, and Arabian reptiles are also hosts

Fig. 16.10 Arabian Horned Viper eating a Cheesman's Gerbil (*Gerbilus cheesmani*). Photo credit: Johannes Els

to these parasites (Maia et al. 2016; Tomé et al. 2021). In a recent study it was discovered that the Sindh Saw-scaled Viper is the host for the tape worm species *Ophiotaenia echidis* (de Chambrier et al. 2021). Amphibian species may also host parasites and be intermediate hosts in the life cycle of some parasites between the aquatic and terrestrial environment. Similar to many of the reptile species, adult Arabian Toads feed on insects, thus aiding in controlling insect populations. They are also a source of food in both the terrestrial and freshwater aquatic ecosystem as tadpoles, which are eaten by larger carnivorous aquatic invertebrates.

16.4 Threats and Conservation of Reptiles and Amphibians

Habitat loss and fragmentation of ranges caused by urban development is the greatest threat to UAE reptiles and amphibians, especially for species with restricted distributions. Snakes in general are affected by persecution, even though most are harmless to humans and may be beneficial in controlling pest species. Amphibian species, although abundant and adapted to arid environments, are affected in parts of their range by the over-utilization of freshwater by agriculture, which may disrupt their reproductive cycles. By default, the network of several protected areas across the country has provided protection to the majority of the widespread species (Burriel-Carranza et al. 2019; Cox et al. 2022), although habitat-specialists with limited ranges, often remain at risk and require protection within the areas they occupy.

Very few conservation efforts in the UAE have focused on reptiles. The first regional Red List for the reptiles of Arabia was completed in 2012, followed by the UAE National Red List in 2019, where conservation priorities were set to determine which species were at risk of extinction. The UAE endemic Emirati Leaf-toed Gecko, with its restricted distribution range along the East coast and severe degradation of its habitat due to development, was assessed both on a national and globally level as 'Critically Endangered' (Carranza et al. 2021). This species is still at the epicenter of several conservation efforts, which include establishing a Key Biodiversity Area and providing special protection to this unique vertebrate of the UAE.

The Wonder Gecko was assessed globally as 'Least Concern' (Els et al. 2019a, b), but due to its limited distribution range within Arabia which is threatened by development, the species was assessed regionally as 'Endangered' (Cox et al. 2012). The continued decline and fragmentation of populations alarmed conservationists, which resulted in the first reptile-specific Conservation Action Plan nationally (Soorae et al. 2018). Subsequently, the conservation status of the Wonder Gecko was nationally assessed in 2017 and 2019 as 'Critically Endangered' (Soorae et al. 2018; Els et al. 2019a, b). As part of several conservation efforts, which included studies on the genetic variability between fragmented populations, the Misnad Protected Area in the Emirates of Sharjah was established to protect this species within its natural habitat.

16.5 Conclusion

Among the resident terrestrial vertebrate fauna of the UAE, reptiles are the most species-rich group and can be found in all terrestrial habitat types, where they are essential components of the ecosystems and the food webs that they occupy. Through physiological and behavioral adaptations, reptiles were able to colonize much of the UAE despite the natural pressures imposed by the arid and thermally variable environment. Unfortunately, several reptile populations have declined recently due to urban development and related threats that have caused populations to become highly fragmented. Some species are habitat specialists, while others are generalists that have been able to colonize urban environments and live in close proximity to humans. Ongoing conservation efforts in various forms have ensured that reptiles are provided with protection, ensuring their survival for future generations.

16.6 Further Reading

For detailed accounts on the distribution of UAE reptiles see Burriel-Carranza et al. (2019). Information related to conservation of the two Critically Endangered reptile species see Tamar et al. (2021) and Carranza et al. (2016). See Šmíd et al. (2021a, b) for an overview of the regional distribution patterns of reptile species included in this chapter within Arabia. Species accounts related to amphibians see Burriel-Carranza et al. (2022), Gardner (2013) and Soorae et al. (2013).

References

Al Mutairi M, Alqahtani A, Mir ZR, Ahmad R, Alsubaie S, Smith M (2023) A new distribution record of Arnold's Gecko *Pristurus minimus* (Arnold 1977) (Squamata Sphaerodactylidae) in Saudi Arabia. Biodivers Data J 11. https://doi.org/10.3897/BDJ.11.e101647

Burriel-Carranza B, Tarroso P, Els J, Gardner A, Soorae P, Mohammed AA, Tubati SRK, Eltayeb MM, Shab JN, Tejero-Cicuéndez H, Simó-Riudalbas M, Pleguezuelos JM, Fernández-Guiberteau D, Šmíd J, Carranza S (2019) An integrative assessment of the diversity, phylogeny, distribution, and conservation of the terrestrial reptiles (Sauropsida, Squamata) of The United Arab Emirates. PLoS One 14(5):e0216273. https://doi.org/10.1371/journal.pone.0216273

Burriel-Carranza B, Els J, Carranza S (2022) Reptiles and amphibians of the Hajar Mountains. Consejo Superior de Investigaciones Científicas, Madrid, p 20. http://libros.csic.es/product_info.php?products_id=1605&language=en

Carranza S, Els J (2021) *Asaccus caudivolvulus*. The IUCN Red List of threatened species 2021:e. T125056608A125056621. https://doi.org/10.2305/IUCN.UK.2021-2.RLTS.T125056608A125056621.en

Carranza S, Simó-Riudalbas M, Jayasinghe S, Wilms T, Els J (2016) Microendemicity in the northern Hajar Mountains of Oman and The United Arab Emirates with the description of two new species of geckos of the genus *Asaccus* (Squamata: Phyllodactylidae). Peer J 4:e2371

Carranza S, Xipell M, Tarroso P, Gardner A, Arnold EN, Robinson MD, Simó-Riudalbas M, Vasconcelos R, de Pous P, Amat F, Šmíd J, Sindaco R, Metallinou M, Els J, Pleguezuelos JM, Machado L, Donaire D, Martínez G, Garcia-Porta J, Mazuch T, Wilms T, Gebhart J, Aznar J, Gallego J, Zwanzig BM, Fernández-Guiberteau D, Papenfuss T, Al Saadi S, Alghafri A, Khalifa S, Al Farqani H, Bilal SB, Alzari IS, Al Adhoobi AS, Al Omairi ZS, Al Shariani M, Al Kiyumi A, Al Sariri T, Al Shukaili AS, Al Akhzami SN (2018) Diversity, distribution and conservation of the terrestrial reptiles of Oman (Sauropsida, Squamata). PLoS One 13:e0190389

Carranza S, Els J, Burriel-Carranza B (2021) A field guide to the reptiles of Oman Consejo. Superior de Investigaciones Científicas, Madrid, p 223. http://libros.csic.es/product_info.php?products_id=1558

Cox NA, Mallon D, Bowles P, Els J, Tognelli MF (2012) The conservation status and distribution of reptiles of the Arabian Peninsula. IUCN and Sharjah UAE Environment and Protected Areas Authority, Cambridge UK and Gland Switzerland

Cox N, Young BE, Bowles P, Fernandez M, Marin J, Rapacciuolo G, Böhm M, Brooks TM, Blair Hedges S, Hilton-Taylor C, Hoffmann M, Jenkins RKB, Tognelli MF, Alexander GJ, Allison A, Ananjeva NB, Auliya M, Avila LJ, Chapple DG, Cisneros-Heredia DF, Cogger HG, Colli GR, de Silva A, Eisemberg CC, Els J, Fong GA, Grant TD, Hitchmough RA, Iskandar DT, Kidera N, Martins M, Meiri S, Mitchell NJ, Molur S, de Nogueira CC, Ortiz JC, Penner J, Rhodin AGJ, Rivas GA, Rödel M, Roll U, Sanders KL, Santos-Barrera G, Shea GM, Spawls S, Stuart BL, Tolley KA, Trape J, Vidal MA, Wagner P, Wallace BP, Xie Y (2022) A global reptile assessment highlights shared conservation needs of tetrapods. Nature 1:6. https://doi.org/10.1038/s41586-022-04664-7

de Chambrier A, Alves PV, Schuster RK, Scholz T (2021) *Ophiotaenia echidis* n sp (Cestoda: Proteocephalidae) from the sawscaled viper, *Echis carinatus sochureki* Stemmler (Ophidia: Viperidae), one of the world's deadliest snakes, from The United Arab Emirates. Int J Parasitol 14:341–354. https://doi.org/10.1016/j.ijppaw.2021.03.006

de Pous P, Machado L, Metallinou M, Červenka J, Kratochvíl L, Paschou N, Mazuch T, Šmíd J, Simó-Riudalbas M, Sanuy D, Carranza S (2016a) Taxonomy and biogeography of *Bunopus spatalurus* (Reptilia; Gekkonidae) from the Arabian Peninsula. J Zool Syst Evol Res 54(1):67–81. https://doi.org/10.1111/jzs.12107

de Pous P, Simo-Riudalbas M, Els J, Jayasinghe S, Amat F, Carranza S (2016b) Phylogeny and biogeography of Arabian populations of the Persian Horned Viper *Pseudocerastes persicus* (Duméril Bibron & Duméril 1854). Zool Middle East 62:231–238

Els J, Allen D, Hilton-Taylor C, Harding K (2019a) UAE National Red List of Herpetofauna: amphibians and terrestrial reptiles, sea snakes and marine turtles. Ministry of Climate Change and Environment, Dubai

Els J, Gardner A, Carranza S, Soorae P, Papenfuss T, Bafti S (2019b) *Teratoscincus keyserlingii*. The IUCN Red List of threatened species 2019:eT164620A1062064. https://doi.org/10.2305/IUCN.UK.2019-2.RLTS.T164620A1062064.en

Garcia-Porta J, Simó-Riudalbas M, Robinson M, Carranza S (2017) Diversification in arid mountains: biogeography and cryptic diversity of *Pristurus rupestris rupestris* in Arabia. J Biogeogr 44(8):1694–1704. https://doi.org/10.1111/jbi.12929

Gardner AS (2013) The amphibians and reptiles of Oman and the UAE. Frankfurt am Main, Chimaira, p 480

Gardner AS, Tovey N, Els J (2010) The Arabian cat snake (*Telescopus dhara* (Forskal, 1775)): a new species record for the UAE, with notes on the species in Oman. Tribulus 18

Geniez P (2018) Snakes of Europe. Princeton University Press, North Africa and the Middle East, p 379

Geniez P, Mateo JA, Geniez M, Pether J (2004) The amphibians and reptiles of Western Sahara. Frankfurt am Main, Chimaira, p 229

Gonçalves DV, Martínez-Freiría F, Crochet PA, Geniez P, Carranza S, Brito JC (2018) The role of climatic cycles and trans-Saharan migration corridors in species diversification: biogeography of *Psammophis schokari* group in North Africa. Mol Phylogenet Evol 118:64–74. https://doi.org/10.1016/j.ympev.2017.09.009

Maia JP, Harris DJ, Carranza S, Gómez-Díaz E (2016) Assessing the diversity, host-specificity and infection patterns of apicomplexan parasites in reptiles from Oman, Arabia. Parasitology 143(13):1730–1747. https://doi.org/10.1017/S0031182016001372

Mendes J, Salvi D, Harris DJ, Els J, Carranza S (2018) Hidden in the Arabian Mountains: multilocus phylogeny reveals cryptic diversity in the endemic *Omanosaura* lizard. J Zool Syst Evol Res 1:13. https://doi.org/10.1111/jzs12210

Metallinou M, Vasconcelos R, Šmíd J, Sindaco R, Carranza S (2014) Filling in the gap: two new records and an updated distribution map for the Gulf Sand gecko *Pseudoceramodactylus khobarensis* Haas 1957. Biodivers Data J 2(1):1–10. https://doi.org/10.3897/BDJ.2.e4011

Phelps T (2010) Old world vipers. In: A natural history of the Azemiophinae and Viperinae. Frankfurt am Main, Chimaira, p 55

Pola L, Hejduk V, Zíka A, Winkelhöfer T, Šmíd J, Carranza S, Shobrak M, Abu Baker M, Amr ZS (2021) Small and overlooked: phylogeny of the genus *Trigonodactylus* (Squamata: Gekkonidae), with the first record of *Trigonodactylus arabicus* from Jordan. Saudi J Biol Sci 28(6):3511–3516. https://doi.org/10.1016/j.sjbs.2021.03.019

Russell FE, Campbell JR (2015) Venomous terrestrial snakes of the Middle East. Frankfurt am Main, Chimaira, p 186

Simó-Riudalbas M, Metallinou M, de Pous P, Els J, Jayasinghe S, Pentek-Zakar E, Wilms T, Al-Saadi S, Carranza S (2017) Cryptic diversity in *Ptyodactylus* (Reptilia: Gekkonidae) from the northern Hajar Mountains of Oman and The United Arab Emirates uncovered by an integrative taxonomic approach. PLoS One 12(8):e0180397. https://doi.org/10.1371/journal.pone.0180397

Simó-Riudalbas M, Tarroso P, Papenfuss T, Al-Sariri T, Carranza S (2018) Systematics, biogeography and evolution of *Asaccus gallagheri* (Squamata, Phyllodactylidae) with the description of a new endemic species from Oman. Syst Biodivers 16(4):323–339. https://doi.org/10.1080/14772000.2017.1403496

Sindaco R, Jeremčenko VK (2008) The reptiles of the Western Palearctic, vol 1. Edizioni Belvedere, Latina, p 579

Sindaco R, Venchi A, Grieco C (2013) The reptiles of the Western Palearctic, vol 2. Edizioni Belvedere, Latina, p 543

Šmíd J, Moravec J, Gvoždík V, Štundl J, Frynta D, Lymberakis P, Kapli P, Wilms T, Schmitz A, Shobrak M, Yousefkhani SH, Rastegar-Pouyani E, Castilla AM, Els J, Mayer W (2017) Cutting the Gordian Knot: phylogenetic and ecological diversification of the *Mesalina brevirostris* species complex (Squamata, Lacertidae). Zool Scr:1–16. https://doi.org/10.1111/zsc.12254

Šmíd J, Sindaco R, Shobrak M, Busais S, Tamar K, Aghova T, Simo-Riudalbas M, Tarroso P, Geniez P, Crochet T, Els J, Burriel-Carranza B, Tejero-Cicuendez H, Carranza S (2021a) Diversity patterns and evolutionary history of Arabian squamates. J Biogeogr 48:1183–1199. https://doi.org/10.1111/jbi.14070

Šmíd J, Uvizl M, Shobrak M, Salim AFA, AlGethami RHM, Algethami AR, Alanazi ASK, Alsubaie SD, Busais S, Carranza S (2021b) Swimming through the sands of the Sahara and Arabian deserts: phylogeny of sandfish skinks (Scincidae, *Scincus*) reveals a recent and rapid diversification. Mol Phylogenet Evol 155:107012. https://doi.org/10.1016/j.ympev.2020.107012

Soorae P, Els J, Gardner D, El Alqamy H (2013) Distribution and ecology of the Arabian and Dhofar toads (*Duttaphrynus arabicus* and *D. dhufarensis*) in The United Arab Emirates and adjacent areas of northern Oman. Zool Middle East 59:229–234

Soorae PS, Mohamed AA, Els J, O'Donovan D, Pedo V Jr, Alzahlawi N, Jones BW, Molur S (2018) Wonder Gecko conservation action plan. December 2017 workshop report. Environment Agency – Abu Dhabi and Conservation Planning Specialist Group, p 47

Tamar K, Scholz S, Crochet PA, Geniez P, Meiri S, Schmitz A, Wilms T, Carranza S (2016a) Evolution around the Red Sea: systematics and biogeography of the agamid genus

Pseudotrapelus (Squamata: Agamidae) from North Africa and Arabia. Mol Phylogenet Evol 97:55–68. https://doi.org/10.1016/j.ympev.2015.12.021

Tamar K, Carranza S, Sindaco R, Moravec J, Trape JF, Meiri S (2016b) Out of Africa: phylogeny and biogeography of the widespread genus *Acanthodactylus* (Reptilia: Lacertide). Mol Phylogenet Evol 103:6–18. https://doi.org/10.1016/j.ympev.2016.07.003

Tamar K, Chirio L, Shobrak M, Busais S, Carranza S (2019) Using multilocus approach to uncover cryptic diversity within *Pseudotrapelus* lizards from Saudi Arabia. Saudi J Biol Sci 26(7):1442–1449. https://doi.org/10.1016/j.sjbs.2019.05.006

Tamar K, Els J, Kornilios P, Soorae P, Tarroso P, Thanou E, Pereira J, Shah JN, Elhassan EEM, Aguhob JC, Badaam SF, Eltayeb ME, Pusey R, Papenfuss TJ, Macey JR, Carranza S (2021) The demise of a wonder: evolutionary history and conservation assessments of the Wonder Gecko *Teratoscincus keyserlingii* (Gekkota, Sphaerodactylidae) in Arabia. PLoS One 16(1):e0244150. https://doi.org/10.1371/journal.pone.0244150

Tomé B, Maia J, Perera A, Carranza S, Vasconcelos R (2021) Parasites in a hotspot: diversity and specificity patterns of apicomplexans infecting reptiles from the Socotra Archipelago. Parasitology 148(1):42–52. https://doi.org/10.1017/S0031182020002000

Uetz P (ed) (2022) The reptile database. http://www.reptile-database.org. Accessed 28 Dec 2022

Whitaker R, Captian A (2007) Snakes of India. Draco Books, Chennai, p 481

Chapter 17
Terrestrial Arthropod Diversity in the United Arab Emirates

Brigitte Howarth

17.1 Introduction

Arthropods belong to the group of animals that don't have a backbone, otherwise known as invertebrates. The lack of a backbone means that there is no internal skeleton to support their tissues, which is why arthropods have an outer shell known as an exoskeleton. The outer shell can be hard, as with some beetles, but in other cases it is soft, as in springtails. Arthropods also have jointed, or articulated, legs. The modern Latin word 'Arthropoda' has its origins in Greek, combining the word 'arthron', meaning 'joint', with the word 'pous' meaning 'foot'. This phylum includes invertebrates such as insects, spiders, camel spiders, scorpions, millipedes, centipedes, and in the sea, organisms such as crabs, shrimps, lobsters, crayfish and many others. Arthropods are found everywhere, from the highest mountains to deserts (whether hot or cold), as well as in the deepest canyons of the seabed. This chapter focuses on the terrestrial arthropods of the United Arab Emirates (UAE). As it is not intended to provide a taxonomic account, arthropods are described in terms of functional groups or their ecological roles. Examples of specific arthropods belonging to two main terrestrial ecosystems found in the UAE, namely, mountains and wadis, and sand dunes or sand seas, are discussed.

B. Howarth (✉)
Department of Culture and Tourism - Abu Dhabi, Natural History Museum Abu Dhabi, Abu Dhabi, UAE

Chair of the Al Ain Chapter of the Emirates Natural History Group, Al Ain, UAE

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_17

17.2 The Emirates in a Global Context

To date, 1,163,161 arthropods have been described worldwide (Catalog of Life, June 2023) with the total number of arthropods—including those yet to be identified—estimated to be between twice to many times that number, constituting this phylum as having the highest biodiversity across the globe. Within the arthropod phylum, the Class known as insects (Insecta) is the most species diverse, representing 84% of all arthropods described and named to date. The class is further subdivided into taxonomic groups (Orders),containing such fauna as beetles (Coleoptera), earwigs (Dermaptera), butterflies and moths (Lepidoptera), flies (Diptera), termites (Isoptera), and barklice (Psocoptera), to name a few.

With arthropods being the most diverse group of animals worldwide, it is not surprising that it is also the animal group with the most species recorded in the Emirates. Of the currently recognized insect orders in existence worldwide today, two-thirds occur in the UAE. As is the case globally, the orders with the most insect species described in the UAE to date are the beetles, flies, butterflies and moths, as well as the order that encompasses the bees, wasps, ants and sawflies (Hymenoptera). Other arthropod orders represented in the UAE include spiders (Araneae), scorpions (Scorpiones), pseudoscorpions (Pseudoscorpiones), sun or camel spiders (Solifugae), tailless whip scorpions also known as whip spiders (Amblypygi), centipedes (Chilopoda), millipedes (Diplopoda), ticks and mites (superorders Parasitiformes and Acariformes), springtails (Collembola), bristletails (Zygentoma), and isopods (Isopoda).

In evolutionary terms, arthropods are very successful animals that have adapted to every type of habitat and have utilized diverse ecological niches, adjusting their body sizes accordingly over time. While there may have been larger prehistoric ancestors of the current arthropods, as can be found in the fossil record, the extant species nonetheless display an impressive size range. The smallest free-living insects are minute wasps known as fairyflies belonging to the family Mymaridae (UAE examples can be seen in Fig. 17.1). In 2019, a new fairyfly species was collected in Hawaii (Huber and Beardsley 2000) that ranges in body length from 0.19 to 0.3 mm in length (190–300 μm), only slightly larger than the width of a human hair. Among the arachnids, the smallest mite is about a tenth of a millimeter. In comparison, the longest insect is a stick insect, with the longest ever recorded measurement being 64 cm, according to *Guinness World Records* (2018).

In the UAE, arthropods also display a vast array of sizes, with the smallest mites being a fraction of a millimeter long, fairyflies of barely a millimeter in length, and the largest beetle (a longhorn beetle) measuring more than 8 cm in length (Tan and Howarth in preparation). Camel spiders can be as large as a human hand. Arthropods are found throughout the entire range of habitats in the UAE, including some of the most inhospitable environments such as sabkha (Hogarth et al. 2002). Some species can live in a variety of different habitats that occur across the nation (generalists), whereas other species require specific biotic and abiotic conditions and are, therefore, only found in areas suitable to their needs (specialists). Progress has been made

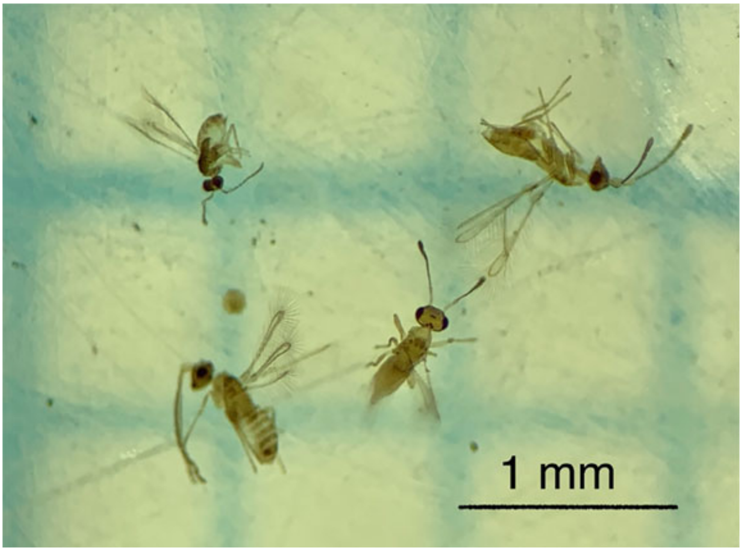


Fig. 17.1 These tiny insects, found in a garden in Al Ain in the Abu Dhabi Emirate, are examples of wasps known as fairyflies (Mymaridae) that elsewhere have been recorded as the smallest free-living insects. Due to their small size, the fairyflies were photographed using a dissecting microscope which reveals a key character that helps to identify the wasps to family level, i.e. the presence of 'feathery' wings. Photo credit: Brigitte Howarth

in cataloguing UAE arthropod diversity, which is now relatively well-known due to recent work to create a species inventory, published in six large volumes and edited by A. van Harten (editor and author) between 2008 and 2015. This work has added thousands of species to the list of UAE arthropods (van Harten (editor) 2008, 2009, 2010, 2011, 2014, 2015). However, their ecology remains poorly understood, especially those identified as 'new to science'.

This chapter tells the story of some of the groups of terrestrial arthropods found in the UAE and aims to galvanize readers' interest in filling the many knowledge gaps. It is necessary to fully understand the complexity of arthropod interactions among themselves, other organisms and their environment—including the myriad of services attributed to local terrestrial arthropods—to be able to engage in meaningful ecosystem conservation.

17.3 Diversity

The earliest records of Arabian fauna and flora were published in 1775 and were the results of a Danish expedition, sponsored by King Friedrich V, that visited the region between 1762 and 1767 (Büttiker 1979). Many initial insect records, and other fauna and flora are attributed to Peter Forsskål (1775) (Forsskål is spelled in a variety of ways in the literature), who was one of the exploration team members. As a student of Linnaeus, Forsskål had been well trained for the documentation of organisms on this journey. Most of his contributions were published posthumously by Carsten Niebuhr who was the sole survivor of the expedition (Büttiker 1979). Despite the many Arabian destinations visited during the journey, the expedition did not extend to the modern UAE territory. As a result, most arthropod records for the UAE date from the mid-1900s onwards—although many of the UAE's faunal and floral records were previously recorded elsewhere in Arabia by Forsskål (e.g., the desert locust *Schistocerca gregaria;* Forsskål 1775). Regional universities have only recently become more research-intensive and, as such, represent a growing but still minor contributor to biodiversity studies. As a result, much of the historical knowledge of the biodiversity of most groups of organisms, including arthropods, has been generated by specialists visiting from other parts of the world, typically Europe and more recently North America (van Lavieren et al. 2011; Vaughan and Burt 2016). Many significant contributions to arthropod records were published between 1979 and1997 in the "Fauna of Saudi Arabia" series (volumes 1–16) which later became "Fauna of Arabia" in 1998, ceasing publication with volume 25 in 2010. Even within the first few pages of the first volume, discussions of arthropod records from the UAE are included, e.g., the scorpion *Vachoniolus globimanus* recorded from Abu Dhabi (Vachon 1979).

Prior to 2008, arthropod records from the UAE were scattered throughout the literature, with species counts difficult to aggregate. Many records were contributed by members of the Emirates Natural History Group (ENHG) following its official creation in 1976. From January 1977 to November 1990, early records and observations were published in the ENHG newsletter (*The Bulletin*). *The Bulletin* later evolved into the ENHG peer-reviewed journal called *Tribulus* in 1991. This journal continues to be published to the present day, with non-professional members of the ENHG chapters in Abu Dhabi, Al Ain and Dubai contributing a significant number of articles to the publication, but also with articles by other scholars and researchers. In 2008, two key milestones in the study of arthropods occurred: (1) all insect records known from the UAE were consolidated and published in a chapter focused on Abu Dhabi emirate arthropods, with the species count of insects alone reported as 1528 species (Howarth and Gillett 2008), and (2) the same year, the van Harten national arthropod inventory project's first volume was published. Field and laboratory work and the first four volumes were sponsored by H.H. Sheikh Tahnoon bin Zayed Al Nahyan. Volume 1 was followed by a further five volumes published in 2009, 2010, 2011, 2014 and 2015, respectively. The consolidation of insect records (Howarth and Gillett 2008) together with the arthropod inventory volumes published by van Harten amount to over 4000 records of arthropods currently known from the UAE (Fig. 17.2). This species count should not be considered exhaustive, as new species continue to be identified and records from past literature continue to be uncovered, but it does represent the most comprehensive assessment of UAE arthropod diversity to date. Nevertheless, Fig. 17.2 speaks to the fact that the arthropod fauna of the UAE has only recently been studied in earnest, suggesting

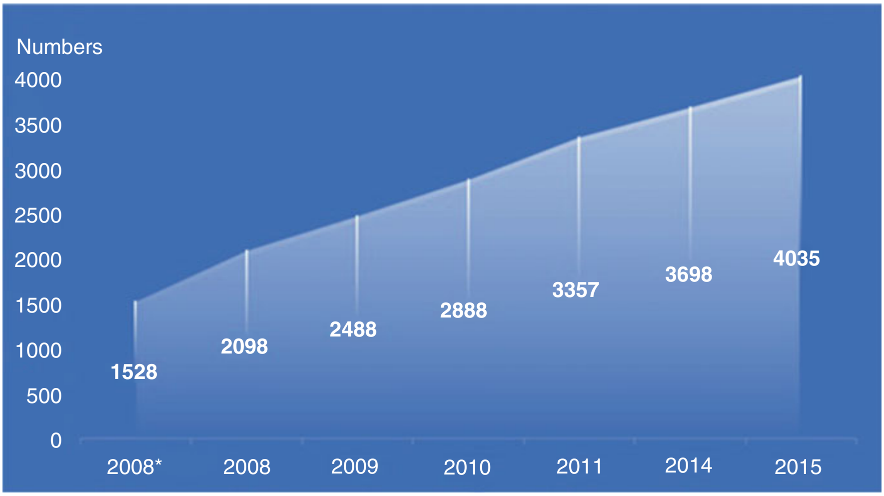


Fig. 17.2 The above depicts amalgamated records of arthropod species diversity in the UAE from 2008 to 2015. The initial species count consolidated by Howarth and Gillett (2008) (shown as *) included both their own and other published records, and show the baseline of knowledge that existed prior to the start of the insect inventory project (see various van Harten references) which added thousands of records new to the UAE, including records of arthropods new to science

that far more in-depth research is needed to shed light on the ecology of the many species we now know to occur in the UAE.

The records added by van Harten's inventory were significant in their own right, however, what should not be understated is the large number of species that were new to science (i.e., previously undescribed globally) (Fig. 17.3). Although it is possible that some of these species may subsequently also be found in other (most likely regional) countries, especially for those species occurring in continuous habitats that cross country borders, they are nevertheless significant, comprising species currently only known from the UAE. At present, however, it is only their occurrence within the Emirates that has been recorded and nothing is known of their ecology—their population sizes, biological interactions, habitat usage or environmental preferences. This means that it is currently impossible to evaluate these species in terms of their conservation status. Given the rapid development of many habitats across the Emirates, this suggests that long-term monitoring and research on arthropods (and many other fauna) should be considered a priority.

As suggested above, arthropod diversity (both records new to the UAE and new to science) continues to grow as authors continue to contribute new records. For example, the following represent only a fraction of recent contributions to the UAE arthropod diversity records: Al-Deeb et al. (e.g., 2012) and Negm (2014) added new mite records along with ecological information, Cassola et al. (2012) added a species of tiger beetle only otherwise known from Iran and Pakistan, van Andel (2014) and Feulner and Roobas (2015) contributed to the otherwise poorly known spider fauna,

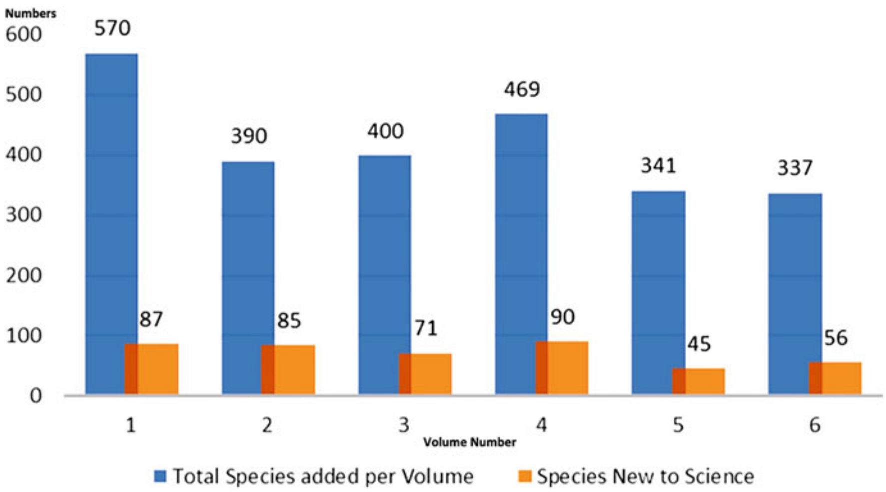


Fig. 17.3 From 2008 to 2015 van Harten edited (and contributed as author) a six-volume biodiversity inventory titled '*Arthropod Fauna of the UAE*', which added a significant number of new species records to the overall knowledge of arthropod diversity, including many that are new to science. Each blue bar accounts for the total number of new species added per volume to the knowledge of arthropod diversity of the UAE. Of the total number of species added to the list by van Harten in the six volumes (2507 species), 17% of the records were species that were new to science (the orange bars make up the number of species per volume that were new to science)

and Saji and Whittington (2008) and Dobosz et al. (2017) added to the knowledge of lacewings.

17.4 Distribution, Habitats and Importance of UAE's Arthropod Diversity

Ecosystem services provided by arthropods have been linked to the UN Sustainable Development Goals (Dangles and Casas 2019), establishing their importance to humans in a variety of ways, including welfare, health and provision of resources (Brock et al. 2021). Ecosystem services are provided by arthropods in all the varied habitats of the UAE, despite the challenges they may face in its hyper-arid desert environment. To cope with the extreme climatic conditions, arthropods have devised ingenious strategies and adaptations to maximize their success. Whether these are nocturnal strategies, seasonal emergence timing, emergence following rain, or ephemeral life-history strategies, all approaches can be found within the arthropod fauna of the UAE, though for most species, very little local ecological data exists. Discussed elsewhere are the various terrestrial ecosystems found in the UAE (see Chaps. 2 and 6). Ideally, for the purpose of addressing the ecology of the UAE arthropod fauna, each ecosystem should be examined closely to better understand the many complex food webs and other interactions between arthropods and their environment. However, the deficit of ecological data for many of these taxa prevents such a treatment. To highlight the complexity of arthropod ecology in the UAE, some representative examples are mentioned below, focusing on, where known, their ecological role within ecosystems including their distribution and habitat preference.

17.4.1 Pollination

Pollination is the initial process that is necessary for reproductive success by sexual means in plants. In simple terms, for pollination to occur, the pollen of one flower must find its way to the stigma of another flower of the same species. Chapter 13 highlights the various pollination methods in flowering plants.

Pollination by arthropods is often a byproduct of their search for food, with an incidental benefit to the host plant. When thinking of pollination, many are tempted to think that this service is primarily carried out by social honeybees. Indeed, honeybees do play a part and do occur in the UAE, but many more arthropods are involved globally, including in the Middle East (e.g., Alqarni et al. 2017). Pollination occurs by several physical means (e.g., wind-pollination), but it also occurs through organisms such as birds, bats, and many arthropods e.g., beetles, flies, wasps, moths, spiders, thrips, and many others.

An example of plant pollination by insects, but not social honeybees, in the UAE is the desert campion (*Silene villosa*) depicted in Fig. 17.4. This annual plant flowers during the spring and is generally found in stable sand and between dunes (Jongbloed et al. 2003). Campion species found in other parts of the world, e.g., *Silene alba*, begin to open their flowers at dusk and are fully open during the night and into the next morning (Young 2002). Given the right conditions, desert campion can grow as a carpet of plants, and in the early evening in spring this desert annual releases a heady perfume as the buds begin to open. By the following morning, the flowers begin to degrade, and are often seen wilted by the next afternoon. Night-flowering plants such as the desert campion rely mainly on nocturnal pollinators, although they may incidentally benefit from daytime visitors early the following morning. However, a study of bee and wasp flower visits conducted during the daytime in the UAE did not record any visitors to the desert campion (Gess and Roosenschoon 2016). For this reason, it is speculated that the desert campion is mainly pollinated at night by species of noctuid moths, though the specific relationships are yet to be confirmed for the UAE.

Apart from the desert campion, it is undoubtedly the case that other flowering plant species occurring in the UAE are associated with specialized pollinators, rather than generalists visiting multiple plant species. For example, nectaries of flowers such as locally occurring lavender (*Lavandula subnuda*) and a UAE species of sage (*Salvia aegyptiaca*) are only accessible to insects that possess a sufficiently long

Fig. 17.4 The desert campion, *Silene villosa*, is generally found with its flowers open during the night and is thought to be pollinated by nocturnal moths. Photo credit: Brigitte Howarth

proboscis (i.e., a tube-like sucking mouthpart) due to the long flower nectary tubes of these plants.

Butterflies and beeflies both have long mouthparts, but just having a long proboscis may not be the only prerequisite for the success of specialized plant-pollinator interactions, as plants have devised more elaborate mechanisms to maximize their successful pollination. Sage flowers possess two modified, lever-like stamens (i.e., the male flowering parts that develop pollen) that are involved in pollen deposition onto a pollinator. As the pollinator pushes into the flower and against the interior of the flower, the stamens bend downwards depositing pollen onto the back of the insect. A study of several sage species in Turkey identified both specialist and generalist bee pollinators, with ecologically specialised sage species being pollinated by only a single bee species (Celep et al. 2020). The study also showed that ecological specialization was correlated with floral traits such as color, corolla length, size and type of staminal-lever mechanisms as well as flowering time. A selection of some plant-pollinator interactions found in the UAE are depicted in Fig. 17.5.

It is possible that specialized plant-pollinator interactions occur among the insect fauna observed visiting local sage species, and these may not be bees but flies instead. During spring 2019 this author and Dr. Gary Brown observed beeflies (Bombyliidae) on the sage *S. aegyptiaca* in wadis of the Hajar mountains (Fig. 17.5d). During the time of observation there were virtually no other insect species visiting the plant, suggesting that beeflies may be an important pollinator for this species, rather than bees. More in-depth study is required to confirm whether this insect-plant interaction is specific, which may include analyses of pollen collected

Fig. 17.5 Pollination of wild flowers by insects. The insects represent just a small number of the many that are found foraging for pollen or nectar from wild flowers in the UAE. (**a**) Arabian Paper wasp (*Polistes wattii*) visiting *Ochradenus aucheri*; (**b**) melliferous (honey producing) wasp *Celonites yemenensis* on *Morettia parviflora*; (**c**) mating oil beetles (Meloidae) on a species of *Tribulus*; (**d**) beefly (Bombyliidae) visiting *Salvia aegyptiaca*; (**e**) potter wasp (Eumeninae) visiting a species of *Echinops*; (**f**) Painted Lady butterfly (*Vanessa cardui*) on lavender (*Lavandula subnuda*); (**g**) bee wolf *Philanthus triangulum* and a carpet beetle (Dermestidae) on *Ochradenus aucheri*. Images of interactions **a**, **d**, **e**, **f**, and **g** were captured in wadis of the Hajar Mountains. Image **b** was taken at the base of Jebel Hafit, and the beetles in **c** were observed at the Dubai Desert Conservation Reserve (DDCR). Photo credits: Brigitte Howarth (**a**, **b**, **c**, **e**, **f**, **g**) and Gary Brown (**d**)

from the body of beeflies, measurement of corolla and proboscis lengths, as well as seasonal studies of visitors to the sage plants to identify potential pollinators. In contrast to observations of insect-plant interactions on sage, flowers that are easily accessible for both pollen and nectar feeders attract many different insect species, e.g., the plant *Ochradenus aucheri* (Fig. 17.5a and g), and are less likely to have specialized pollinators.

Beetles are also frequent pollinators of wild flowers, especially some of the smaller beetles that occur in the UAE, such as ant-like flower beetles (Anthicidae) which superficially resemble ants. These, and other small beetles, are often seen congregating within or on flower-heads. As part of the arthropod inventory project, an account of the ant-like flower beetle species occurring in the UAE was published in 2008, with a total of 25 species recorded, 3 of which were known, and 4 of which were species new to science (Telnov 2008). Some ant-like flower beetles are cosmopolitan and were recorded at various locations throughout the UAE, while some appear to prefer more specific habitats, such as the newly described species *Stricticollis desolatius* that was only recorded from Wadi Wurayah thus far. However, more detailed ecological information was not recorded for any of the species, as most were collected using passive trapping methods, as is typical when establishing species diversity inventories.

In a pollination ecology study of an acacia tree species in Saudi Arabia, known as Talh (*Acacia gerrardii*), researchers used active collection techniques to directly establish which flower-visiting insects were involved in pollination by using sweep-netting and hand-picking (Alqarni et al. 2017). Of all the insects collected, 41% were beetles, and included two species that also occur in the UAE: an ant-like flower beetle (*Omonadus floralis*) and a carpet beetle (*Attagenus posticalis*). Alqarni (2017) also concluded that the insects that contributed most to flower visitation were members of the wasp and bee family (Hymenoptera), and specifically honeybees, some solitary bees (Megachilidae), and ants. Almost no such studies have been conducted in the UAE, except for a study of flower visits by aculeate wasps and bees in the Dubai Desert Conservation Reserve (DDCR) (Gess and Roosenschoon 2016). Of the 79 species of bees and wasps recorded in the study (which includes areas outside of the DDCR), 25 species were recorded visiting 21 plant species within the DDCR. It should be noted that 11% of the species observed in the study are known to occur only in the Arabian Peninsula, suggesting that regional endemics play an important role in plant pollination. These are of specific interest, as they are most likely to have more specialized foraging behaviors that are worthy of study. Gess and Roosenschoon (2016) concluded that very few species of wasps and bees encountered were, in fact, specialists, adding that the interactions of specialists recorded were not obligate, with the plants not relying on the wasp and bee specialists but that they were likely the most dependable of the pollinators. Relationships such as those observed by Gees and Roosenschoon are important to begin to understand plant-pollinator interactions and many more studies are needed to understand the ecology of flower-visiting insects, including other pollinators such as hoverflies, butterflies, ants, and the insect orders mentioned earlier (e.g., beetles, social and solitary bees and wasps, and moths, among others).

At times, pollination may not be due to arthropod foraging behavior, but rather due to incidental activity that brings the fauna close to flowers, resulting in accidental pollen transfer. For example, spiders are often seen in and around plants, and in some cases are very well camouflaged, waiting to ambush flower-visiting insects (Fig. 17.6). While the impact on pollination success by spiders and other arthropods that incidentally associate with flowers is likely minimal in comparison to pollen and nectar-feeding insects, it should not be underestimated as an ecosystem service that warrants further study.

17.4.2 Nutrient Cycling and Soil Fertility

Despite the appearance of being uniform, sandy desert soil is complex. Within the UAE, a total of 74 soil series have been identified based on aspects such as soil chemistry, physics, mineralogy, and vulnerability to land degradation (Shahid et al. 2014). Soils are composed of biotic and abiotic components, with a large proportion of the biotic components being organisms that interact with soil. It has been

Fig. 17.6 A crab spider (Thomisidae) waits in ambush on a lavender plant (*Lavandula subnuda*). Despite its distinct markings, this crab spider remains unidentified. During the observations of this spider, it moved multiple times over the blossoms. Photo credit: Brigitte Howarth

estimated that soil fauna may represent 23% of all described organisms globally, of which arthropods form the largest proportion (85%) (Decaëns et al. 2006).

Arthropods found in leaf litter and upper soil horizons include spiders, springtails, pseudoscorpions, millipedes and centipedes, woodlice, insects, mites, and bristletails, all of which occur in the UAE. In some soils globally, the springtails and mites are among the highest in abundance and diversity of the soil arthropod community (Culliney 2013). As soil arthropods can be quite small, studying their ecology can be challenging. Indeed, springtails and mites are among the smallest arthropods in the UAE, measuring between a fraction of a millimeter to two millimeters in length, although a large mite group known as giant red velvet mites also occurs in the UAE (Fig. 17.7b), and can be over a centimeter long. Giant red velvet mites *(Dinothrombidium*) are known locally as 'daughter of the rain' (بنت المطر) as they are often seen on sand dunes following precipitation. In their discussion of a giant velvet mite's ecology, Tevis and Newell (1962) note that soil particle size is an important factor that affects the organism's distribution. The authors also note that the organism only emerges from sand following rain, which is in agreement with UAE folklore and the Arabic name. Feeding behavior was rarely observed, although predation on termites has been recorded (Tevis and Newell 1962).

Springtails occur in various habitats around the world, frequently found in damp leaf litter, but semi-aquatic species also exist. Despite the UAE's arid conditions and lack of continuous or deep leaf litter layers that are typically found in temperate regions of the world, to date 18 springtail species have been recorded for the Emirates, with 3 of these being new to science (Barra and van Harten 2009; Schulz and van Harten 2014) (Fig. 17.7a is an example of a UAE springtail). Springtails are soft-bodied invertebrates with a life cycle that begins with an egg that develops into a nymph and then becomes an adult, molting 6–8 times before reaching the mature

Fig. 17.7 Two arthropods associated with UAE soils: (**a**) a globular springtail (Family Bourletiellida) collected from a malaise trap in Wadi Shawkha, Ras Al Khaimah, and (**b**) a velvet mite at the base of a possible termite mound on a sandy track in the Jebel Hafit National Park in January 2023. Photographers: (**a**) Brigitte Howarth; (**b**) Gary Brown

adult stage. Their name stems from their means of locomotion. A fork-like structure at the end of their abdomen, called a furcula, is used to 'spring' the organism away when facing danger or needing to move. When getting ready to jump, the furcula that is tucked under the organism's body is pushed downwards, and the organism is propelled upwards, spiraling into the air. Springtails feed on fungus, bacteria, fresh and decaying plant material, but also pollen and lichen, with some being predaceous (Macnamara 1924; Poole 1959; Christiansen 1964; Culliney 2013). Springtails therefore contribute to nutrient cycling and soil health in a variety of ways, including the spread of fungal spores through soil. A dry-land springtail *Seira ferrarii* that occurs in the UAE, but also elsewhere, is a lithophilous (loving/inhabiting stony places) and thermophilous (warmth loving) species (Tosi and Parisi 1990). It has been found at elevations of 566 meters as well as at sea level on a beach (4 m) in Spain (Cipola et al. 2018), and even from sediments below the Black and Mediterranean seas (Da Gama 1966; Jacquemart and Jacques 1980; Shaw et al. 2011). In the UAE, it was recorded from the mountainous Wadi Wurayah and from Sharjah Desert Park, showing some versatility in habitat usage. Another UAE springtail species (*Sphaeridia pumilis*) is a cosmopolitan species known to be able to survive in many habitats. In contrast, at least one of the three endemic species recorded from the UAE *(Denisiella bretfeldi)* appears to be habitat-specific, having only been collected in one location (Wadi Maidaq, Fujairah) (Schultz and van Harten 2014). How UAE species are involved in nutrient cycling and soil fertility requires further study.

Soil fertility refers to a soil's ability to satisfy plant demands for water, nutrients and a suitable substrate in which roots can develop (Culliney 2013). Arthropods are involved in the provision of these conditions through their ability to break down leaf litter (e.g., as performed by springtails described above) and as ecosystem engineers through their burrowing to allow gas exchange for roots. Ecosystem engineers are

Fig. 17.8 A female mydas fly (*Eremomidas arabicus*) was observed burying itself deep into the sand by moving backwards and downwards until only the tips of its wings and its head remained outside of the sand. It is suspected that the fly was first probing for suitable ovipositing substrate, followed by egg-laying, as it remained buried for several minutes before lifting out of the sand, probing and searching again a little further away before repeating the burying behavior. This individual repeated this behavior three times before flying away. Photo credit: Brigitte Howarth

organisms that can alter the physical character of a habitat, directly or indirectly, facilitating the success of other species (Jones et al. 1994). Soil turnover is considered essential to the development of a soil profile, an ecosystem service commonly provided by ants and termites in arid and semiarid environments (Whitford 2000). A study of the effects of harvester ant (*Messorebeninus*) nests on the soil and plants in a dwarf shrub community in Kuwait revealed that soil properties changed substantially in the circular zones around the nests of the ant, with elevated levels of nutrients and organic matter recorded (Brown et al. 2012). In addition, plant productivity and richness were reported to be significantly enhanced in these zones, with the researchers concluding that the ant *Messorebeninus* is an important ecosystem engineer. There are many species of ants in the UAE, including the same species reported by Brown et al. (2012) which was first recorded from the UAE in 1993 (Tigar and Collingwood 1993). However, similar studies to evaluate the importance of this or other ant or termite species on UAE ecosystems have not yet been carried out.

To a lesser degree, arthropods that spend most time on the wing in the air rather than in the soil, but that deposit eggs into sandy habitats, may also contribute to soil health and the maintenance of such ecosystems either by their burrowing activity or through the provision of food for other soil-dwelling organisms. Such an example is the mydas fly *Eremomidas arabicus*. It is the largest species of mydas fly found in the Arabian Peninsula, with females having a wing length of 17.5–18.2 mm (Dikow 2010). The species is sexually dimorphic, with the males quite a bit smaller and grey in appearance, in contrast with the larger, orange-colored females. Members of this fly family deposit their eggs into sand, behavior which the author observed at Zakher pools, Al Ain, during October 2010. The female, laden with eggs, was finding it difficult to fly, and eventually buried herself up to her neck in sand, presumably in search for optimal areas to oviposit eggs (see Fig. 17.8). Mydas flies appear to be very seasonal in the UAE and are not observed every year. A mydas fly new to science and only discovered in a Nevadan desert in the United States in 2007 appears to be absent in years of drought and was only recorded in years of moderate or heavy rainfall (Rogers and Van Dam 2007), and it is possible that in the UAE *E. arabicus* follows a similar pattern. In the United States, another species of mydas fly is the only true fly that has been listed as 'endangered' under the U.S. Endangered Species Act due to its restricted habitat range and the threat of habitat loss (Rogers and van Dam 2007). Mydas flies in the UAE are likely also vulnerable to habitat loss and degradation, requiring research to learn more about their ecology.

17.4.3 Population Regulation

In the context of food webs, the presence of many trophic levels (i.e., feeding strategies) in a given ecosystem could indicate complex habitat structures, synonymous with a diverse and functioning ecosystem. Arthropods are involved at many trophic levels, providing valuable services and energy sources for other invertebrates and vertebrates alike. While there have been some studies of species assemblages in the UAE (e.g., Hogarth et al. 2002), more studies of trophic levels found within species assemblages of different local habitats are needed. Yet, many observations have been noted on predator-prey interactions that can be considered as ecosystem services through population regulation. Such an observation was made by Gillett (2009), who identified possible prey species of some ground beetles (Carabidae) found in the UAE. Predatory arthropods of the UAE include spiders, scorpions, camel spiders, beetles, dragonflies, flies, wasps, lacewings, mites, pseudoscorpions, centipedes, and many others, although most have yet to be studied in depth. Camel spiders (Fig. 17.9) include some of the largest arthropods found in the UAE, yet they are also among the most elusive. Camel spider ecology is generally poorly known (Punzo 1998). In a study comparing the functional morphology and bite

Fig. 17.9 Camel spiders are generally poorly known which could be due to their great agility, and mainly nocturnal nature. The individual photographed belongs to the genus *Galeodes* and was found in the sandy habitat of Wadi Nabbagh, Al Ain. Photo credit: Brigitte Howarth

Fig. 17.10 Regulatory ecosystem services are frequently provided by members of the aculeate Hymenoptera, such as the paper wasp *Polistes wattii.* During 2010 when observations of mydas fly egg-laying were made, a paper wasp was recorded devouring a female mydas fly. Photo credit: Brigitte Howarth

performance of two camel spider genera from Egypt and Morocco, researchers were able to show significant differences, suggesting possible specialization on prey species (van der Meijden et al. 2012). Camel spiders macerate arthropod prey with powerful jaws without immobilizing their prey with venom as is the case with other arachnids (van der Meijden et al. 2012). The authors investigated anatomical differences as well as bite performance. Both genera investigated are represented in the UAE and have been observed in specific habitats, with *Galeodes* frequently encountered in sandy areas, and *Rhagodes* recorded from rocky areas such as mountains or gravel plains. Further study would not only contribute important information on the ecological role of camel spiders, but shed much needed light on their biology.

Another arthropod group that is usually overlooked when considering ecosystem services is aculeate wasps. Wasps in this group possess a stinger. The stinger is a modified egg-laying structure or ovipositor. In addition to the pollination services of wasps that were discussed above, wasps also hunt other arthropods, either as predators or as parasites that lay their eggs on or within other organisms (Goulet and Huber 1993; Grissell 2010). This interaction provides a regulatory service, limiting populations of the arthropod prey or host species (Fig. 17.10 depicts the social paper wasp *Polistes wattii* consuming a mydas fly at Zakher Pools, Al Ain).

Wasps and bees are either social or solitary, with far more known about social bees and wasps in comparison to solitary members of this group. Brock et al. (2021) provide a detailed review of ecosystem services provided by aculeate wasps, stating that solitary wasps are, by far, the most diverse group of wasps, making up approximately 97% of all wasps. Gess and Roosenschoon (2016) list 53 species of aculeate wasps in their study of the Dubai Desert Conservation Reserve (DDCR) and

Fig. 17.11 The insects depicted both belong to the order Odonata which includes both (**a**) damselfies and (**b**) dragonflies. Damselflies are usually slenderer in comparison to dragonflies and hold their wings over the abdomen when at rest, as is seen in the first image (**a**) depicting a male Evan's Bluetail damselfly (*Ischnura evansi*), whereas dragonflies spread their wings out while perched or at rest. The second image (**b**) depicts an immature male Gulley Darter dragonfly (*Trithemis arteriosa*), which will turn red on maturity. Photo credits: Brigitte Howarth

other localities, with 39 of these visiting flowers and likely providing important pollination services. Many of the observed species are likely contributing to regulatory ecosystem services by preying on or parasitizing other insects. Other wasps involved in such ecosystem services are parasitic wasps belonging to families such as the Ichneumonidae, Braconidae and the superfamily Chalcidoidea, all of which are represented in the UAE.

Some of the most agile predators in the UAE are among the Odonata (dragonflies and damselflies) (see Fig. 17.11 for differences between dragonflies and damselflies); both the aquatic larvae and the aerial adults are predacious. The Odonata is likely the insect order that has been most intensively studied in the UAE, with key contributions including Giles (1998), Feulner (1999), Feulner et al. (2007), Reimer et al. (2009), Campbell and Reimer (2011), Reimer (2011), Feulner and Judas (2013), Campbell (2017), Lambret et al. (2017) and others. These authors have added much information with regards to distribution and ecology that highlights the importance of freshwater habitats in the UAE, which are utilized by larvae of this group until they are developed to the stage where they can emerge as adults. For example, Lambret et al. (2017) contributed detailed descriptions of habitat use and mating behavior, though observations of feeding behavior remain sparse. Of note is

Fig. 17.12 A rare sighting of a female longhorn beetle (*Anthracocentrus arabicus*) ovipositing into sand (**a**); (**b**) the head and thorax remains of a longhorn beetle impaled on a desert shrub suggests that this species forms part of the diet of a shrike species; (**c**) evidence of longhorn beetle remains in eagle owl pellets provide evidence that *A. arabicus* forms part of the diet of eagle owls. Photo credits: Brigitte Howarth

the assessment of conservation status of Odonata occurring in the Arabian Peninsula (Schneider and Samraoui 2015). One species of the assessed taxa was listed as 'Critically Endangered (CR)', nine as 'Endangered' (EN), five as 'Vulnerable' (VU) and four species as 'Near Threatened' taxa (NT). Of these 19 species, 6 are considered endemics that only occur in Arabia. A further 32 species are listed as 'Least Concern' (LC), with 8 species not categorized or listed as being data deficient (DD). Of 59 species examined, 23 occur in the UAE. Schneider and Samraoui (2015) list the main threats to Odonata as including rapid development and modifications to natural systems such as the creation of dams, water abstraction, the destruction of riparian habitats, pollution, agriculture and aquaculture. The listed threats that are impacting the Odonata are also serious threats for the many other arthropod species that are dependent on aquatic ecosystems in the UAE (many insects, for example, have aquatic larval phases and cannot complete their life cycle without access to freshwater). As Odonata contribute to regulatory ecosystem services, the threats listed could potentially impact key foodweb interactions, modifying species dynamics in freshwater ecosystems of the UAE.

Arthropods in the UAE are beneficial to other organisms that either feed on their dead bodies as detritivores, or that actively hunt them as food, such as reptiles, small mammals and birds. A longhorn beetle species that occurs in the UAE is the largest beetle species found regionally. The beetle, *Anthracocentrus arabicus*, was largely unnoticed for many years, with only carcasses of dead beetles found at the base of Ghaf trees (*Prosopis cineraria*). In recent years, this author and Dr. M. Gillett, and later the author and Dr. J. Tan, conducted studies to learn more about this species (e.g., Tan and Howarth in prep.). Observations of note, captured in Fig. 17.12, included the impalement of a longhorn individual on a spike, with most of the body missing. Tan and Howarth observed a shrike species in the vicinity and conclude that the longhorn beetle likely forms part of this bird's diet. Another observation was the presence of *A. arabicus* remains in eagle owl pellets, suggesting that they may represent an important prey species for eagle owls. Both observations add valuable ecological data for an otherwise poorly known species.

17.5 Threats to UAE's Arthropod Diversity

In 2020, a landmark assessment of global insect population trends revealed what many had suspected for a long time: insect populations are in drastic decline (Wagner et al. 2021), with an annual abundance decline of 1–2% reported. The study also summarizes the most likely stressors involved, including climate change, pollution and insecticides, alien or introduced species, agricultural intensification, deforestation of the tropics and urbanization, with the last three stressors leading to habitat loss, degradation and fragmentation. Many of the same stressors occur in the UAE (Gardner and Howarth 2009), with the loss of terrestrial habitat being the main concern, such as through widespread quarrying activities that have resulted in the loss of pristine mountain and wadi habitats in the Hajar range (see also Chap. 6). While Wagner et al. (2020) were able to base their assessment on a myriad of studies from many countries, there currently is no monitoring study (past or ongoing) with sufficient baseline information to assess the stressors behind potential arthropod loss in the UAE. This author has been involved in a 5-year malaise trap arthropod study in a mountain wadi (Fig. 17.13), along with a 1-year malaise trap study of Ghaf trees (*Prosopis cineraria*) in the sandy habitats of the Dubai Desert Conservation Reserve (DDCR), with information that will likely provide valuable insights about composition and trends in arthropod communities in the Emirates.

Some species will suffer more than others in the UAE due to their specific habitat requirements. For example, several of the UAE's tiger beetles, such as *Callytron monalisa*, first recorded from the UAE in 2007 (Cassola et al. 2012), live and reproduce on intertidal mudflats and adjacent sandy shores that occur along the Arabian Gulf coast of the UAE (Feulner and Roobas 2014), a habitat under threat from coastal development (Burt 2014). Another beetle species threatened by the consequences of habitat loss is the longhorn beetle, *Anthracocentrus arabicus*, discussed above. This is a large longhorn beetle species that is associated with Ghaf trees. Ghaf populations are found in dune habitats mainly in the north-east of the UAE, with increasing amounts of their habitat fragmented by roads and urbanization. This encloses local individuals or populations within a 'Juzur' or habitat island, restricting the capacity for dispersal of many species associated with Ghaf ecosystems. This, in turn, can lead to genetic isolation, which could lead to the loss of species such as *A. arabicus*, impacting not only the beetle but its ecosystem function within the habitat, where it forms an integral part of food webs. While some biological information is available for the above two beetle species, such information remains unknown for many arthropods in the UAE, making it more difficult to assess

Fig. 17.13 Studying species abundance is often conducted using passive trapping methods, such as the tent-like malaise trap shown here. Flying insects usually fly into the middle of the trap, not seeing the transparent fabric, and then will attempt to fly to the highest point towards the sun to escape. The front part of the malaise trap is higher than the back with an opening in it, allowing insects to pass through into the receptacle that contains 70% ethanol. Many non-flying arthropods have been sampled this way, including spiders, camel spiders, scorpions, mites and springtails. Photo credit: Brigitte Howarth

the impact of stressors on their populations and therefore the ecosystems they inhabit.

In the case of total loss or severe degradation of habitats, such as that caused by quarrying, the impacts are extremely concerning, especially for species associated primarily with mountain and wadi systems, which includes most of the UAE's dragonflies and damselfies. The Desert Basker dragonfly (*Urothemis thomasi*) was only recently added to the UAE faunal list (Feulner and Judas 2013). It was recorded from Wadi Wurayah on the East Coast of the UAE in the Hajar Mountains. Some Odonata are among the few arthropods occurring in the UAE for which an IUCN status exists. For example, the Desert Basker has been assessed as decreasing globally and is classified as 'endangered' (Boudot 2018). While Wadi Wurayah is a protected area and has more permanent water than other UAE wadis, it is very likely that the Desert Basker will be found in other mountain wadis along the UAE's

Hajar Mountains. Further habitat loss through quarrying could, therefore, impact its status even further, along with many species that have not yet been assessed.

As well as habitat destruction, many of the tourism and leisure activities that occur throughout the UAE are of concern. With regard to sand dunes, the many organisms that live within the top layer of the sand are specifically under threat. The mydas fly *Eremomidas arabicus* depicted in Fig. 17.8 lays its eggs in the upper sand, between 4 and 8 cm into the substrate. 'Dune bashing' and off-road driving activities churn up and compact sand, very likely causing damage or death to organisms that live in it, including arthropods. While hiking itself is usually not destructive, wading through freshwater pools with sunscreen could potentially leave an oily residue on the surface of pools, with many individuals crushed and their habitat, eggs and larvae disturbed through the activity.

Land-use changes include habitat remodeling, such as the creation of artificial lakes. In several of the emirates, artificial bodies of water have been created, whether to store runoff or grey water, or for amenity. This can cause displacement of species that had utilized that habitat, although they may serve as a water body for other species requiring water for the aquatic larval portion of their life cycle. Malaise trap studies of sandy habitats in Dubai Emirate have shown that most of the arthropod biomass near artificial lakes differs in species diversity and evenness usually found in sandy habitats, with an overall decrease in arthropod diversity but an increase in biomass of species that rely on water for parts of their life cycles such as midges and mosquitos (personal observation).

An additional concern is the lack of IUCN Red List extinction threat assessments for arthropods globally. This is likely due to the sheer numbers of arthropods and the difficulty associated with studying their populations. Nevertheless, this makes the evaluation of their status difficult, and impacts most arthropod groups, with few exceptions. Because many UAE ecosystems have not been studied in detail and their species assemblages are largely unknown, it is therefore also difficult to evaluate the impact on shifts and losses of ecosystem functioning caused by stressors and the consequences for fauna and flora that rely on arthropods either for ecosystem services or as a food source.

17.6 Conservation and Future Research

Sandy deserts are often described with words such as 'barren' or 'hostile'. This creates an association of a landscape that is devoid of life and not worth considering in conservation efforts. In the first instance, a paradigm shift needs to occur to move away from this association to recognize that the word 'desert' describes a biome that lacks regular precipitation and is therefore associated with periods of drought. While this does mean that fewer organisms live in such habitats in comparison to tropical rainforests, it does not mean that deserts are barren. On the contrary, organisms found in such a habitat are specifically adapted to cope with the abiotic stresses they face. Conservation efforts for arthropods involve ecosystem approaches rather than a focus on a particular species, because arthropods are part of complex food webs involving many taxa and their environments. As is evident from this account, there is a poor understanding of food webs of organisms in the UAE and the role that arthropods play in them, which means that conservation efforts here would have to rely on the findings of studies carried out in foreign desert environments. Yet, vegetation composition, geology, topography and weather conditions are specific to the UAE, as is elaborated on in Chaps. 2, 3 and 5. Except for very few of the arthropod groups mentioned in this chapter, the life histories, habitat requirements, interactions and conservation status of most UAE arthropod species remains largely unknown. As elaborated earlier, thanks to the six volumes edited and contributed to by van Harten et al., as well as other professional and amateur contributors, a reasonable arthropod inventory now exists. Although this, too, remains incomplete, with some habitats continuing to be under-studied (e.g. gravel plains). Equally, there currently is no definitive local arthropod specimen reference collection in the UAE that can easily be consulted, which is an additional obstacle (although this will be addressed with the establishment of the Natural History Museum Abu Dhabi, currently under construction).

Just as habitat fragmentation and destruction leads to species loss globally, the same is likely the case here in the UAE. Many mountain, wadi, coastal and inland sand dune habitats have been lost through development and urbanization, though there are still vast sand seas south and west of Abu Dhabi, which can be considered ancient in nature. Though new dunes form frequently from shifting sands, much of the inland sand seas consist of Quaternary sand with older underlying geology (Glennie 2005). Ancient, reasonably undisturbed, habitats are becoming rarer globally as most land surfaces have been transformed in one way or another by human activity. The ancient mountain and sand habitats of the UAE contain a vast array of arthropod communities that have evolved over time to survive under hyper-arid conditions. These intact communities require in-depth study to understand how they continue to exist under such conditions.

The limestone and ophiolite mountains and wadis of the UAE are home to large numbers of plants with many arthropod-plant interactions both above and below ground, but these interactions remain to be studied, and the heavy overgrazing likely represents a substantial threat to the vegetation that supports the arthropod communities and wider food webs in these areas (see Chap. 5). An urgency, therefore, exists in the UAE to study arthropods whilst remnants of these habitats still exist. The large number of species recently recorded as new to science from the UAE is exciting, as these can be considered endemic to the UAE or eastern Arabia. All require in-depth study. Arthropods are often difficult to locate due to their varied life history strategies such as being seasonal, nocturnal or burying in strata such as mudflats or sand. Many species have evolved complex life histories to ensure their survival. Some species occurring in the UAE may be indicator species of undisturbed local environments or be keystone species, but more information is needed on their life histories, and interactions within food webs, before such designations can be made. Within each of the larger habitats there are smaller microhabitats such as ephemeral pools of water, blossoming regional trees, or tributary wadi habitats. To fully comprehend how arthropods are contributing to the survival of healthy ecosystems, microhabitats and their associated arthropod communities must be described, and species interactions recorded and studied. Studies of arthropod communities require long-term monitoring to tease out whether changes to species assemblages are due to long-term trends (e.g., climate change or habitat loss) or to the variable year-to-year dynamics of processes like rainfall and drought. Such data is complex and only possible to understand through long-term monitoring. This does mean that there are many opportunities for further study of the arthropods of the UAE. Once more ecological knowledge exists, it will contribute to effective ecosystem conservation planning, and possibly to habitat restoration.

17.7 Conclusion

The current account of arthropod ecology in the UAE is intended to provide a brief overview of some of the interactions that are known, along with the many unanswered questions that remain in the hope that others will endeavor to attempt to add to the existing body of knowledge.

17.8 Recommended Readings

While not meant to be exhaustive, additional resources for the UAE arthropod fauna can be found in a variety of publications, such as Feulner et al. (2021) for butterflies, van Harten's *Arthropod Fauna of the UAE* volumes (2008–2015), and papers in the nearly 30 volumes of the journal of the Emirates Natural History Group, *Tribulus* (available online at http://enhg.org/) e.g., Feulner and Roobas (2015) for spiders. In other publications as discussed in the text above, Saji and Whittington (2008) have contributed to the knowledge of antlions, and Howarth and Gillett (2008) summarized a general overview of arthropods that occur in the Abu Dhabi Emirate, applicable to the UAE as a whole.

References

Al-Deeb MA, Muzaffar SB, Sharif EM, Goodacre S (2012) Interactions between Phoretic Mites and the Arabian rhinoceros beetle, *Oryctes agamemnon arabicus*. J Insect Sci 12(1)

Alqarni AS, Awad AM, Raweh HSA, Owayss AA (2017) Pollination ecology of Acacia gerrardii Benth. (Fabaceae: Mimosoideae) under extremely hot-dry conditions. Saudi J Biol Sci 24(7): 1741–1750

Barra J-A, van Harten A (2009) Subclass Collembola, Order Entomobryomorpha, Arthropod fauna of the UAE, pp 43–48

Boudot J-P (2018) *Urothemis thomasi*. The IUCN Red List of threatened species 2018: e. T22817A83841808. https://doi.org/10.2305/IUCN.UK.2018-1.RLTS.T22817A83841808.en

Brock RE, Cini A, Sumner S (2021) Ecosystem services provided by aculeate wasps. Biol Rev 96(4):1645–1675

Brown G, Scherber C, Ramos P Jr, Ebrahim EK (2012) The effects of harvester ant (*Messorebeninus* Forel) nests on vegetation and soil properties in a desert dwarf shrub community in North-Eastern Arabia. Flora 207:503–511

Burt J (2014) The environmental costs of coastal urbanization in the Arabian Gulf. City 18:760–770. https://doi.org/10.1080/13604813.2014.962889

Büttiker W (1979) Fauna of Saudi Arabia: zoological collections from Saudi Arabia, vol 1. Ciba-Geigy Ltd, pp 1–22

Campbell O (2017) A record of the Bladetail Lindenia tetraphylla (Vander Linden, 1825) (Odonata: Anisoptera: Gomphidae) from Abu Dhabi, United Arab Emirates. J Emirat Nat Hist Group 25(25):81

Campbell OJ, Reimer RW (2011) An influx of Sympetrum fonscolombii Selys in The United Arab Emirates. Agrion 15(1):20â

Cassola F, Gardner D, Feulner GR, Howarth B (2012) *Callytron monalisa* (W. Horn, 1927) from the Arabian Peninsula (coleoptera: cicindelidae). Zool Middle East 55(1):137–138. https://doi.org/10.1080/09397140.2012.10648931

Celep F, Atalay Z, Dikmen F, Doğan M, Sytsma KJ, Classen-Bockhoff R (2020) Pollination ecology, specialization, and genetic isolation in sympatric bee-pollinated Salvia (Lamiaceae). Int J Plant Sci 181(8):800–811

Christiansen K (1964) Bionomics of collembola. Annu Rev Entomol 9(1):147–178

Cipola NG, Arbea J, Baquero E, Jordana R, Morais JW, Bellini BC (2018) The survey Seira Lubbock, 1870 (Collembola, Entomobryidae, Seirinae) from Iberian Peninsula and Canary Islands, including three new species. Zootaxa 4458(1):1–66

Culliney TW (2013) Role of arthropods in maintaining soil fertility. Agriculture 3(4):629–659

Da Gama MM (1966) Notes taxonomiques sur quelques espèces de Collemboles. Mem Est Mus Zool Univ Coimbra 295:1–17

Dangles O, Casas J (2019) Ecosystem services provided by insects for achieving sustainable development goals. Ecosyst Serv 35:109–115

Decaëns T, Jiménez JJ, Gioia C, Measey GJ, Lavelle P (2006) The values of soil animals for conservation biology. Eur J Soil Biol 42:S23–S38

Dikow T (2010) Order Diptera, Family Mydidae. Arthropod Fauna UAE 3:608–615

Dobosz R, Levente A, Roberts H (2017) Interesting lacewings (Neuroptera: Berothidae, Nemopteridae, Myrmeleontidae) from the United Arab Emirates

Feulner GR (1999) Two new UAE damselflies: Ceriagrion glabrum and Pseudagrion decorum. Tribulus 9:31

Feulner GR, Judas J (2013) First UAE records of two Odonata: the dragonfly Urothemis thomasi and the damselfly Ischnura nursei. Tribulus 21:4–13

Feulner GR, Roobas B (2014) Observations on the habitat, colouration and behaviour of the tiger beetle *Callytron monalisa* (W. Horn, 1927) (Coleoptera: Cicindelidae) on the Arabian Gulf coast of The United Arab Emirates. J Emirat Nat Hist Group 22:57

Feulner GR, Roobas B (2015) Spiders of The United Arab Emirates: an introductory catalogue. Tribulus 23:4–98

Feulner GR, Reimer RW, Hornby RJ (2007) Updated and illustrated checklist of dragonflies of the UAE. Tribulus 17:37–62

Feulner GR, Roobas B, Hitchings VH, Otto HHH, Roberts HGB, Campbell O, Hornby RJ, Howarth B (2021) Butterflies of The United Arab Emirates including Northern Oman. Motivate Publishing

Forsskål P (1775) Descriptiones animalium avium, amphibiorum, piscium, insectorum, vermium; quae in itinere orientali observavit Petrus Forskål. Hauniae:164

Gardner A, Howarth B (2009) Urbanisation in The United Arab Emirates: the challenges for ecological mitigation in a rapidly developing country. BioRisk 3:27–38
Gess SK, Roosenschoon PA (2016) A preliminary survey of flower visiting by aculeate wasps and bees in the Dubai Desert Conservation Reserve, UAE. J Hymenopt Res 52:81–141
Gillett MP (2009) Unknown or little-known large ground beetles from The United Arab Emirates (Coleoptera: Carabidae: Scaritinae, Harpalinae, Platyninae). Tribulus 18:62–64
Glennie KW (2005) The desert of Southeast Arabia. Gulf PetroLink, Bahrain
Goulet H, Huber JT (1993) Hymenoptera of the world: an identification guide to families. Canada Communication Group-Publishing, Ottawa
Grissell E (2010) Bees, wasps, and ants: the indispensable role of Hymenoptera in gardens. Timber Press, Portland
Hogarth PJ, Tigar BJ, Barth HJ, Böer B (2002) Ecology of sabkha arthropods. Sabkha ecosystems 1:267–282
Howarth B, Gillett MP (2008) The terrestrial and freshwater arthropods of Abu Dhabi Emirate. In: Terrestrial environment of Abu Dhabi Emirate. Environment Agency, Abu Dhabi, pp 380–463
Huber JT, Beardsley JW (2000) A new genus of Fairyfly, Kikiki, from the Hawaiian Islands (Hymenoptera: Mymaridae). Proc Hawaiian Entomol Soc 34:65–70
Jacquemart S, Jacques J-M (1980) A propos d'un Collembole entomobryen à la fois marin et desertique. Annl Soc R Zool Belg 109:9–18
Jones CG, Lawton JH, Shachak M (1994) Organisms as ecosystem engineers. In: Ecosystem management. Springer, New York, pp 130–147
Jongbloed MVD, Feulner GR, Böer B, Western AR (2003) The comprehensive guide to the wild flowers of The United Arab Emirates. ERWDA, Abu Dhabi
Lambret P, Boudot JP, Chelmick D, De Knijf G, Durand É, Judas J, Stoquert A (2017) Odonata surveys 2010–2016 in The United Arab Emirates and the Sultanate of Oman, with emphasis on some regional heritage species. Odonatologica 46(3/4):153–205
Macnamara C (1924) The food of Collembola. Canad Entomol 56(5):99–105
Negm MW (2014) Increasing knowledge of the mite fauna of The United Arab Emirates: new records and a checklist. Acarologia 54(1):113–120
Poole TB (1959) Studies on the food of Collembola in a Douglas fir plantation. In: Proceedings of the zoological Society of London, vol 132. Blackwell Publishing, Oxford, pp 71–82
Punzo F (1998) The biology of camel-spiders: Arachnida, Solifugae. Springer
Reimer RW (2011) Trameabasilaris (Beauvais [sic], 1817) new to UAE. Agrion 15:22–23
Reimer RW, Feulner GR, Hornby RJ (2009) Errata and addenda: updated checklist of dragonflies of the UAE – including a third species of Ischnura damselfly. Tribulus 18:28–36
Rogers R, Van Dam MH (2007) Two new species of Rhaphiomidas (Diptera: Mydidae). Zootaxa 1664(1):61–68
Saji A, Whittington AE (2008) Ant-lion fauna recorded in the Abu Dhabi Emirate (Neuroptera: Myrmeleontidae). Zool Middle East 44(1):83–100
Schneider W, Samraoui B (2015) The status and distribution of dragonflies and damselflies (Odonata) in the Arabian Peninsula. The status and distribution of freshwater biodiversity in the Arabian Peninsula, pp 39–55
Schulz H-J, van Harten A (2014) Subclass Collembola, order Symphypleona. Arthropod Fauna UAE 5:13–21
Shahid SA, Abdelfattah MA, Wilson MA, Kelley JA, Chiaretti JV (2014) United Arab Emirates keys to soil taxonomy. Springer, Netherlands, Dordrecht
Shaw P, Dunscombe M, Robertson A (2011) Collembola in the hyporheos of a karstic river: an overlooked habitat for Collembola containing a new genus for the UK. Soil Organ 83(3): 507–514
Tan J, Howarth B (in preparation) Morphometric analysis of two populations of *Anthracocentrus arabicus* (Thompson, 1877) (Coleoptera: Cerambycidae) from the United Arab Emirates
Telnov D (2008) Order coleoptera, family anthicidae. In: Arthropod fauna of the UAE, vol 1, pp 270–292

Tevis L, Newell IM (1962) Studies on the biology and seasonal cycle of the giant red velvet mite, *Dinothrombium pandorae* (Acari, Trombidiidae). Ecology 43(3):497–505

Tigar BJ, Collingwood CA (1993) A preliminary list of ant records from Abu Dhabi Emirate, UAE. Tribulus 3:13–14

Tosi L, Parisi V (1990) Seira tongiorgii, a new species of Collembola from a volcanic environment. Ital J Zool 57(3):277–281

Vachon M (1979) Arachnids of Saudi Arabia: scorpions. In: Fauna of Saudi Arabia, vol 1. Ciba-Geigy, pp 30–66

van Andel P (2014) First distribution record of a tarantula spider (Araneae, Theraphosidae) found in The United Arab Emirates. Tribulus 22:4–8

van der Meijden A, Langer F, Boistel R, Vagovic P, Heethoff M (2012) Functional morphology and bite performance of raptorial chelicerae of camel spiders (Solifugae). J Exp Biol 215(19): 3411–3418

van Harten A (2008) Arthropod fauna of The United Arab Emirates, vol 1. Dar Al Ummah, Abu Dhabi

van Harten A (2009) Arthropod fauna of The United Arab Emirates, vol 2. Dar Al Ummah, Abu Dhabi

van Harten A (2010) Arthropod fauna of The United Arab Emirates, vol 3. Dar Al Ummah, Abu Dhabi

van Harten A (2011) Arthropod fauna of The United Arab Emirates, vol 4. Dar Al Ummah, Abu Dhabi

van Harten A (2014) Arthropod fauna of The United Arab Emirates, vol 5. Department of the President's Affairs, Abu Dhabi, United Arab Emirates

van Harten A (2015) Arthropod fauna of The United Arab Emirates, vol 6. Department of the President's Affairs, Abu Dhabi, United Arab Emirates

van Lavieren H, Burt J, Feary D, Cavalcante G, Marquis E, Benedetti L, Trick C, Kjerfve B, Sale PF (2011) Managing the growing impacts of development on fragile coastal and marine systems: lessons from the Gulf. A policy report. United Nations University – Institute for Water, Environment, and Health, Hamilton, ON, Canada

Vaughan GO, Burt JA (2016) The changing dynamics of coral reef science in Arabia. Mar Pollut Bull 105:441–458. https://doi.org/10.1016/j.marpolbul.2015.10.052

Wagner DL, Grames EM, Forister ML, Berenbaum MR, Stopak D (2021) Insect decline in the Anthropocene: death by a thousand cuts. PNAS 118(2):e2023989118

Whitford WG (2000) Keystone arthropods as webmasters in desert ecosystems. Invertebrates as webmasters in ecosystems, pp 25–41

Young HJ (2002) Diurnal and nocturnal pollination of Silene alba (Caryophyllaceae). Am J Bot 89(3):433–440

Website

Bugs beyond belief! Shining the spotlight on celebrity creepy-crawlies. Guinness World Records. (2018, Nov 29). https://www.catalogueoflife.org/data/taxon/RT. Accessed 19 Jul 2022

Chapter 18
Marine Mammals of the Emirates: Whales, Dolphins, Porpoises and Dugongs

Ada Natoli and Shamsa Al Hameli

18.1 Marine Mammals from Life on Land to Life Back to Water

Marine mammals comprise a wide range of taxonomic groups that span from polar bears and otters (Carnivora), seals (Pinnipeds), whales, dolphins and porpoises (Cetaceans) and dugongs and manatees (Sirenians). While the survival of each of these groups is tightly dependent on the aquatic environment, only the last two have evolved to spend their entire life in water. Cetaceans (whales, dolphins and porpoises) and Sirenians (dugongs and manatees), in fact, complete all phases of their life cycle in water without relying on returning to land.

Adaptation to the aquatic environment happened independently and at different times for each group of marine mammals (Fig. 18.1). This is supported by the fact that each of them belong to different taxonomic orders that had evolved from different ancestors. Bears, otters and pinnipeds belong to the Order Carnivora, whales, dolphins and porpoises (Cetaceans) belong to the order Artiodactyla (Prothero et al. 2022) and dugongs and manatees (Sirenians) to the superorder Afrotheria (Graphodatsky et al. 2011). The United Arab Emirates, and the broader Arabian region, is home only to marine mammal species belonging to Cetacea and Sirenia, and therefore we will focus our attention on these two main groups.

The infraorder Cetacea evolved approximately 34–40 million years ago (MYA) (McGowen et al. 2009) across the Eocene-Oligocene transition characterized by a drastic climate shift from a warmer planet to an ice dominated one (Hutchinson et al.

A. Natoli (✉)
College of Natural and Health Science, Zayed University, Abu Dhabi, United Arab Emirates

UAE Dolphin Project Initiative, Dubai, United Arab Emirates
e-mail: ada.natoli@zu.ac.ae

S. Al Hameli
Environment Agency Abu Dhabi, Abu Dhabi, United Arab Emirates

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_18

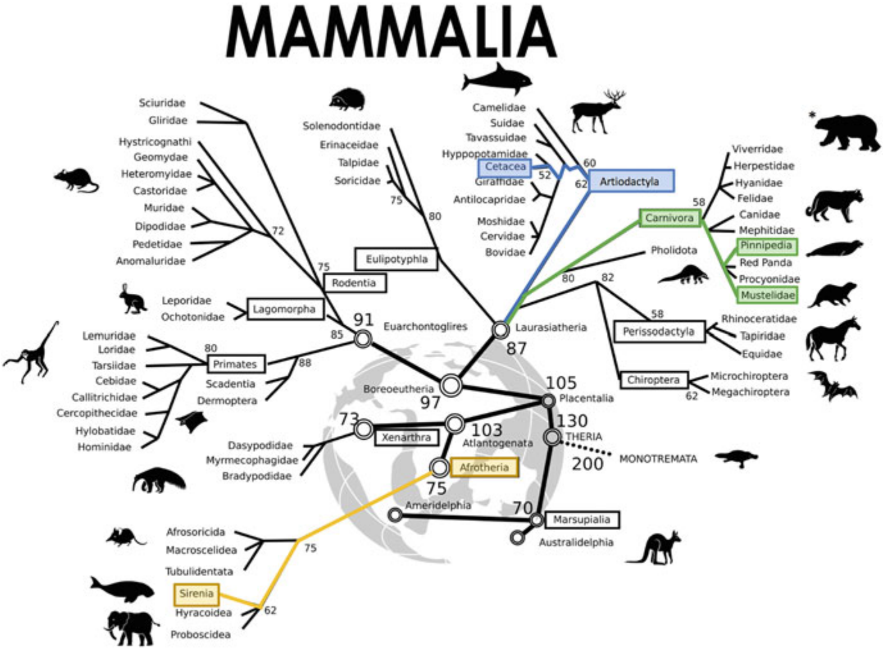


Fig. 18.1 Adaptation to life in water happened independently starting from three different taxonomic groups: Artiodactyla (blue), Carnivora (green) and Afrotheria (yellow). All marine mammals originated from these three groups at different times. Image source: Modified from *An evolutionary tree of mammals* by Pixelsquid, used under Creative Commons (CC-BY-2.0)

2021). This global cooling coincided with the disappearance of the suborder Archaeoceti, whose fossils have been retrieved from around the world. The cooling of ocean waters likely impacted productivity and fuelled the rapid evolutionary radiation of new species more adapted to exploit the newly available resources. The ancestor of modern whales, dolphins and porpoises (Cetacea) has been identified in the genus *Pakicetus* (Fig. 18.2), a four-legged semi-aquatic predator belonging to the late Archaeocetis, which remains were first excavated in Pakistan (Gingerich and Russell 1981; Bajpai and Gingerich 1998).

Cetaceans speciated into two groups both still in existence: Mysticetes and Odontocetes. Currently they comprise a total of 93 officially recognised species (Marine mammal Taxonomy Committee 2022). Mysticetes include all the “real whales” (i.e. baleen whales, as they all have filter-feeding baleen structures instead of teeth) subdivided into 4 families totalling 15 species. The Odontocetes include all the toothed whales, dolphins and porpoises and is subdivided into 10 families for a total of 78 different species, of which one, the river dolphin or “bajii”, that used to inhabit the Yangtze River (China) was declared extinct in 2006 (Society of Marine Mammology 2022).

Evidence of the early Sirenians appeared in the Eocene (approximately 56-33.9 MYA), when three of the four families of Sirenians, Prorastomidae, Protosirendiae,

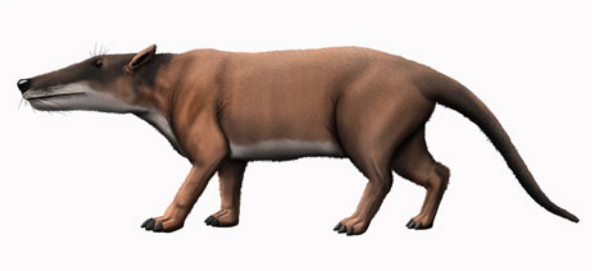


Fig. 18.2 Reconstruction of a species of *Pakicetus* ancestor of whales, dolphins and porpoises, from bone remains. These creatures were endemic to Pakistan approximately 50 MYA (Eocene period). (Source: Pakicetus inachus by Zerosmany, used under Creative Commons (CC-BY-SA 4.0)

Dugongidae occurred, while Tricherchidae only appeared later in the Oligocene (approximately 33.9-23 MYA). Today only two families of the modern Sirenian exist, the families Dugongidae and Tricherchidae. Dugongidae consist of many extinct fossil species and only two modern species: the larger Steller's sea cow (*Hydrodamalis gigas*) which has been declared extinct in 1768, when it was hunted to extinction (Anderson 1995) and the dugong (*Dugong dugon*), still existing today. Tricherchidae also exhibits a number of fossil extinct species, but three species are still extant today. These include the Amazonian manatee (*Trichechus inunguis*), the West Indian manatee (*Trichechus manatus*) and the African manatee (*Trichechus senegalensis*).

For a mammal, adapting to a full life in water involves overcoming some considerable physiological challenges, mostly linked to the different physiochemical characteristics of the aquatic environment versus a terrestrial/air-based habitat. Water is much denser than air, implying higher friction and therefore more energy is required to move through it. On the other hand, it offers more buoyancy enabling bigger size organisms to exist without being overcome by gravity. Sound travels faster and heat is dispersed more quickly in water than in air, whereas diffusion is slower compared to a gaseous medium and light does not travel long distances.

Marine mammals and in particular whales, dolphins, porpoises and dugongs (Cetaceans and Sirenians) evolved to overcome and exploit these characteristics and they are one of the best represented examples, in terms of fossil records, of macroevolutionary adaptation to a new environment (Thewissen and Bajpai 2001; McGowen et al. 2014; Springer et al. 2015).

18.1.1 Mastering Movement in a Liquid Environment

Cetaceans and Sirenians evolved by modifying their body to optimise movement in an aquatic environment, maximising speed and minimising energy consumption.

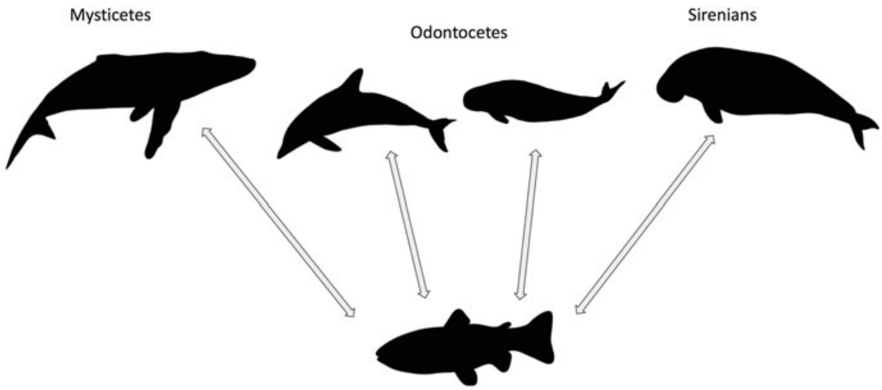


Fig. 18.3 Despite no direct evolutionary link, all marine mammal groups that fully adapted to live in water have converged to a very similar body shape to fish, as this is the most efficient shape to move in water. Note that in all marine mammals the tail is perpendicular to the body axis, whereas in all fish it is positioned on the same axis. Image source: Authors own work; Ada Natoli

The posterior limbs have been reduced to two vestigial bones and the body re-converged to a fusiform fish-like shape, to optimise hydrodynamics (Fig. 18.3).

The propelling force is produced by the fluke connected with strong dorsal muscles (Fish et al. 2008; Domning 2000). Skin also plays an important role to minimise friction. Cetaceans have completely lost any type of hair (few hairs are usually visible only in newborns on top of their snout (or rostrum)) as well as sudoriferous (sweat) and sebaceous (oil) glands, and their skin is extremely compact and smooth compared to terrestrial mammals. The external skin cells are replaced extremely frequently to maintain smoothness and they is covered by a thin layer of jelly-lipid droplets to minimise friction (Hicks et al. 1985). Dugongs still have scattered hair across their body, and it is denser around the muzzle and mouth area. For movement, dugongs also rely on their strong fluke and they manoeuvre using their flippers which are roughly 15% of their body length (Spain and Heinsohn 1975).

18.1.2 Breathing Air While Living in Water

Although they live in water, Cetaceans and Sirenians, being mammals, have lungs and need to breathe air. However, some species can stay underwater for an extended time. For example, sperm whales can spend up to 2 hours immersed without returning to the surface. This is achieved through different adaptive physical and physiological changes. Lungs are proportionally bigger than in terrestrial mammals allowing more air intake in one breath. Furthermore, oxygen is stored principally in the muscles, thanks to the presence of high quantities of a modified myoglobin molecule with a higher affinity to oxygen than the one found in other mammal muscles. Ultimately, during diving, cetaceans are able to reduce the peripheral circulation, channelling the blood, and therefore oxygen, only to the vital organs and muscles needed during the underwater activity. In Cetaceans, the nostrils have moved on the back of the body in what is known as a "blowhole" to facilitate breathing while surfacing. During diving, the nasal passages are closed by the nasal plugs to avoid water entering the upper respiratory tract. Real whales (Mysticetes) have two separated nasal passages and therefore the blowhole presents two openings. In tooth whales, dolphins and porpoises (Odontocetes) instead, the nasal passages are fused and therefore the blowhole has only one opening, except in the sperm whale, where they are fused only at the proximity of the blowhole, causing the sideway blow characteristic of this species (Fig. 18.4).

Unlike Cetaceans, Sirenians do not have blowholes, instead, they have nostril openings located on top of their snout (Nishiwaki and Marsh 1985). They breathe when they break the surface, at times starting to exhale no more than 10 cm below the water, breaking the surface with a loud exhale, wrinkling their snout to elevate their narial openings above the surface to inhale (Anderson and Birtles 1978). Studies showed that dugongs have been recorded at depths of up to 70 m (Marsh and Saalfeld 1989) but they spend over 70% of their time at depths no more than 3 m (Louise Chilvers et al. 2004).

18.1.3 Maintaining Warm Bodies

Being mammals and therefore warm-blooded animals, Cetaceans and Sirenians have developed physiological mechanisms to counteract the faster loss of heat that takes place in water. Under their thick skin, the body is surrounded by a thick layer of blubber, which functions as energy storage, but also importantly as a thermal insulator in cooler waters. Interestingly, it seems that the blubber has also an important function in ensuring a constant temperature in warmer waters, like the UAE waters, where for most of the year the temperature is above 30 °C reaching peaks of 36–38 °C in summer. In this situation, the blubber appears to function as a "heat sink" allowing the body temperature to be maintained at the optimal level (Heath and Ridgway 1999). Furthermore, the overall body circulation is re-organized with deep arteries bringing warm blood from the inner parts of the body, pairing with the veins returning blood from the peripheral areas (bringing colder blood back to the core). This ensures that the temperature of the blood is maintained homogeneously throughout the body.

18.1.4 How to "Smell" Food in Water

Cetaceans and Sirenians have practically lost their sense of smell, as water does not support the fast dispersion of volatile molecules as they do in air. This is an example

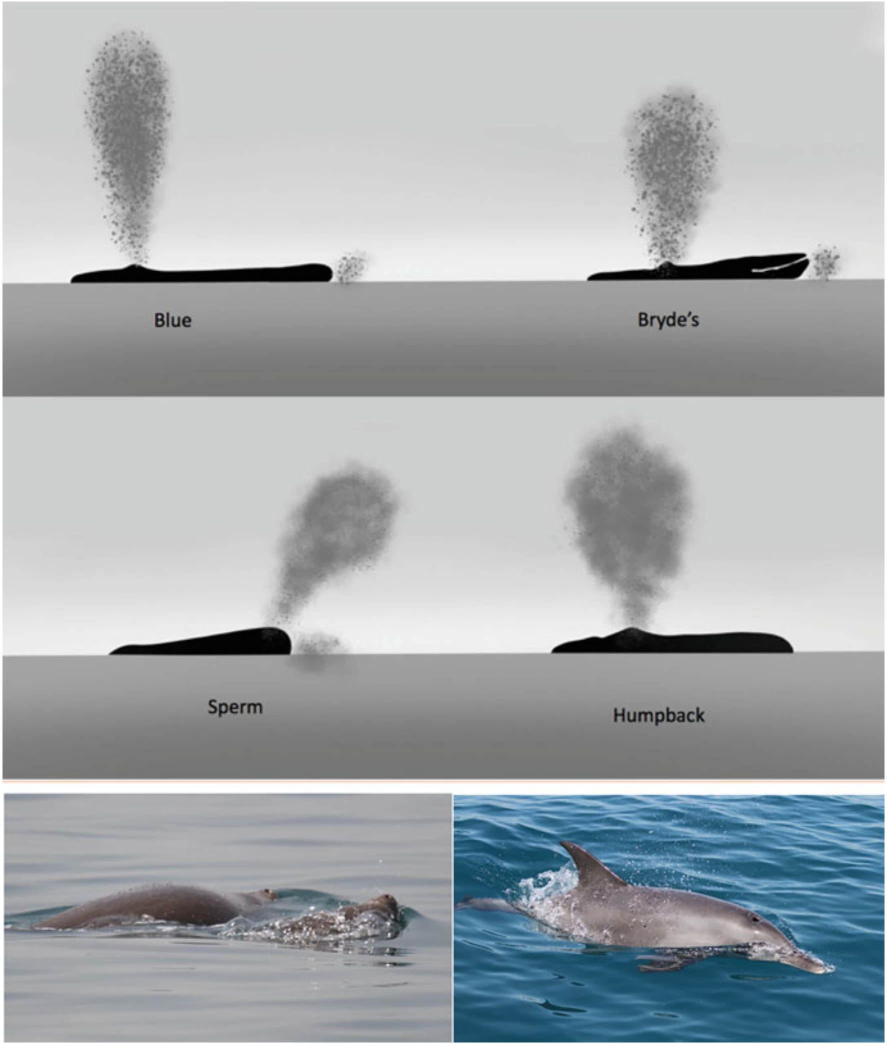


Fig. 18.4 Above: at sea, whales and large toothed whale species can be identified by the shape of the blow, often visible from far away. Below: dolphins (right) and dugongs (left) surfacing. Dolphins and porpoises generally surface with the blowhole curving their body whereas dugongs surface with the nostrils first and then submerge curving their body. Image and photo credits: Ada Natoli

of convergent degeneration of a sense that is not useful in an environment such as water (Liu et al. 2019) and this is also observed in sea snakes (Kishida 2021). On the other hand, these groups of animals have developed other means of navigating and searching for food resources, such as echolocation and somatosensation (Marriott et al. 2013).

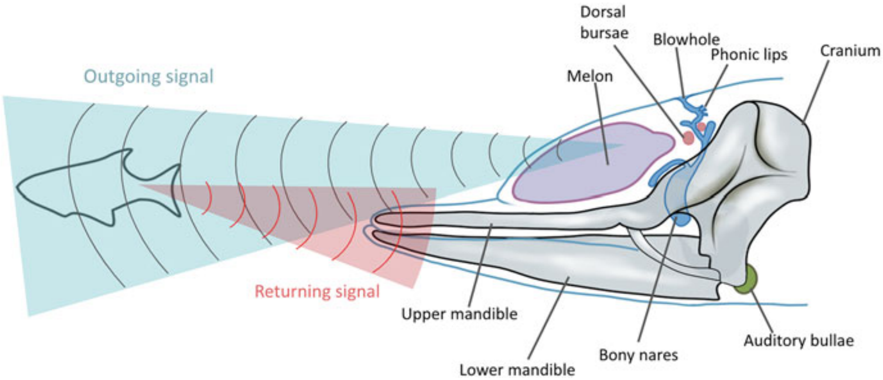


Fig. 18.5 Echolocation in Odontocetes explained. The sound is produced in the nasal area and sent through the melon that regulates its intensity and direction. The returning sound is detected through the lower mandible and ultimately processed by the brain. Modified from *Toothed Whale Echolocation* by Achat (CC BY-SA 4.0) and Toothed whale sound production by Joota (CC BY-SA 4.0)

In real whales (Mysticetes), it is suggested that although reduced in size, the olfactory system is still present and may still play a role in detecting dimethylsulfoxide in the air while surfacing to breathe. This compound is produced during the grazing by zooplankton on phytoplankton (Marriott et al. 2013); detecting this, enables these filter-feeding mammals to identify potentially rich feeding grounds and maximise the catch.

Tooth whales, dolphin and porpoises (Odontocetes), on the other hand, have perfected the use of echolocation, exploiting the fact that in water, sound travels faster than in air. Echolocation involves the production of a beam of sound (clicks) at a certain frequency (usually high frequency sound). The sound travels and hits an object or prey and is reflected back slightly modified, depending on the characteristics of the object (shape consistency, size etc.). The returning sound is detected and the difference in signal is processed by the brain, providing the animal with the information needed to define the object (or prey) detected. The sound is produced in the nasal passage through structures called “monkey-lips” and its intensity and direction are modulated by the melon, a fat-based organ positioned on the forehead of the animal. The returning sound is then detected through a sound sensitive area in the jaw bone (Fig. 18.5). Odontocetes utilise echolocation mainly for hunting, navigating and investigating the surrounding environment.

As light travels shorter distances in water, echolocation has become the main system utilised by tooth whales, dolphins and porpoises (Odontocetes) to “see” their environment. This is particularly true for those species that live in very muddy waters or species that inhabit riverine waters or prefer estuarine shallow areas. Most of the river dolphins have lost the ability of sight and rely solely on echolocation to inspect their surroundings, hunt and navigate. The Arabian Gulf coastal waters are notoriously pretty murky, mainly due to their sandy bottom, and coastal species, such as humpback dolphins and finless porpoises would heavily utilise echolocations. Also deep diving species, like beaked and sperm whales, heavily rely on echolocation. They usually hunt at depths where light cannot penetrate, like in the waters off the Fujairah Emirates, where the continental slope reaches about 700 m depth. In these habitats echolocation is crucial for survival. The sound is not only utilise to locate the prey, but it is often so powerful that stuns the prey so it can be promptly caught.

Dugongs (Sirenians) do not have underwater olfactory capabilities, which led them to adopt and use other ways of sensing their environment. They have a developed tactile sensory system that relies on sensitive whisker-like functional hairs known as vibrissae that function as a sensory organ, helping them navigate, explore their environment and detect seagrass to feed on (Griebel and Schmid 1996; Marriott et al. 2013; Marshall et al. 1998, 2003; Newman and Robinson 2006; Reep et al. 1998). In UAE seagrass meadows are highly concentrated in the central region of the Abu Dhabi Emirate and strictly linked to the presence of dugongs.

18.1.5 Keeping in Touch Underwater

No matter how transparent water may be, light travels a limited distance underwater and therefore sight is not an effective method to navigate or look for food underwater. All Cetaceans and Sirenians have monocular vision, meaning that their eyes are located on the sides of the head. In Cetaceans, visual detection and acuity vary between species, and variation in performance at different light levels and distances is generally linked to preferred habitats and behaviour. Dugongs have very small eyes and generally have poor vision (Wirdzek and Ketten 1999).

In water, as the ability to keep each other in sight is difficult, sound becomes a crucial tool for communication among groups of organisms. Cetaceans rely on strong social structures to ensure survival, and to maintain that, communication among individuals is imperative. Their social structures enable the protection of the individuals and their calves as a group, allows for the implementation of group-hunting techniques to maximise the catch, the successful reproduction and the transfer of knowledge from one generation to the next, and ensures that information such as the location of feeding or breeding grounds and specific hunting techniques suitable for the local environment are not lost (Cantor and Whitehead 2013; Rendell and Whitehead 2001). Dugongs appear to have a strong bond only between mother and calf (Fig. 18.6), but they can gather in the hundreds, and herds of up to 600 individuals have been recorded in the Gulf (Preen 2004). There is no evidence that these herds have a social structure and it is suggested that these aggregations are based on resource availability, like seagrass, shelter, and water temperature (Marsh et al. 2011).

In Cetaceans, sound-based communication can be non-vocal and vocal (Dudzinski et al. 2009). The first one is generally based on behavioural actions such as tail slaps, breaching or leaping of an individual (Fig. 18.7).

Fig. 18.6 Left: a dugong mother-calf pair Marawah, Al Dhafra Region (Credit: Maitha Al Hameli). The mother calf bond appears to be the main strong bond between individuals. Right: a group of Indo-Pacific bottlenose dolphins travelling together. Photo credits: Ada Natoli

Fig. 18.7 Typical dolphin's behavioural events that can be used as non-vocal communication among individuals. From left to right clockwise: tailslap, inverted leap, side leap. Tailslap is usually consider as sign of distress/warning for the group. Photo credits: Ada Natoli

These actions produce a sound that can be heard by other members of the group at long distances. Vocal communication is instead based on sounds produced directly by the individual's larynx, and this can be finely controlled and produced by the animal. Real whales (Mysticetes) generally utilise low-frequency (deep bass) sounds that can travel long distances and allow individuals to keep in contact even if dispersed across areas of thousands of kilometers. Mating songs are among the best known examples, especially for humpback whales, and they are usually population specific. Tooth whales, dolphins and porpoises (Odontocetes) utilise higher frequency sounds (whistles and clicks) to communicate with each other. The frequency and sound profile can be species specific, though some species utilise the same frequency spectrum. Species in this group have a highly complex language that we still do not fully comprehend. Signature whistles have been documented for a number of years both in captive and wild populations and recent studies have confirmed that they are used to call individuals among the group (King et al. 2013).

In Sirenians, especially dugongs, little is known about their communication, but they have been described to communicate in chirps, whistles, squeals, barks, trills and squeaks (Dudzinski et al. 2009). It has also been recorded that mothers and calves exchange communication to keep track of each other. They have also been known to vocalize while foraging (Anderson and Barclay 1995) and vocalization is also believed to be used to attract mates (Reynolds and Odell 1991). As in Cetaceans, in addition to verbal communication, there have been signs of non-verbal communication, like tail slapping (Anderson and Barclay 1995).

18.2 Ecological Role in the Marine Environment

Cetaceans are crucial for maintaining a healthy marine ecosystem. Like all predators, they all have an important role in regulating and controlling their prey populations. Toothed whales, dolphins and porpoises generally feed on other marine species such as fishes and cephalopods (e.g. squid), preying selectively on the weakest individuals of a group, and so strengthening the overall prey population. On the other hand, whales feed aspecifically, principally on copepods and small fish shoals. Due to their considerable body size, and therefore the conspicuous amount of food needed, they can put substantial pressure on their prey population. However, they also strongly promote the ocean's primary production recirculating essential nutrients through their excrement, proportionate to their body size, and this ultimately enhances the growth of the prey populations (Roman et al. 2014). Whales facilitate the exchange of nutrients both across seas, through their migration patterns, promoting the transfer of nutrients from nutrient-rich areas to nutrient-deprived areas. They also move nutrients across the marine column by feeding at different depths and releasing wastes at the surface (Roman and McCarthy 2010).

Due to their size and long lifespan (whales can live up to 100 years with some species reaching up to 200 years), whales represent a very effective long-term carbon sequestration system. When deceased, whales' bodies sink to the bottom of the sea where they also become a hotspot of biodiversity for deep sea scavenger species that recycle the nutrients.

Dugongs are herbivores and feed principally on seagrass and seaweed. They play an extremely important role in maintaining the seagrass beds and increasing seagrass resilience. Their feeding behaviour helps decrease the organic matter in the sediments, which in turn stimulates biodiversity, decreases hypoxia and improves the health of the seagrass beds (Valentine and Duffy 2006). It can also help decrease the risk of harmful algal overgrowth, as well as decrease the number of seagrass leaf diseases (Valentine and Duffy 2006). This means that areas that support large numbers of dugongs can provide better quality food than those that support few or no dugongs (Aragones and Marsh 2000). An explanation of this may be in the fact that grazing allows the necessary natural turnover of nutrients and therefore enhance the seagrass growth. It has also been recorded that the nutritional value of seagrasses can increase after being damaged, including the damage caused by grazing (Karban and Myers 1989). It has also been demonstrated that dugongs assist in the dispersal of seagrass seeds (Tol et al. 2016).

Cetaceans are considered “sentinel species”, meaning that their status reflects the health of the whole marine ecosystem. Sitting at the top of the marine food chain, spending the whole life in water, feeding exclusively on seafood and having a long lifespan, their health is directly and immediately affected by changes happening at any level of the marine ecosystem (Bossart 2011; Schwacke et al. 2013). Monitoring their health can give advance notice of the presence of any health risk factor in the marine environment that can ultimately also affect humans. For example, the presence of toxic contaminants, marine litter (Fossi et al. 2020), toxic algae blooms or emerging diseases. Cetaceans are also recognised as indicators of climate change (Williamson et al. 2021).

18.3 Marine Mammal Diversity in UAE

The UAE overlooks both the Arabian Gulf and the Sea of Oman. These two basins exhibit very different oceanographic characteristics. The Gulf is a shallow enclosed sea characterized by extreme fluctuations in water temperature and salinity, whereas the Sea of Oman is part of the northern Indian Ocean and reaches a depth of over 1500 m (See Chap. 4). These characteristics affect the type of marine mammal species encountered in each sea.

Of the 93 species of cetaceans currently recognised to occur worldwide, a total of 17 species of cetaceans have been confirmed to occur in the Emirates: 3 species of real whales (Mysticetes), 14 species among tooth whales, dolphins and porpoises (Odontocetes) and one species of Sirenian, the dugong, with 14 species occurring in the Sea of Oman (Fujairah and Sharjah) and 11 in the Arabian Gulf waters (Table 18.1).

The records for most cetacean species in UAE waters is mainly based on occasional sightings or strandings (Fig. 18.8). Information on population identity, population size, migration routes and residency is still unknown for most species, as dedicated surveys are limited and usually only include coastal areas. The limited information is particularly true for those species that usually frequent areas further offshore, especially on the Arabian Gulf coast, as regular dedicated offshore surveys to investigate the cetacean occurrence have not yet been performed.

The UAE’s Sea of Oman waters exhibit a higher number of cetacean species, in particular deep diver species, like the sperm whale and typical pelagic species such

Table 18.1 List of the species of marine mammals recorded in the United Arab Emirates waters with respective common name, scientific name and Arabic name (with correspondent English pronunciation). In UAE some species are locally called as: [a] □□□ (diqes), [b] □□□□ (feyaymah). The IUCN Global and National Red list status and occurrence in the different basins is also reported

	Classification	Species	English name	Arabic name	English Pronunciation	IUCN Global Red List status	IUCN National Red List status 2019	Gulf	Sea of Oman
1	Artiodactyla, Balaenopteridae	*Balaenoptera edeni*	Bryde's whale	حوت بريدي	Hoot Brydey	LC	DD	x	x
2	Artiodactyla, Balaenopteridae	*Balaenoptera musculus*	Blue whale	حوت أزرق	Hoot Azraq	EN	DD		x
3	Artiodactyla, Balaenopteridae	*Megaptera novaeangliae*	Humpback whale (Arabian Sea subpopulation)	حوت أحدب الظهر	Hoot Ahdab Al Dhaher	EN	EN	x	x
4	Artiodactyla, Physeteridae	*Physeter macrocephalus*	Sperm whale	حوت العنبر	Hoot Al Anmab	VU	DD		x
5	Artiodactyla, Kogiidae	*Kogia sima*	Dwarf sperm whale	حوت العنبر القزم	Hoot Al Anmab Al Gazam	LC	DD	x	x
6	Artiodactyla, Delphinidae	*Delphinus delphis tropicalis*	Indo-Pacific common dolphin	دلفين[a] المحيط الهندي/الهادي الشائع	Dolfeen Al Moheet Al Hindy Al Hadey Al Shaia'a	LC	DD	x	x
7	Artiodactyla, Delphinidae	*Grampus griseus*	Risso's dolphin	دلفين ريسو	Dolfeen riso	LC	DD		x
8	Artiodactyla, Delphinidae	*Orcinus orca*	Killer whale	حوت قاتل	Hoot Gatil	DD	DD	x	x
9	Artiodactyla, Delphinidae	*Pseudorca crassidens*	False killer whale	حوت القاتل الكاذب	Hoot Al Gatil Al Kathib	NT	DD	x	x
10	Artiodactyla, Delphinidae	*Sousa plumbea*	Indian Ocean humpback dolphin	دلفين[a] المحيط الهندي أحدب الظهر	Dolfeen Al Moheet Al Hindy Ahdab Al Dhaher	EN	EN	x	

11	Artiodactyla, Delphinidae	*Stenella attenuata*	Pantropical spotted dolphin	دلفين مداري منقط	Dolfeen Al Madary Al Mnagad	LC	DD		x
12	Artiodactyla, Delphinidae	*Stenella coeruleoalba*	Striped dolphin	دلفين مخطط	Dolfeen Mokhatat	LC	DD		x
13	Artiodactyla, Delphinidae	*Stenella longirostris*	Spinner dolphin	دلفين الدوار	Dolfeen Al Dawar	LC	DD	x	x
14	Artiodactyla, Delphinidae	*Steno bredanensis*	Rough-toothed dolphin	دلفين خشن الأسنان	Dolfeen Khashin Al Asnan	LC	DD		x
15	Artiodactyla, Delphinidae	*Tursiops aduncus*	Indo-Pacific bottlenose dolphin	دلفين[a] الهندي/ الهادي قاروري الأنف	Dolfeen Al Hindy/Al Hadey Garoory Al Anf	NT	EN	x	
16	Artiodactyla, Delphinidae	*Tursiops truncatus*	Common bottlenose dolphin	دلفين شائع قاروري الأنف	Dolfeen Shaia'a Garoory Al Anf	LC	DD		x
17	Artiodactyla, Phocoenidae	*Neophocaena phocaenoides*	Indo-Pacific finless porpoise	خنزير[b] المحيط الهندي/ الهادي عديم الزعنفة	Khanzeer Al Moheet Al Hindy Al Hady Adeem Al Zenofah	VU	EN	x	
18	Sirenia, Dugongidae	*Dugong dugon*	Dugong	بقرة بحر	Bagarat Bahar	VU	NT	x	

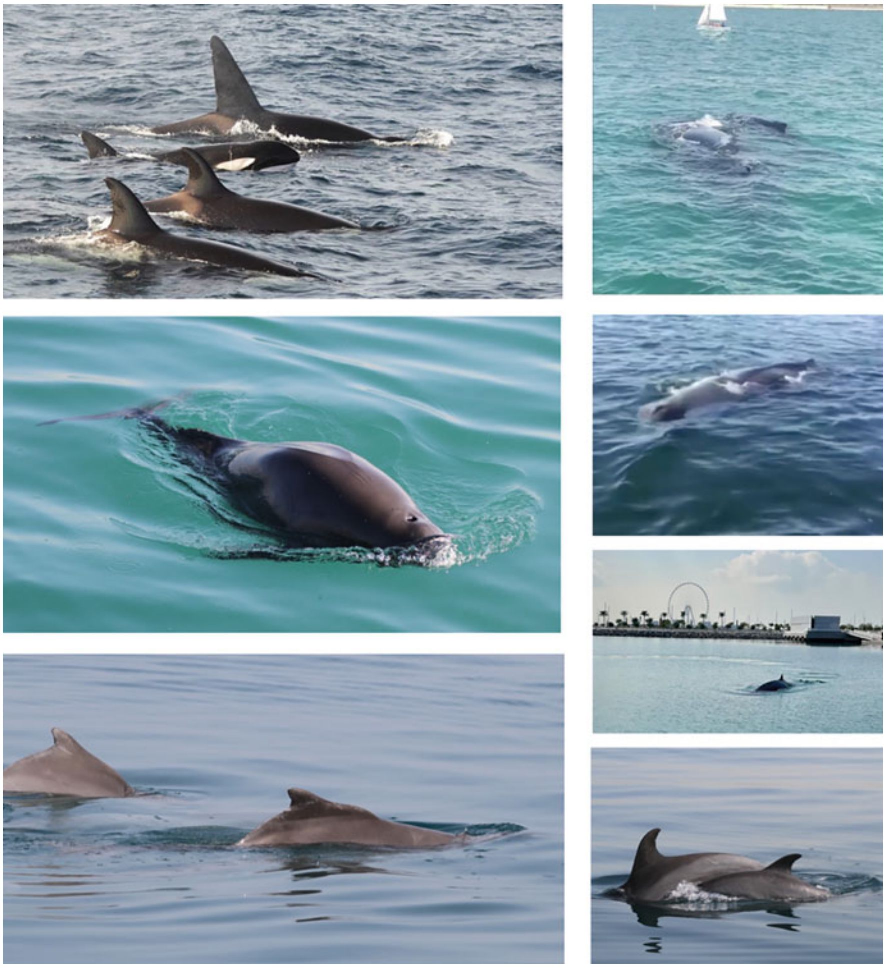


Fig. 18.8 Some of the cetacean species occurring in UAE waters. From top left clockwise: four rare species reported through citizen science “Report a sighting” programme (see Box 18.2). Killer whales, rare but regular in UAE waters. The male (tallest fin) and one of the females reported in this picture have been sighted twice in UAE waters in different years and once in Sri Lanka (Credit: Chammika Kumara/Northern Indian Ocean Killer Whale Alliance) proving long distance migration of this species in the northern Indian Ocean. Arabian Sea humpback whale mother and calf sighted in front of Kite Beach, Dubai in November 2017. A juvenile sperm whale reported off Dibba in February 2016. A juvenile Bryde’s whale in Dubai Harbour in January 2022 (Credit: Jasmin Alice). Following, the three most regular coastal species in UAE waters: Indo Pacific bottlenose dolphin (mother and calf), Indian Ocean humpback dolphin and the small Indo-Pacific finless porpoise. Unless otherwise noted, image credits: Ada Natoli)

as the Risso’s dolphin, rough-toothed dolphin, and striped dolphins. This is expected considering the oceanographic characteristics of the area that include the presence of a deep canyon that reaches up to 700 m depth. On the other hand, the Gulf UAE coastal waters are home to more resident coastal species, such as the Indian Ocean Humpback dolphin, Indo-Pacific finless porpoise, the Indo-Pacific bottlenose dolphins and the dugong, which generally favour shallow waters. These species do not occur on the UAE's Sea of Oman waters, nor across most of the Oman coast, creating a significant distribution gap.

The genetic and demographic connectivity of the cetacean populations occuring in UAE waters has not been investigated. Considering the young age of the Gulf, which flooded to its current coastline only ca. 6000 years ago due to sea level rise following the cessation of the most recent ice age (See Chap. 4), it is undoubtable that all marine species present in the Gulf waters originated from the northern Indian Ocean populations.

Population differentiation and consequently speciation may happen in a relatively short evolutionary time, especially in species that tend to be resident, and/or if a sudden physical barrier to the movement of individuals across regions appears, and/or in situations of adjacent drastic different environments (see Box 18.1).

Bioregions have been identified as a possible cause of population differentiation in other species (Vargas-Fonseca et al. 2021; Wiszniewski et al. 2010). Although the Strait of Hormuz may not represent a physical barrier to the movement of highly mobile species, such as marine mammals, the environmental characteristics of the Gulf compared to the neighbouring Sea of Oman are drastically different (Chap. 4). Those species that reside in the Gulf were likely forced through a fast adaptation process in order to be able to survive in such a different environment and this specialisation to the local environment may have driven and drive population differentiation.

Genetically distinct populations between the Arabian Gulf and the Sea of Oman have been identified for a number of marine species including coral (Smith et al. 2022; Torquato et al. 2022), scarface rockskipper (Mehraban et al. 2020), silver pomfret (Golestani et al. 2010) and even large mobile species such as sailfish (Hoolihan et al. 2004). Based on these considerations, we cannot exclude that especially for those small cetacean species resident in the Gulf waters, the Gulf populations may be differentiated from their peers inhabiting the Indian Ocean. Both morphological and genetic studies are needed to clarify this, as this has important implications for conservation and management.

For migratory species, this may not be the case. Except for the blue whale, the other two species of Mysticetes, Bryde's and humpback whales have been recorded in both the Arabian Gulf and the Sea of Oman. To date, studies on assessing the migratory movements of these animals in the region have not been conducted and the occurrence in both basins is mainly based on data from citizen science projects across the region. The presence in both basins, however, suggests that it is likely that these species' home ranges include the whole Gulf and the broad northern Indian Ocean and they utilise the Gulf waters periodically. For humpback whales the Gulf has been identified as part of their original home range based on historical records (Dakhteh et al. 2017). The Arabian Sea humpback whale population inhabiting the Northern Indian Ocean has been identified as a distinct population, genetically separated from the other southern hemisphere populations (Pomilla et al. 2014) and the most threatened humpback whale population in the world, with an estimated number of mature individuals below 100 that makes it listed as Endangered according to the IUCN Red List (Minton et al. 2008).

Killer whales represent another example. Despite the deficit of data on this species in the whole Indian Ocean and Arabian region, thanks to citizen science initiatives (e.g. Northern Indian Ocean Killer Whale Alliance, Orca Project Sri Lanka, UAE Dolphin Project Initiative), scientists have been able to demonstrate movements of individuals across the Arabian Gulf and through the northern Indian Ocean. Based on photographic images gathered by the public and published in the news, two individuals, one male and one female, were sighted in Abu Dhabi waters in 2008, then in Sri Lanka in 2015, and then back in UAE waters in 2019 (Natoli, Pers. Comm.). These data, although opportunistically collected, highlighted for the first time the long migratory route that this species is undertaking in this region.

The rare pygmy sperm whale, another deep diving species for which data are extremely scarce worldwide, has also been recorded in both of the UAE's basins, but only based on two individual strandings (one in Dubai and one in Fujairah).

Box 18.1 Speciation Can Happen Fast: The Case of the Black Sea Cetaceans

The Black Sea is an enclosed basin, situated adjacent to the Mediterranean Sea and connected only through the narrow Turkish strait system. Compared to the adjacent Mediterranean Sea, the Black Sea is characterised by lower average temperatures and lower salinity due to the inflow of fresh water from rivers. It is a recent basin that originated around 7800 years ago (Ryan et al. 1997). There are three species of small cetaceans that inhabit the Black Sea: the Black Sea bottlenose dolphin (*Tursiops truncatus ponticus*), the Black Sea common dolphin (*Delphinus delphis ponticus*) and the Black Sea harbour porpoise (*Phocoena phocoena relicta*). Each has been recognised as distinct sub-species of their neighbouring Mediterranean and Atlantic populations based on morphological, genetic and life history data (Natoli et al. 2005, 2008; Viaud-Martínez et al. 2007, 2008; Moura et al. 2013).

18.4 Distribution and Habitats

The distribution of small or sessile species is generally correlated to their inability to move extensive distances or having sedentary lifestyles. Highly mobile species, such as marine mammals, are potentially able to cover great distances and, therefore, defining their distribution is more challenging. Although they can potentially move, not all highly mobile species are ubiquitous, as their distribution (or spatial use) is usually driven by factors such as prey availability that, in turn, are linked to specific habitat characteristics.

In the marine realm identifying these characteristics, and therefore defining habitats, is more challenging than on land as we still do not have a clear understanding of all the interactions between abiotic and biotic factors that are involved in defining a specific habitat. The marine environment also implies a third dimension as different habitats can occur at different depths in the same location. These are characterised not only by the depth but also by other factors such as currents, amount of light, etc. that in turn support the presence of different prey species.

The distribution of different marine mammals is surely influenced by prey availability, as different species specialise in different food resources. For highly specialised species, this means that they will likely occur where their food resources occur and therefore in a specific habitat. Dugongs, for example, feeding solely on seagrass, mainly occur in correspondence of seagrass meadows. Their presence is an indicator of healthy seagrass habitat and their role in maintaining a healthy seagrass meadow is crucial (Cleguer et al. 2020). However, highly opportunistic species, for example, bottlenose dolphins may feed on a wide variety of prey, but still they exhibit a specific distribution, and in many cases individuals of a population unlikely move more than a few hundred km of range. Aside from food resources, distribution in cetaceans is also driven by social structure, behaviour and knowledge transfer across generations.

In UAE coastal waters there are four main species of marine mammal for which there are sufficient data to attempt to define their distribution. Dugong distribution was investigated in 1986 and 1999 with two dedicated aerial surveys that included Saudi Arabia, Bahrain, Qatar and Abu Dhabi waters and found the highest abundance of this species in the Marawah Marine Biosphere Reserve in Abu Dhabi (which was established after this study) and between Bahrain and Qatar (Preen 2004). These surveys act as a baseline for the dugong population in the Gulf. Continuous monitoring in Abu Dhabi waters is conducted yearly by the Environment Agency Abu Dhabi which estimated a fairly stable population of almost 3000 individuals. Overall, the Gulf is believed to host the second largest population of dugongs in the world after Australia, following an estimate of approximately 5800 dugongs reported for the southern and south-western Gulf area in 1989 (Preen 2004). In UAE, Dugongs are rarely reported north of Abu Dhabi city, with occasional rare sightings recorded in Dubai waters (Preen 2004; Natoli, Pers. Comm.). There is archaeological evidence from UAE studies that Dugongs were a means of livelihood for the coastal communities of the Gulf, as a source of meat, oil, fat and hide (Beech 2010). No dugongs have been recorded along the east coast of the UAE.

Two dolphin species, the Indian Ocean humpback dolphin and the Indo-Pacific bottlenose dolphin are regularly utilising the Gulf UAE coastal waters, as well as the only species of porpoise present in the region: the Indo-Pacific finless porpoise (Fig. 18.9). The distribution of these species in UAE waters appears to extensively overlap as they all are found in coastal waters and a number of mixed sightings have also been recorded (Natoli, Pers. Comm.).

However, a more in-depth habitat modelling analysis, based on over 1200 sightings opportunistically reported by the public as part of a citizen science project,

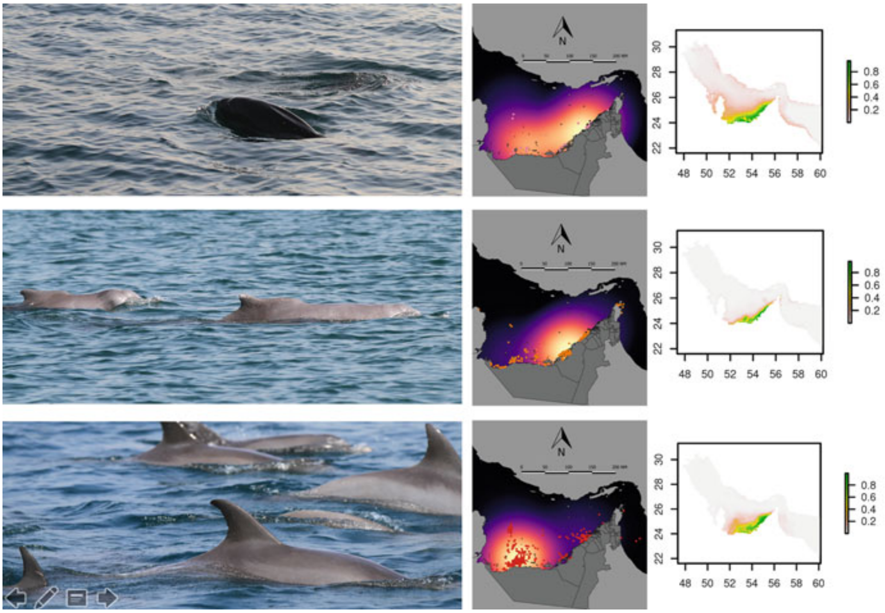


Fig. 18.9 The three main species of small cetaceans regularly occurring in UAE coastal waters, corresponding heat maps representing the density of sightings reported by the public (center) and maps showing the most probable suitable habitat in the Gulf (Maxent habitat suitability model analysis). From the top: Indo-Pacific finless porpoise, Indian ocean humpback dolphin and Indo Pacific Bottlenose dolphin. Photo credits: Ada Natoli; Maps modified from Figs. 18.2 and 18.3 in Natoli et al. (2022), under license

has suggested fine-scale dietary partitioning among them that, in turn, delineates different preferred habitats (Natoli et al. 2022).

The distribution of the Indo-Pacific finless porpoise principally includes the coastline of Abu Dhabi Emirate up to Dubai. It is generally observed close to the coast, but sightings have also been recorded up to 20 km offshore of Dubai. As few offshore surveys have been conducted, we do not have information on whether it may also utilise the offshore waters of the Gulf and whether the deficit of recordings far from shore simply represents a sampling bias. Finless porpoises have never been reported along the east coast of the UAE in Fujairah and Sharjah emirates nor along the Musandam peninsula; in the UAE, its distribution appears to be confined to the Gulf waters. Its presence is confirmed in the Iranian waters of Qeshm Island, along the Pakistan coastline as well as along the west coast of India. In the Gulf, it has also been recorded in Saudi Arabia, between Bahrain and Qatar, and Kuwait waters though not frequently. The ecological niche modelling (Fig. 18.9) revealed that the finless porpoise shows the broadest habitat suitability among the three species and is likely feeding on a different variety of prey sitting at different trophic (feeding) levels than the other two dolphin species (Natoli et al. 2022).

Fig. 18.10 Typical social behaviour observed in Indian ocean bottlenose dolphins (left) and Indian Ocean humpback dolphins (right). Tooth marks and scratches visible on the bodies are results of interactions between individuals. Photo credits: Ada Natoli

The two dolphin species, the Indian Ocean humpback dolphin and the Indo-Pacific bottlenose dolphin instead appear to sit at the same trophic level, possibly feeding on similar species and having similar energy requirements. However, the main factor that appears to play a key role in differentiating their habitat is "distance from coast", with the humpback dolphin strongly favouring waters no more than a few hundred metres away from the shore, whereas bottlenose dolphins prefer coastal waters but further away from the shore. This leaves the Indian Ocean humpback dolphin with a very restricted preferred habitat which is highly anthropogenic impacted, as it overlaps with the waters most utilised by humans, especially in proximity to the UAE main cities.

In Cetaceans, spatial utilisation across a range can also be influenced by behaviour. Cetaceans are highly intelligent species with advanced cognitive abilities and complex language. They exhibit a strong social organisation and this, in turn, can influence their population structure and distribution. For example, in a number of regions, it has been observed that bottlenose dolphins, despite being potentially able to travel thousands of kilometres, form distinct subpopulations with a limited home range of a few hundred kilometres. These subpopulations rarely intersect with the neighbouring subpopulations, and their home range does not overlap in space nor time (Pleslić et al. 2019; Genov et al. 2019). Individuals within a subpopulations form long-term relationships beyond the mother/calf or opportunistic aggregation to better exploit food resources. Individuals often form long-term bonds with peers or among individuals of the same sex, or they develop relationships that follow a hierarchical structure (Fig.18.10). Language and communication also play an extremely important role to connect individuals, and exchange information and knowledge transfer across generations (Rendell and Whitehead 2001). Social organisation can vary among species, with some species exhibiting a more open structure (for example more oceanic species such as common or stripe dolphins) while others exhibit more closed structure, such as coastal bottlenose dolphins or humpback dolphins (Pleslić et al. 2019; Wang et al. 2015). The more subpopulations are isolated, the less resilient to environmental stressors are. The same stressor can affect different subpopulations in a different way, or different subpopulations can be exposed to different environmental stressors. If they are isolated the lack of individual exchange can further exacerbate the stressors' effect.

In the UAE, in particular for coastal species, such as the Indo-Pacific bottlenose dolphin and the Indian Ocean humpback dolphins, it is plausible to believe that distinct subpopulations may occur across the coastline. However, detailed studies aiming to assess the population and social structure have not been conducted, yet.

18.5 Conservation of Marine Mammals in the UAE

In the UAE, there are archaeological records showing the use of marine mammals by humans since prehistoric times (Stewart et al. 2011; Beech and Glover 2005). Despite this long relationship, information on these species in the UAE is still extremely scarce. Also, the general general public is usually unaware of their existence in UAE waters and this makes it even more difficult to promote conservation measures.

Despite a number of marine mammal surveys conducted in the 1980s and onwards, detailed distribution and population abundance estimates are still not available for most of the cetacean species, and for many only occurrence (presence/absence) data over time are available. The first estimate of a population trend for small cetaceans was obtained from two aerial surveys conducted in Abu Dhabi waters in 1986 and in 1999. The comparison of the number of dolphin sightings recorded, reported an alarming decrease and suggested a 71% decline across the 13 years period (Preen 2004). However, specific population abundance estimates for each species were not calculated. To date, the only available population abundance estimates were obtained from boat-based surveys conducted in 2014–2015 in Abu Dhabi coastal waters, and focused only on the Indian Ocean humpback dolphin (701 individuals estimated, 95%CI: 473–845; Díaz López et al. 2017) individuals and the Indo-Pacific bottlenose dolphin (782 individuals, 95%CI: 496–1294; Díaz López et al. 2021).

The lack of historic baseline information raises concerns, as we currently have no means to assess the population trends for these species over time – during a period in which the UAE, and across the region, have been drastically affected by anthropogenic activity (Sheppard et al. 2010). The risk is “shifting baselines”: considering that what we experience today is the “natural status” of our environment, not having any means of understanding how it was in the past (Pauly 1995). This is of even more concern for long-living species and those with slow reproduction rates, such as marine mammals. The risk involved is that conservation measures based on recent data may not be sufficient to allow the population to recover to a sustainable level to ensure the long-term persistence of the species. The deficit in monitoring also prevents evaluation of the effectiveness of any management or conservation efforts that have been put in place (e.g. MPA establishment) (Fanning et al. 2021).

The main threats that affect marine mammals are common worldwide: bycatch in fishing activities, disturbance (boat traffic, land reclamation activities), habitat loss, pollution, prey depletion (overfishing), ship strikes, direct capture, underwater noise, and climate change. However, in UAE, and in the broader Arabian region, there have been no detailed threat assessments for factors that may affect each species. It is, therefore, difficult to act in order to minimise these threats through management intervention. No country in the GCC has an effective national stranding network through which mortality is reported or data are shared, preventing cross-border collaboration that is necessary for management of mobile species.

In the UAE marine mammals are protected under "The Federal Law No. 23, Chapter 4, article 28 of the year 1999 concerning Exploitation, Protection and Development of the Living Aquatic Resources In the State Of The United Arab Emirates" that states: "...It is also impermissible to catch whales, sea cows (Alatwam) and other sea mammals of all species and sizes... except for scientific research purposes and after obtaining a written permission from the Competent Authority." However, no specific legislation is in place to enhance their protection or to minimise the primary threats to marine mammals. Specific legislation is considered more urgent for more sedentary, resident coastal species as they are the most affected by the rapid increase in human activities due to their limited movement.

When research information is available, threats can be identified and targeted regulations can be formulated and implemented. In the Abu Dhabi emirate, annual dugong population monitoring has been conducted since the late 1990's. In 2018, surface net-fishing was banned to help the recovery of fish stocks; this change incidentally will help marine mammals - 80 dugongs had been discovered drowned in illegal nets since 2014 (Al Hameli, pers. comm.). Scientific data has also been utilised to define the Marawah Marine Biosphere Reserve. This marine protected area (MPA) was declared a protected area per the Emirate Decree No. 18 of 2001 with the aim of protecting ecosystems, fisheries, and endangered and threatened species such as dugongs and sea turtles. The Marawah Marine Biosphere hosts large seagrass beds and is, therefore, vital for supporting dugong population in the southern Arabian Gulf.

Cetacean information across the UAE remains poorly developed. Based on the IUCN National Red list assessment, 76% of the cetacean species occurring in UAE are data deficient, meaning that insufficient data are available to assess their extinction risk status in UAE waters. No MPA's have been defined based on the habitat requirements of these species in the UAE nor elsewhere in northeastern Arabia.

In the past decade in the UAE a number of new initiatives have taked place that focused on increasing public knowledge of cetaceans. The UAE Dolphin Project Initiative started in 2012 with the aim of gathering scientific information on whales and dolphins in order to support conservation measures for their protection. A public awareness and citizen science campaign was initiated to engage the public to report sightings (Box 18.2: Report a Sighting Campaign). The initiative conducted the first cetacean-dedicated year-long survey in Dubai waters in 2013–2014, under the auspices of Dubai Municipality and with the support of private stakeholders. This campaign confirmed the regular occurrence of three species of cetaceans and collecting photo-identification data for the Indian Ocean Humpback and the Indo-Pacific bottlenose dolphins. The initiative also actively collected stranding information and data across UAE. In collaboration with Zayed University and with the support of private stakeholders, a second boat-based survey was initiated

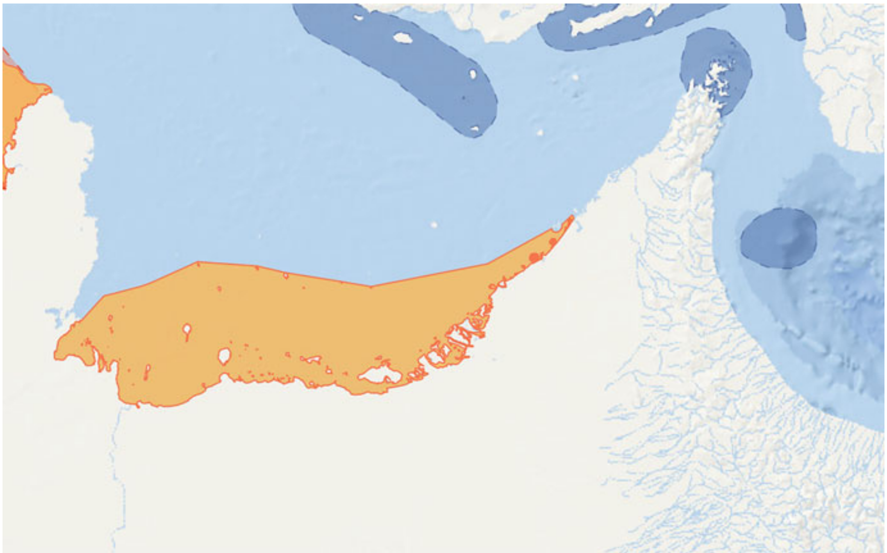


Fig. 18.11 The Southern Gulf and Coastal Waters Important Marine Mammal Area (orange) extends from Qatar to the northern border of the Dubai Emirate. The Offshore Waters of the Emirate of Fujairah Area of Interest (blue) is hoping to be recognised as IMMA in the future if more data will become available to support its importance for marine mammals. Map from IUCN-MMPATF (2023) and reused under their Terms of Service (CC BY-NC-SA 4.0)

in 2021 and continued through 2022, passive acoustic monitoring surveys and stomach contents analyses from stranded cetaceans was added to the research program.

As part of the conservation efforts, the Environment Agency Abu Dhabi started a dedicated vessel-based dolphin survey in 2014, in partnership with the Bottlenose Dolphin Research Institute. The surveys, conducted twice a year, covered the entire coast of the Abu Dhabi emirate, helped delineate Abu Dhabi dolphins' occurrence, population, distribution, abundance and threats (Díaz López et al. 2018, 2021).

Fujairah Whales and Dolphins Project began conducting regular boat-based and aerial surveys in 2015 with the aim to provide information on the marine mammal species occurring in the offshore waters of the Fujairah emirate, which is characterised by deep oceanic waters. To date, the project has reported a remarkable diversity of cetaceans occurring in the area, recording two new species that had not previously been known for the region (Baldwin et al. 2018).

The Sharjah Environment Protected Areas Authority launched a Stranding Response Programme in 2021 aiming to expand the existing knowledge on the biodiversity, ecology, and threats of marine fauna, and support the development of conservation policies while also educating the community on the importance of species conservation.

In 2019, based on the published and unpublished scientific information, the Abu Dhabi and Dubai coastal waters have been internationally identified as Important Marine Mammal Areas (The Southern Gulf and Coastal Waters IMMA), whereas the Offshore Waters of the Emirate of Fujairah have been identified as Area of Interest (AoL) for marine mammals (https://www.marinemammalhabitat.org/immas/) (Fig. 18.11).

This is already a remarkable achievement, but more research and regional scientific collaboration on these species are needed, as well as the urgent formulation and implementation of specific conservation measures to ensure their protection in the UAE and the whole Gulf.

Box 18.2 Report Your Sightings! Everyone Can Contribute to the Conservation of Marine Mammals. If You Encounter a Whale or a Dolphin the Information You Can Collect Is Extremely Useful to Science!

1. Take videos or pictures (if you can). You are there at that moment so you are the scientist! Only you can make a difference! Every image of any quality is better than nothing and will help experts to confirm the species. If you can take pictures and videos when you are on the side of the whale or the dolphins so the fin is clearly visible and can help scientists to track the individuals, but please keep a safe distance!
2. Take note of the date, time, and approximate location (if not GPS is available, a dot on google map works great!). If you can, report how many individuals you see and if there are babies.
3. CALL as soon as possible if you are witnessing a special sighting or you encounter a dead animal so an expert can hopefully reach the site and gather more information.
4. Share your data: www.uaedolphinproject.org, Facebook, Instagram, WhatsApp or call 0566717164.

18.6 Recommended Readings

For more detailed information on the evolution of marine mammals see Sutaria et al. (2015). For more information on the individual marine mammal species discussed here, see Notarbartolo di Sciara et al. (2021).

Acknowledgment We would like to thank Francesca Rognoni for the production of the graphics.

References

Anderson PK (1995) Competition, predation, and the evolution and extinction of Steller's sea cow, Hydrodamalis gigas. Mar Mamm Sci 11(3):391–394

Anderson PK, Barclay RMR (1995) Acoustic signals of solitary dugongs: physical characteristics and behavioral correlates. J Mammal 76(4):1226–1237

Anderson PK, Birtles A (1978) Behaviour and ecology of the dugong, Dugong Dugon (Sirenia): observations in Shoalwater and Cleveland Bays, Queensland. Wildl Res 5(1):1. https://doi.org/10.1071/wr9780001

Aragones L, Marsh H (1999) Impact of dugong grazing and turtle cropping on tropical seagrass communities. Pac Conserv Biol 5(4):277–288

Bajpai S, Gingerich PD (1998) A new Eocene archaeocete (Mammalia, Cetacea) from India and the time of origin of whales. PNAS 95(26):15464–15468

Baldwin R, Willson A, Looker E, Buzás B (2018) Growing knowledge of cetacean fauna in the Emirate of Fujairah, UAE. Tribulus 26:32–42

Beech MJ (2010) 'Mermaids of the Arabian Gulf: archaeological evidence for the exploitation of dugongs from prehistory to the present. Liwa (J Nat Center Doc Res) 2(3):3–18

Beech MJ, Glover E (2005) The environment and economy of an Ubaid-related settlement on Dalma Island, United Arab Emirates. Paléorient 2005:97–107

Bossart GD (2011) Marine mammals as sentinel species for oceans and human health. Vet Pathol 48(3):676–690

Cantor M, Whitehead H (2013) The interplay between social networks and culture: theoretically and among whales and dolphins. Philos Trans R Soc B Biol Sci 368(1618):20120340

Cleguer C, Garrigue C, Marsh H (2020) Dugong (*Dugong dugon*) movements and habitat use in a coral reef lagoonal ecosystem. Endanger Species Res 43:167–181

Dakhteh SMH, Ranjbar S, Moazeni M, Mohsenian N, Delshab H (2017) The Persian Gulf is part of the habitual range of the Arabian Sea humpback whale population. J Mar Biol Oceanogr 6(3):2

Díaz López B, Grandcourt E, Methion S, Das H, Bugla I, Al Hameli M, Al Ameri H, Abdulla M, Al Blooshi A, Al Dhaheri S (2017) The distribution, abundance and group dynamics of Indian Ocean humpback dolphins (*Sousa plumbea*) in the emirate of Abu Dhabi (UAE). J Mar Biol Assoc U K 98(5):1119–1127

Díaz López B, Grandcourt E, Methion S, Das H, Bugla I, Al Hameli M, Al DS et al (2018) The distribution, abundance and group dynamics of Indian Ocean humpback dolphins (*Sousa plumbea*) in the Emirate of Abu Dhabi (UAE). J Mar Biol Assoc U K 98(5):1119–1127

Díaz López B, Methion S, Das H, Bugla I, Al Hameli M, Al Ameri H, Grandcourt E et al (2021) Vulnerability of a top marine predator in one of the world's most impacted marine environments (Arabian Gulf). Mar Biol 168(7):1–11

Domning DP (2000) The readaptation of Eocene sirenians to life in water. Hist Biol 14(1–2): 115–119

Dudzinski KM, Thomas JA, Gregg JD (2009) Communication in marine mammals. In: Encyclopedia of marine mammals. Academic Press, New York, pp 260–269. https://doi.org/10.1016/b978-0-12-373553-9.00064-x

Fanning LM, Al-Naimi MN, Range P, Ali A-SM, Bouwmeester J, Al-Jamali F, Burt JA, Ben-Hamadou R (2021) Applying the ecosystem services - EBM framework to sustainably manage Qatar's coral reefs and seagrass beds. Ocean Coast Manag 205:1–16. https://doi.org/10.1016/j.ocecoaman.2021.105566

Fish FE, Howle LE, Murray MM (2008) Hydrodynamic flow control in marine mammals. Integr Comp Biol 48(6):788–800

Fossi MC, Baini M, Simmonds MP (2020) Cetaceans as ocean health indicators of marine litter impact at global scale. Front Environ Sci 8:586627

Genov T, Centrih T, Kotnjek P, Hace A (2019) Behavioural and temporal partitioning of dolphin social groups in the northern Adriatic Sea. Mar Biol 166(1):1–14

Gingerich PD, Russell DE (1981) *Pakicetus inachus*, a new archaeocete (Mammalia, Cetacea) from the early-middle Eocene Kuldana formation of Kohat (Pakistan)

Golestani N, Gilkolaei SR, Safari R, Reyhani S (2010) Population genetic structure of the silver Pomfret, *Pampus argenteus* (Euphrasén, 1788), in the Persian Gulf and the sea of Oman as revealed by microsatellite variation. Zool Middle East 49(1):63–72

Graphodatsky AS, Trifonov VA, Stanyon R (2011) The genome diversity and karyotype evolution of mammals. Mol Cytogenet 4(1):1–16

Griebel U, Schmid A (1996) Color vision in the manatee (*Trichechus manatus*). Vis Res 36:2757–2747

Heath ME, Ridgway SH (1999) How dolphins use their blubber to avoid heat stress during encounters with warm water. Am J Phys Regul Integr Comp Phys 276(4):R1188–R1194

Hicks BD, Aubin DJS, Geraci JR, Brown WR (1985) Epidermal growth in the bottlenose dolphin, *Tursiops truncatus*. J Investig Dermatol 85(1):60–63

Hoolihan JP, Premanandh J, D'Aloia-Palmieri MA, Benzie JAH (2004) Intraspecific phylogeographic isolation of Arabian Gulf sailfish Istiophorus platypterus inferred from mitochondrial DNA. Mar Biol 145:465–475

Hutchinson DK, Coxall HK, Lunt DJ, Steinthorsdottir M, De Boer AM, Baatsen M, Zhang Z (2021) The Eocene–Oligocene transition: a review of marine and terrestrial proxy data, models and model–data comparisons. Clim Past 17(1):269–315

IUCN-MMPATF (2023, March) Global dataset of important marine mammal areas (IUCN-IMMA). Made available under agreement on terms of use by the IUCN Joint SSC/WCPA marine mammal protected areas task force and made. https://www.marinemammalhabitat.org/imma-eatlas

Karban R, Myers JH (1989) Induced plant responses to herbivory. Annu Rev Ecol Syst 20(1):331–348

King SL, Sayigh LS, Wells RS, Fellner W, Janik VM (2013) Vocal copying of individually distinctive signature whistles in bottlenose dolphins. Proc R Soc B Biol Sci 280 (1757):20130053

Kishida T (2021) Olfaction of aquatic amniotes. Cell Tissue Res 383(1):353–365

Liu A, He F, Shen L, Liu R, Wang Z, Zhou J (2019) Convergent degeneration of olfactory receptor gene repertoires in marine mammals. BMC Genomics 20(1):1–14

Louise Chilvers B, Delean S, Gales NJ, Holley DK, Lawler IR, Marsh H, Preen AR (2004) Diving behaviour of dugongs, *Dugong dugon*. J Exp Mar Biol Ecol 304(2):203–224. https://doi.org/10.1016/j.jembe.2003.12.010

Marine Mammal Taxonomy Committee (2022) https://marinemammalscience.org/science-and-publications/list-marine-mammal-species-subspecies/

Marriott S, Cowan E, Cohen J, Hallock RM (2013) Somatosensation, echolocation, and underwater sniffing: adaptations allow mammals without traditional olfactory capabilities to forage for food underwater. Zool Sci 30(2):69–75

Marshall CD, Huth GD, Edmonds VM et al (1998) Prehensile use of perioral bristles during feeding and associated behaviors of the Florida manatee (*Trichechus manatus latirostris*). Mar Mamm Sci 14:274–289

Marsh H, Saalfeld WK (1989) Distribution and abundance of dugongs in the northern great barrier-reef Marine park. Wildl Res 16(4):429–440

Marsh H, O'Shea TJ, Reynolds JE III (2011) Ecology and conservation of the Sirenia: dugongs and manatees, vol No. 18. Cambridge University Press

Marshall CD, Maeda H, Iwata M, Furuta M, Asano S, Rosas S, Reep RL (2003) Orofacial morphology and feeding behavior of the dugong, Amazonian, west African and Antillean manatees (Mammalia: Sirenia): functional morphology of the muscular-vibrissal complex. J Zool 259(3):245–260

McGowen MR, Gatesy J, Wildman DE (2014) Molecular evolution tracks macroevolutionary transitions in Cetacea. Trends Ecol Evol 29(6):336–346

McGowen MR, Spaulding M, Gatesy J (2009) Divergence date estimation and a comprehensive molecular tree of extant cetaceans. Mol Phylogenet Evol 53(3):891–906

Mehraban H, Esmaeili HR, Zarei F, Ebrahimi M, Gholamhosseini A (2020) Genetic diversification, population structure, and geophylogeny of the Scarface rockskipper *Istiblennius pox* (Teleostei: Blenniidae) in the Persian Gulf and Oman Sea. Mar Biodivers 50(2):1–12

Minton G, Collins T, Pomilla C, Findlay KP, Rosenbaum H, Baldwin R, Brownell Jr, RL (2008) *Megaptera novaeangliae* (Arabian Sea subpopulation). The IUCN Red List of Threatened Species 2008:e.T132835A3464679. https://doi.org/10.2305/IUCN.UK.2008.RLTS.T132835A3464679.en

Moura AE, Nielsen SC, Vilstrup JT, Moreno-Mayar JV, Gilbert MTP, Gray HW, Hoelzel AR et al (2013) Recent diversification of a marine genus (*Tursiops* spp.) tracks habitat preference and environmental change. Syst Biol 62(6):865–877

Natoli A, Birkun A, Aguilar A, Lopez A, Hoelzel AR (2005) Habitat structure and the dispersal of male and female bottlenose dolphins (*Tursiops truncatus*). Proc R Soc B Biol Sci 272(1569): 1217–1226

Natoli A, Canadas A, Vaquero C, Politi E, Fernandez-Navarro P, Hoelzel AR (2008) Conservation genetics of the short-beaked common dolphin (*Delphinus delphis*) in the Mediterranean Sea and in the eastern North Atlantic Ocean. Conserv Genet 9(6):1479–1487

Natoli A, Moura AE, Sillero N (2022) Citizen science data of cetaceans in the Arabian/Persian Gulf: occurrence and habitat preferences of the three most reported species. Mar Mamm Sci 38(1): 235–255

Newman LA, Robinson PR (2006) The visual pigments of the west Indian manatee (*Trichechus manatus*). Vis Res 46:3326–3330

Nishiwaki N, Marsh H (1985) Dugong, Dugong dugon (Muller, 19776)—Handbook of marine mammals

Notarbartolo di Sciara G, Baldwin R, Braulik G, Collins T, Natoli A (2021) Marine mammals of the Arabian seas. In: The Arabian seas: biodiversity, environmental challenges and conservation measures. Springer, Cham, pp 637–678

Pauly D (1995) Anecdotes and the shifting baseline syndrome of fisheries. Trends Ecol Evol 10 (10):430

Pleslić G, Rako-Gospić N, Miočić-Stošić J, Blazinić Vučur T, Radulović M, Mackelworth P, Holcer D et al (2019) Social structure and spatial distribution of bottlenose dolphins (*Tursiops truncatus*) along the Croatian Adriatic coast. Aquat Conserv Mar Freshwat Ecosyst 29(12): 2116–2132

Pomilla C, Amaral AR, Collins T, Minton G, Findlay K, Leslie MS, Rosenbaum H et al (2014) The world's most isolated and distinct whale population? Humpback whales of the Arabian Sea. PLoS One 9(12):e114162

Preen A (2004) Distribution, abundance and conservation status of dugongs and dolphins in the southern and western Arabian Gulf. Biol Conserv 118(2):205–218. https://doi.org/10.1016/j.biocon.2003.08.014

Prothero DR, Domning D, Fordyce RE, Foss S, Janis C, Lucas S, Uhen M et al (2022) On the unnecessary and misleading taxon "Cetartiodactyla". J Mamm Evol 29(1):93–97

Reep RL, Marshall CD, Stoll ML, Whitaker DM (1998) Distribution and innervation of facial bristles and hairs in the Florida manatee (*Trichechus manatus latirostris*). Mar Mamm Sci 14: 257–273

Rendell L, Whitehead H (2001) Culture in whales and dolphins. Behav Brain Sci 24(2):309–324

Reynolds JE III, Odell DK (1991) Manatees and dugongs. Facts on File, New York

Roman J, McCarthy JJ (2010) The whale pump: marine mammals enhance primary productivity in a coastal basin. PLoS One 5(10):e13255

Roman J, Estes JA, Morissette L, Smith C, Costa D, McCarthy J, Smetacek V et al (2014) Whales as marine ecosystem engineers. Front Ecol Environ 12(7):377–385

Ryan WB, Pitman WC III, Major CO, Shimkus K, Moskalenko V, Jones GA, Yüce H et al (1997) An abrupt drowning of the Black Sea shelf. Mar Geol 138(1–2):119–126

Schwacke LH, Gulland FM, White S (2013) Sentinel species in oceans and human health. In: Environmental toxicology. Springer, New York, pp 503–528

Spain AV, Heinsohn GE (1975) Size and weight allometry in a north Queensland population of Dugong dugon (Muller)(Mammalia: Sirenia). Aust J Zool 23(2):159–168

Sheppard C, Al-Husiani M, Al-Jamali F, Al-Yamani F, Baldwin R, Bishop J, Zainal K et al (2010) The Gulf: a young sea in decline. Mar Pollut Bull 60(1):13–38

Smith EG, Hazzouri KM, Choi JY, Delaney P, Al-Kharafi M, Howells EJ, Aranda M, Burt JA (2022) Signatures of selection underpinning rapid coral adaptation to the world's warmest reefs. Sci Adv 8(2):eabl7287

Society of Marine Mammology (2022) https://marinemammalscience.org/science-and-publications/list-marine-mammal-species-subspecies/

Springer MS, Signore AV, Paijmans JL, Vélez-Juarbe J, Domning DP, Bauer CE, Campbell KL (2015) Interordinal gene capture, the phylogenetic position of Steller's sea cow based on molecular and morphological data, and the macroevolutionary history of Sirenia. Mol Phylogenet Evol 91:178–193

Stewart JR, Aspinall S, Beech M, Fenberg P, Hellyer P, Larkin N, Strohmenger CJ et al (2011) Biotically constrained palaeoenvironmental conditions of a mid-Holocene intertidal lagoon on the southern shore of the Arabian gulf: evidence associated with a whale skeleton at Musaffah, Abu Dhabi, UAE. Quat Sci Rev 30(25–26):3675–3690

Sutaria D, Arthur R, Sathasivam K (2015) Marine mammals in subcontinental waters. In: Johnsingh AJT, Manjrekar N (eds) Mammals of South Asia. Permanent Black, New Delhi

Thewissen JGM, Bajpai S (2001) Whale origins as a poster child for macroevolution: fossils collected in the last decade document the ways in which cetacea (whales, dolphins, and porpoises) became aquatic, a transition that is one of the best documented examples of macroevolution in mammals. BioScience 51(12):1037–1049

Tol SJ, Coles RG, Congdon BC (2016) Dugong dugon feeding in tropical Australian seagrass meadows: implications for conservation planning. PeerJ 4:e2194

Torquato F, Bouwmeester J, Range P, Marshell A, Priest MA, Burt JA, Møller PR, Ben-Hamadou R (2022) Population genetic structure of a major reef-building coral species Acropora downingi in northeastern Arabian Peninsula. Coral Reefs 41(3):743–752

Valentine JF, Duffy JE (2006) The central role of grazing in seagrass ecology. In: Larkum AW, Orth RJ, Duarte CM (eds) Seagrasses: biology, ecology and conservation, Chapter 20, pp 463–501

Vargas-Fonseca OA, Yates P, Kirkman SP, Pistorius PA, Moore DM, Natoli A, Hoelzel AR et al (2021) Population structure associated with bioregion and seasonal prey distribution for Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) in South Africa. Mol Ecol 30(19):4642–4659

Viaud-Martínez KA, Vergara MM, Goldin PE, Ridoux V, Öztürk AA, Öztürk B, Bohonak AJ et al (2007) Morphological and genetic differentiation of the Black Sea harbour porpoise *Phocoena phocoena*. Mar Ecol Prog Ser 338:281–294

Viaud-Martinez KA, Brownell RL Jr, Komnenou A, Bohonak AJ (2008) Genetic isolation and morphological divergence of Black Sea bottlenose dolphins. Biol Conserv 141(6):1600–1611

Wang X, Wu F, Turvey ST, Rosso M, Tao C, Ding X, Zhu Q (2015) Social organization and distribution patterns inform conservation management of a threatened Indo-Pacific humpback dolphin population. J Mammal 96(5):964–971

Williamson MJ, ten Doeschate MT, Deaville R, Brownlow AC, Taylor NL (2021) Cetaceans as sentinels for informing climate change policy in UK waters. Mar Policy 131:104634

Wirdzek D, Ketten DR (1999) Marine mammal sensory systems. In: Biology of marine mammals, vol 1. Smithsonian Institution Press, Washington, DC, pp 117–175

Wiszniewski J, Beheregaray LB, Allen SJ, Möller LM (2010) Environmental and social influences on the genetic structure of bottlenose dolphins (Tursiops aduncus) in south eastern Australia. Conserv Genet 11(4):1405–1419

Chapter 19
Marine Reptiles of the United Arab Emirates

Fadi Yaghmour, Johannes Els, Clara Jimena Rodríguez-Zarate, and Brendan Whittington-Jones

19.1 Introduction

Marine reptiles are ectothermic (i.e. cold-blooded) and air-breathing species (see Fig. 19.1) found in tropical and subtropical waters, with the exception of one species which have feeding areas in colder Atlantic waters. Through several unique adaptations, marine reptiles can sustain life at sea, although some species retain ancestral terrestrial reproductive and physiologically-driven behaviors. With the exception of sea turtles, limited information is available on the ecology, behavior and habitat preference of other marine reptiles (Rasmussen et al. 2011; Fuentes et al. 2012). Present-day living (hereafter extant) species of marine reptiles include seven species of sea turtles, an estimated 62 species of sea snakes and one species of marine iguana subdivided into eleven sub-species. Within the waters of the UAE, there are five species of sea turtles, two of which are breeding residents and the remainder forage and migrate through UAE waters; as well as nine sea snake species.

F. Yaghmour (✉)
Hefaiyah Mountain Conservation Centre (Scientific Research Department), Environment and Protected Areas Authority, Kalba, Sharjah, United Arab Emirates

J. Els
Environment and Protected Areas Authority, Breeding Centre for Endangered Arabian Wildlife, Sharjah, United Arab Emirates

C. J. Rodríguez-Zarate · B. Whittington-Jones
Sharjah Desert Park (Scientific Research Department), Environment and Protected Areas Authority, Sharjah, United Arab Emirates

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_19

Fig. 19.1 Green Sea Turtle, juvenile, taking a breath on the surface in the Gulf of Oman, UAE. Photo: Fadi Yaghmour

19.2 Sea Turtles

Sea turtles along with terrestrial tortoises and freshwater turtles are members of the Order Testudines. Sea turtles are distinguished from other turtles by their inability to retract their head into their shell, having streamlined hydrodynamic form, flattened paddle-like limbs (hereafter flippers) and they spend their entire life at sea with the exception of when they are nesting (Rasmussen et al. 2011; Fuentes et al. 2012; Manire et al. 2017). Their well-developed salt glands allow for the excretion of excess salts from the body. Sea turtle body sizes are much larger than freshwater turtles, allowing for gigantothermy—the ability to retain body temperature through reduced surface area to volume ratio (Manire et al. 2017; Paladino et al. 1990). The largest sea turtle species, Leatherback, is physiologically adapted for its pelagic habits and navigate cold, subpolar waters; and are able to dive to great depths for long periods of time (Bostrom et al. 2010).

19.2.1 Habits and Behavior of Sea Turtles

During nesting season, gravid female sea turtles emerge from the water to nest on sandy beaches, responding to a combination of physiological and environmental factors that in some cases influence mass nesting-events like those observed in Olive Ridley Sea Turtles (*Lepidochelys olivacea*). All sea turtle species chose particular sectors on the beach to nest, usually avoiding the portion of beaches that is reached by tides, and thus prone to erosion or inundation. The upper portion of beaches, where vegetation and dunes are present, is usually favored by Green Sea Turtles (*Chelonia mydas*) and Hawksbill Sea Turtles (*Eretmochelys imbricata*), while open sandy areas in the middle section are preferred by Olive Ridley Sea Turtles, Loggerhead Sea Turtles (*Caretta caretta*) and Leatherback Sea Turtles (*Dermochelys coriacea*), with the later found to nest closer to the water. Once the turtle has selected a suitable area, the nesting process starts by building a body pit and then digging a hole in the sand at an average depth of 35 cm to lay the eggs. Nest depth varies according to the species reaching depths up to 80–100 cm for Green and Leatherback Sea Turtles. After the turtle finishes laying her eggs, she covers and camouflages the nest with sand.

After about 2 months of in-nest incubation, the turtles begin hatching. Once hatched, turtles simultaneously dig out of the sand to reach the surface and emerge from their nest en masse. This behavior triggered by diel cycles rather than sand temperature (with turtles increasing digging activity at night) is thought to help avoid predators. Synchronous hatching of eggs in sea turtles has not yet been fully investigated and more experimental research is needed to clarify the physiological mechanisms and potential environmental cues involved. It is believed that the movements of each hatchling stimulate adjacent turtles to break out of their eggs. Other hypotheses suggest that CO_2 buildup on the nest can increase the metabolic rate of under-develop eggs facilitating synchronous hatching of eggs and some evidence points to vocalizations between eggs to also potentially play a part en masse hatching, as was demonstrated in other reptiles such as terrapins and crocodiles (Vergne and Mathevon 2008; Ferrara et al. 2013).

After hatching from their soft-shelled eggs, the hatchlings take 2–3 days to dig their way up to the surface of the nesting beach. There, the hatchlings rapidly crawl towards the ocean, which is brightened by the reflection of the stars and moon, allowing individuals to visually orient towards the sea. However, in developed coastal areas, artificial lighting can confuse and disorient these hatchlings from finding the ocean (see Chap. 23; Tuxbury and Salmon 2005). On their journey across the beach, these hatchlings are exposed to predators such as ghost crabs and seabirds. Once in the water, hatchlings begin to swim swiftly to avoid predators at sea, such as large fish and birds (Witherington and Salmon 1992). During this swimming frenzy, turtles do not feed and live from the yolk reserve they hold. Those hatchlings that succeed in moving further out to sea will decrease their swimming activity or swimming frenzy and spend their first years adrift feeding in the safety of the open-ocean in what is known as the pelagic stage of their life cycle.

As these juveniles continue to grow, they migrate to inshore habitats such as estuaries and reefs where they remain until mature. Mature sea turtles will then begin long-distance reproductive migrations, with females returning to the area on the beaches where they hatched, which they locate using olfactory cues, chemical imprinting and the earth's magnetic field.

19.2.2 Diversity of Sea Turtles in the UAE

Historically, there were four families of sea turtles during the Cretaceous period (145–65 million years ago), which diversified later into the ancestors of both the land and sea turtles. Today, only two extant families of sea turtles occur in the world's ocean: the hard-shelled sea turtles (Cheloniidae) and the leathery-shelled sea turtles (Dermochelyidae). The leathery-shelled sea turtles are distinguished from the hard-shelled sea turtles by having a smooth skin resembling fine leather with spikes on the top-shell (hereafter carapace). The hard-shelled sea turtles (Fig. 19.2) consists of six extant species of turtles: Flatback (*Natator depressus*), Green, Hawksbill, Loggerhead, Kemp's Ridley (*Lepidochelys kempii*), and Olive Ridley. The Dermochelyidae family consists of only one turtle species, the Leatherback. Of these seven marine turtle species, five have been recorded in UAE waters: Green, Hawksbill,

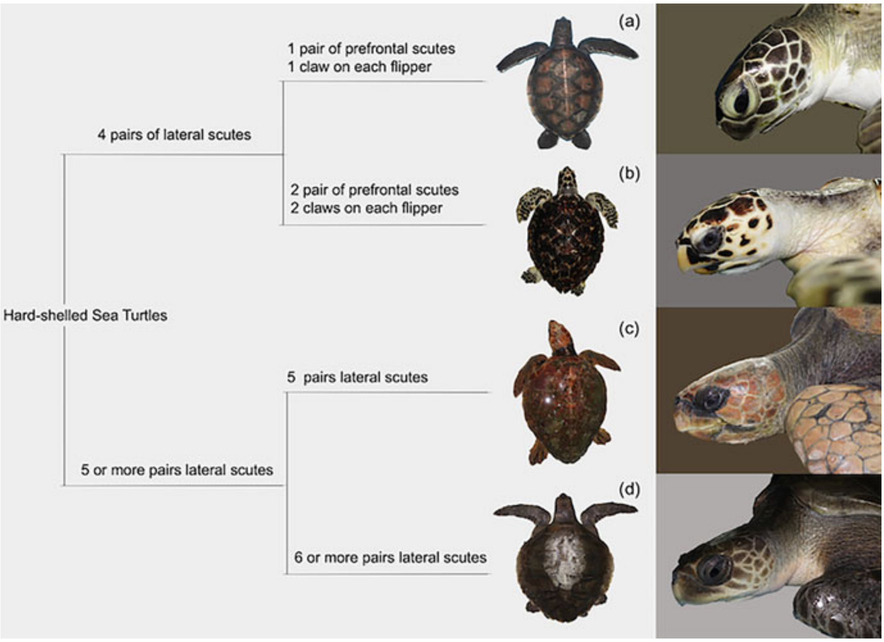


Fig. 19.2 Key to hard-shell sea turtles of the UAE. Green Sea Turtle (**a**); Hawksbill Sea Turtle (**b**); Loggerhead Sea Turtle (**c**); Olive Ridley Sea Turtle (**d**). Photos: Fadi Yaghmour

Loggerhead, Olive Ridley and Leatherback Sea Turtles (Rasmussen et al. 2011; Fuentes et al. 2012; Manire et al. 2017).

19.2.2.1 Hawksbill Sea Turtle (*Eretmochelys imbricata*)

Named for their prominent curved bird-like beaks, Hawksbill Sea Turtles are medium-sized and are distinguished from other species by their long necks, two pairs of prefrontal scutes (scales) between their eyes, an oval carapace with four lateral scutes, pointed saw-like margins and overlapping scutes bearing striking colors (Manire et al. 2017). The coloration of these scutes is golden brown with appealing streaks of red, orange, black and brown. These attractive colors has proven a costly attribute for Hawksbill Sea Turtles, as it has caused them to be the target of unsustainable levels of hunting for centuries for the creation of '*bekko*', accessories and ornaments made from its carapace scutes. Bekko includes a variety of items ranging from guitar picks, hair ornaments, jewelry and other luxury items. Though bekko was perhaps not in high demand locally, it was used to make clips, known as '*fettam*', that helped keep pearl divers' nostrils closed while underwater. As a result of the demand for bekko, along with other threats, Hawksbill Sea Turtle populations have suffered massive declines worldwide, estimated at approximately 90% loss over the last century; they are now the only species of sea turtle listed as Critically Endangered (CE) by the International Union for Conservation of Nature (IUCN) (Mortimer and Donnelly 2008).

Before the 1980s, Hawksbill Sea Turtles were commonly exploited in the UAE and the wider northwestern Indian Ocean for their carapace, meat and eggs (Hirth and Abdel Latif 1980; Aspinall 1995). Current laws such as UAE Federal Law No. (23) of the year 1999 concerning the exploitation, protection and development of living marine resources has long since banned and phased out the common practice of Hawksbill Sea Turtle exploitation in the UAE. However, regional countries including Bahrain, Djibouti, Egypt, Eritrea, Iran, Oman, Qatar, Saudi Arabia, Somalia Sudan and Yemen do report continued but decreasing exploitation of turtle eggs, meat, and carapace (Pilcher and Al-Merghani 2000; Gladstone et al. 2003; PERSGA 2006; Pilcher and Saad 2006; Rees and Baker 2006; Van de Elst 2006; Ficetola 2008; Al Ameri et al. 2020).

In the UAE, Hawksbill Sea Turtles are the second most common species of sea turtle after Green Turtles (see below), and they are also considered the primary nesting species (Fig. 19.3). Hawksbill nesting is confined to the Arabian Gulf coast of the UAE, where they are known to nest on numerous islands and mainland beaches in the territorial waters of Dubai, Abu Dhabi and Sharjah (Pilcher et al. 2014). There their nesting occurs in small assemblages in habitats that include sandy beaches as well as rocky, coarse-sand beaches. It is estimated that ca. 500 females/year nest in the UAE (Ameri et al. 2022), which is comparable to Saudi Arabia, and below key sites in Iran and Oman where larger numbers are reported (~1000 females/year) (Mobaraki 2004; Ross and Barwani 1982). Recent genetic population analyses indicate that turtles across the UAE exhibit low genetic diversity and

Fig. 19.3 Hawksbill Sea Turtle nesting in Sir Bu Nair Protected Area, Sharjah. Photo: Clara Jimena Rodriguez-Zarate

belong to the same Gulf population management unit, which are distinct from the Indian Ocean populations (Natoli et al. 2017), highlighting the importance of conservation actions. The Hawksbill Sea Turtle nesting season in the region is short (3 months) compared to other geographic regions, where it can extend up to 6 to 12 months. In the UAE the start of the nesting season has been reported in some areas as early as March (Rodriguez-Zarate, unpubl. data) extending up to June.

When turtles crawl up the beach to nest they leave a mark or track behind in the sand. Such tracks are distinctive among species by their shape and size, allowing the identification of a turtle species when the animal is not directly observed on the beach. Hawksbill Turtle tracks are asymmetrical in shape, showing alternated diagonal marks left by the simultaneous forward movement of the frontal flippers, accompanied by a serpent central drag-mark from the tail. Hawksbill tracks usually have a width of 65–85 cm. Arabian populations of hawksbill turtles lay 80 to 130 eggs per clutch, and are known to nest more than once within a season, often laying up to 2–3 clutches of eggs per season. Genetic parenting analyses provided evidence of multiple paternity in Hawksbill Sea Turtles only in the nesting area of Sir Bu Nair (Natoli et al. 2017); a phenomenon that has been widely documented for marine turtles worldwide. The incubation period for eggs extends to between 50 to 61 days. However, local variation of these reproductive parameters have not been fully described across nesting areas for Hawksbill Sea Turtles in the UAE. Conversely, the east coast of the UAE on the Gulf of Oman has few and intermittent contemporary records of Hawksbill Sea Turtle nesting activity (Hebbelmann et al. 2016; Yaghmour and Jarwan 2020).

As omnivores, Hawksbill Sea Turtles have a varied diet. Young Hawksbills feed in oceanic waters on planktonic animals including hydroids and floating insects. Juvenile Hawksbills then migrate to shallow coastal habitats such as coral reefs and seagrass meadows to feed on sea cucumbers, anemones, mollusks, cnidarians, algae and sponges. As the turtles mature, sponges comprise an increasingly prominent proportion of their diet. There are no studies investigating the diet of Hawksbill Sea Turtles in the UAE, however, unpublished observations made of gut contents of stranded Hawksbill Sea Turtles from Sharjah include fish bones, sponges, cephalopod beaks, mollusk shells and insects; items comparable to reports from other areas (Yaghmour, unpubl. data).

Further details on Hawksbill feeding activities were reported in an investigation of post-nesting migrations of Hawksbills in Arabian waters. It was found that in the Arabian Gulf, Hawksbills spent approximately 70% of their time occupying discreet foraging grounds. The majority of the foraging grounds in the Arabian Gulf were small reef mounds within seagrass meadows located in the waters of Abu Dhabi and southern Qatar. Hawksbill Sea Turtles were observed to leave these habitats for 2–-3 months during their summer migrations to escape the increasing temperatures of surface water (Pilcher et al. 2014). Comparatively, Hawksbill Sea Turtles in the cooler waters of the Gulf of Oman spent up to 83% of their time in foraging grounds in the waters of Oman. The discrepancy in time spent in foraging areas is a result of summer migration only occurring in Arabian Gulf dwelling Hawksbill Sea Turtles.

19.2.2.2 Green Sea Turtle (*Chelonia mydas*)

Known locally as '*hamas*' or '*shiree*', Green Sea Turtles (see Fig. 19.1) are distinguished from other sea turtles by having only one pair of prefrontal scutes between their eyes, four lateral scutes on their carapace and a blunt beak that consists of tomia (serrations used for cutting into seagrass and algae). Globally, they are the largest of the hard-shelled sea turtle species and the second largest extant species of sea turtle. Contrary to popular belief, the outer body color of Green Sea Turtles are not green, but their name is derived from the greenish color of their cartilage and fat. The coloration of their carapace is olive-gray or brown with streaks and splatters of black or dark brown, while the dorsal surface of their head and flippers is covered by dark scales with lighter seams.

Green Sea Turtle hatchlings and juveniles are omnivores, feeding in oceanic waters on floating algae, inclusive of the variety of associated organisms such as amphipods, bryozoans, tubeworms, marine insects and mollusks. As they grow older, immature turtles undergo developmental shifts and return to nearshore coastal habitats such as mangroves, seagrass meadows and coral reefs. Immature turtles are considered omnivorous, though they heavily favor macroalgae and seagrass, while adults are considered strict herbivores which rarely ingest animals; typically incidentally while feeding on seagrass or algae.

Green Sea Turtles in the UAE consist of a mixture of juveniles, subadults and adults feeding in foraging grounds, with adults seasonally migrating out to mating grounds. Foraging grounds include seagrass beds, primarily of Narrowleaf grass (*Halodule uninervis*) and Spoon grass (*Halophila ovalis*), or mixed-bottoms composed of mangroves and coral reefs close to sea grass or algal beds (see Chap. 9). In the UAE, the largest foraging grounds occur on the extensive seagrass beds of western Abu Dhabi, although they also occur in lagoons and other sheltered areas across the emirates (see Chap. 8). While juveniles favor these habitats as they mature to adulthood, adults utilize these resources when foraging between reproductive periods (Musick and Limpus 1997). Studies investigating the gut contents of Green Sea Turtles from the Gulf of Oman suggest that the diet consists mostly of seagrasses (*Halophila uninervis, H. ovalis* and *H. ovata*) and algae (*Lychaete herpestica. Nizamudinnia zanardinii, Chaetomorpha aerea* and *Sargassum illicifolium*) (Ross 1985; Ferreira et al. 2006).

The migratory patterns of adult Green Sea Turtles in the UAE has also been investigated in recent studies. These studies suggest that adult Green Sea Turtles remain close to shore while undertaking reproductive migrations from feeding areas in the UAE, mainly in the southwestern Gulf basin in Abu Dhabi waters, to nesting areas located in Oman, moving in a narrow corridor of approximately 10-20 km off the coast (Pilcher et al. 2020). In this study few turtles ventured to deeper waters during their migration or performed migration loops into the Indian Ocean en route to nesting beaches; these route selections are not yet fully understood. Similar habitat-use patterns were reported by Rees et al. (2012) for post-nesting Green Sea Turtles in Oman.

Despite being the most common turtle species in the UAE, Green Sea Turtle nesting sites are considered rare and sporadic. On Sir Bu Nair island (Sharjah) the successful nesting of two Green Sea Turtles was corroborated by the observation of hatchlings and exhumation of their nest in 2010 (EPAA 2012). Unsuccessful nesting attempts were identified by tracks left on the sand by the turtles and sporadically a few are still reported today at this location (Rodriguez-Zarate, unpubl. data). Unlike Hawksbill Sea Turtles, Green Sea Turtles have a symmetrical sand track consisting of deeply cut and symmetrical diagonal marks made by the front flippers and a straight center drag mark from the tail. Being larger in size compared to Hawksbill Sea Turtles, Green Sea Turtle tracks are wider, typically 85–130 cm. Green Sea Turtles lay 80 to 120 eggs per clutch and are known to nest more than one time within the same nesting season, ranging from two to four clutches. The incubation period is between 60 to 65 days. Major nesting rookeries of Green Sea Turtles in the Arabian region are located in Ras al Hadd (Oman) (~20,000 Green Sea Turtles nest annually (Ross and Barwani 1982)) and Sharma-Jethmoun area (Yemen) where over 27,000 turtles nested in 2014 (Nasher and Al Jumaily 2013). Relatively large nesting aggregations (~1000 nesting females/year) are also found at Karan and Jana islands (Arabian Gulf coast, Saudi Arabia) (Pilcher 2000).

19.2.2.3 Loggerhead Sea Turtle (*Caretta caretta*)

Known locally as '*murah*', Loggerhead Sea Turtles are distinguished from other turtle species by their disproportionately large head. They have two pairs of pre-frontal scutes between their eyes and a heart shaped, mahogany to red-brown colored carapace with five lateral scutes. As adults, Loggerhead Sea Turtles are smaller than Green Sea Turtles but much larger than Hawksbills. They are rarely observed along the UAE's Arabian Gulf coast but are frequently observed in the Gulf of Oman coast, due to its proximity to Masirah island in Oman. Island beaches are important nesting habitats for the critically endangered Northwest Indian Ocean subpopulation of Loggerhead Sea Turtles and it is known to be among the most important Loggerhead Sea Turtle rookeries in the world. To date, no Loggerhead nesting has been recorded in the UAE.

Loggerhead Sea Turtles are carnivorous bottom feeders, which search the deeper waters of the continental shelf for crustaceans, gastropods, jellyfish along with other sessile or slow-moving prey (Wallace et al. 2009). Across the region, limited information exists of this species feeding ecology, however, unpublished observations made of gut contents of stranded Loggerhead Sea Turtles from the waters along Sharjah's East coast included Sea Urchin (*Diadema setosum*), Sea Cucumber (*Holothuria scabra*), Sand Dollar (*Echinodiscus auritus*), gastropods consisting mostly of False Venus (*Murex scolopax*), cuttlefishes, fishes, bivalves and crabs (F. Yaghmour, unpubl. data). In addition to being an important part of their diet, evidence exists that the Columbus Crab coexist symbiotically with Loggerhead Sea Turtles in the UAE (Yaghmour and Al Naqbi 2020; see Box 19.1).

Box 19.1 Loggerhead Sea Turtles and Their Relationship with Columbus Crabs

A study by Yaghmour and Al Naqbi (2020) revealed that some Loggerhead Sea Turtles in the UAE are associated with Columbus Crab (*Planes minutus*) (Fig. 19.4). This crab is often observed on the tail or hind flippers of Loggerhead Sea Turtles and are believed to ingest the excrement of their host. This relationship would be known as 'commensalism' as one species benefits (the crab) while the other is unaffected (the turtle). However, other studies suggest that they might also clean the host turtle's carapace by feeding on the sessile epibiota on its surface (Crane 1937; Frick et al. 2004). In this case, as both the crab and the turtle would benefit (food for the crab, less energy-taxing swimming for the turtle) the relationship would be defined as 'mutualism'.

Further details on the habits of Loggerhead Sea Turtles were revealed through satellite tracking to identify feeding grounds and which areas are frequently used. Satellite trackers attached to post-nesting Loggerhead Sea Turtles in Masirah island (Oman) revealed extensive post-nesting movements. Turtles foraged in the oceanic zone for the majority of their time (76%) but also used shallow coastal shelf habitats.

Fig. 19.4 Columbus Crab. Photo: Fadi Yaghmour

This data supports the theorizing of behavioral plasticity and a bimodal foraging strategy where turtles move between 400 km to 1400 km offshore from Oman and Yemen (Rees et al. 2010, 2018). This bimodal feeding strategy was also reported in studies of other Loggerhead populations (McClellan et al. 2010) where individuals in the coastal shelf remain as benthic feeders, while oceanic individuals feed opportunistically in open waters on mid-water organisms such as jellyfish or crustaceans (McClellan et al. 2010; Frick et al. 2004).

19.2.2.4 Olive Ridley Sea Turtle (*Lepidochelys olivacea*)

The smallest of the UAE's marine turtles, Olive Ridley Sea Turtles are distinguished from other species in the region by their nearly circular carapace, which can measure equal in length and width. Their carapace also carries at least six lateral scutes and the inframarginal scutes on their plastron (bottom-shell) bear pores, a characteristic unique to the Olive Ridley Sea Turtle and Kemp's Ridley Sea (*Lepidochelys kempii*). Olive Ridley Sea Turtles are predominantly carnivorous, feeding on salps, mollusks, crustaceans, bryozoans and on algae in oceanic waters and coastal waters. There are no studies investigating the diets of Olive Ridley Sea Turtles in the UAE, although unpublished observations made of gut contents of stranded Olive Ridley Sea Turtles from Sharjah include macroalgae, fish, cephalopod beaks and insects (F. Yaghmour, unpubl. data).

In the region, Olive Ridley Sea Turtles have been observed in the waters of Pakistan, India, Iran, Oman and UAE (Abreu-Grobois and Plotkin 2008). Olive Ridley Sea Turtles are known to nest on Masirah island located in the Gulf of Oman (Rees et al. 2012) but satellite tracking data suggests they swim north to settle along the East coast of the UAE during post-nesting migrations (Rees et al. 2012).

Little is known about the ecology of this species in the Arabian Gulf. Olive Ridley Sea Turtles were first recorded in the Arabian Gulf along the coastal waters of Kuwait in 2003 by Bishop et al. (2007). Since then there have been records in Iran (Qeshm Island, Larak island, Bushehr town, Kharg island), Bahrain (Rees et al. 2012) and the UAE (Yaghmour 2019a). To date there is only a single record of an Olive Ridley Sea Turtle nesting in the Arabian Gulf, which was recorded in 2013 at the Nayband Marine-Coastal National Park, Iran. In the UAE, an Olive Ridley Sea Turtle nest was reported on the beach of Khor Kalba, Sharjah in 2021 (Yaghmour and Rodríguez-Zárate 2021).

19.2.2.5 Leatherback Sea Turtle (*Dermochelys coriacea*)

Weighing up to 1000 Kg and measuring up to 3 meters in length, Leatherbacks are the largest among marine reptiles. They are also easily distinguished from any other turtle species due to the lack of a hard carapace with scutes; instead their teardrop shaped carapace has a fleshy surface with seven longitudinal ridges known as keels. The coloration of their dorsal surface is black to dark-gray with light-gray spatters. Their beak sheaths are relatively weak and specially adapted for consuming gelatinous prey. At all stages of their life, Leatherbacks will primarily consume gelatinous marine animals including hydroids, medusae, salps and primosomes. Information on Leatherback Sea Turtles in Arabian waters is limited to sporadic observations and through strandings in UAE waters during the past few decades. In the UAE, Leatherbacks have been reported from the coasts of Dubai, Khor Kalba and Fujairah (Gardner 2013; Buzás et al. 2018).

19.3 Sea Snakes

Restricted to life at sea, 'true' sea snakes are members of the Order Squamata from the family Elapidae (subfamily Hydrophiinae) and are the most widely distributed group of marine snakes. With the exception of the Yellow-bellied Sea Snake, the collective range of sea snakes extends along the coastal waters from the Arabian Gulf eastwards into the tropical waters of Asia and Australia, through to the islands of southwestern Pacific and northward to Japan and China (Heatwole 1999; Sindaco et al. 2013). The habitats which sea snakes can occupy is limited by ocean temperatures thus their global distribution is restricted to the broad continental shelves of warm tropical and subtropical waters. Sea snakes, although they are solely restricted to a marine environment (see Box 19.2), share several similarities with terrestrial snakes in that they are air-breathing, the body is covered with scales, and they have a forked tongue, lidless eyes and no limbs. Sea snakes range in size from half a meter to one meter in length depending on the species, with exceptions such as the Yellow Sea Snake which can reach lengths of up to 2.75 meters in parts of its distribution range (Minton 1975; Heatwole 1999; Gardner 2013). Sea snakes are venomous and through their short hollow fangs positioned on both sides of the upper jaw towards the front (proteroglyphous), they can deliver neurotoxins to subdue large prey. Sea snakes can be a difficult group to identify as several species appear morphologically similar and they may vary in coloration and pattern during different life stages.

19.3.1 Habits and Behavior of Sea Snakes

Among marine reptiles, sea snakes are the most understudied group with research limited to a handful of species of which the majority of the species studied to date are those within Australian waters. With the exception of documenting species diversity within the waters of the UAE, there are limited studies focusing on elements of their natural history. Habits and behaviors of the species covered by this chapter are concluded from observations from other parts of their range, along with anecdotal observations to provide baseline information.

Sea snakes appear not to be territorial, with home ranges overlapping among individuals of the same species (Heatwole 1999). Territorial defensive behavior has not been observed and is not known among the several species occurring within the waters of the UAE. Sexual dimorphism (i.e. different appearance between males and females) varies between species, but this is largely subjected to the availability of data among the different species. Depending on the species, some may have larger females than males, similar to what is often observed in terrestrial snakes, or males larger than females, while within some species there are no size differences between the species (Heatwole 1999; de Silva et al. 2011a, b; Buzás et al. 2018). Among those where sexual dimorphism exists, a difference in the number and character of scales may be observed. As an example, among the Arabian Gulf Sea Snake (*Hydrophis lapemoides*) sexual dimorphism can be noted between reproductive mature males and females, with males having prominent enlarge keeled dorsal scales.

Reproduction among sea snakes is similar to terrestrial snakes. The male has two copulatory organs, called hemipenes, which are located on either side of the base of the tail behind the cloaca vent. The hemipene has spike and hook-like structures which aids it to keep in place during mating. Mating may be sustained over several breathing cycles, with the female controlling the breathing rhythm, while the male must breathe air at the same time the female surface (Heatwole 1999). The timing of breeding of most sea snake species is not well understood and varies between regions. All true sea snakes are viviparous (live-bearing) and young are positioned forward in the body in comparison to terrestrial snakes, to reduce interference with swimming movements. Gestation periods can vary greatly between species, ranging from 3 to 4 months, or up to 11 months for species such as the Beaked Sea Snake (Heatwole 1999). The gestation period of females for each species may influence the period between breeding, with those with longer gestation periods having an intervening non-breeding season to replenish energy reserves.

It has been suggested that pregnant females may resort, en masse, to protected bays to give birth to their young (Dunson 1975). A female will give birth to the young underwater and shortly after the newborns surface for their first breath. Litter sizes vary between species and it depends on the size of the individual female. The Arabian Gulf Sea Snake has larger young and small litter sizes in comparison with much larger Beaked Sea Snake which can have a litter size of up to 18 young (Heatwole 1999; de Silva et al. 2011a, b). There is no parental care of the young by the female. Limited information on the growth rate of sea snakes are available, most appear to have a rapid growth rate until sexual maturity. Sexual maturity in some species such as the Beaked Sea Snake varies from 1.5 years for males and 1.5–2 years for females (Heatwole 1999), but this may vary between different regions across their distribution range. Typically, in the same manner terrestrial snakes shed their skin (ecdysis), sea snakes shed their skin throughout their lifetime. The frequency between ecdysis will be higher in younger individuals and decrease as they mature. Ecdysis may also further aid in controlling external parasites and other organisms which were attached to the skin (Zann 1975).

Sea snakes are diurnal, nocturnal or both, varying between species, and this may be influenced by temperature fluctuations during the seasons. Irrelevant to their preferred activity periods, they must surface to breath. Sea snakes predominantly feed on fish (piscivorous) and based on their diet preferences they are often grouped into either specialist or generalist categories. It is dietary specialization which was suggested as the reason for unique body shapes and sizes among sea snake species (Sherratt et al. 2018).

19.3.2 Diversity of Sea Snakes

Among the monophyletic assemblage of the estimated 62 species of sea snakes (Sanders et al. 2012) the highest diversity of species is found in northern Australia, Malaysia and the Indonesian archipelago. Species richness decreases towards the Arabian Sea with 10 species recorded in the Arabian Gulf and the Gulf of Oman (Egan 2007; Gardner 2013; Rezaie-Atagholipour et al. 2016; Carranza et al. 2021; Chowdhury et al. 2021). The 10 species in the Arabian Gulf represent the westernmost limit of this group of sea snakes, with the exception of the Yellow-bellied Sea Snake, which reaches the eastern coast of Africa. Within the territorial waters of the UAE, nine species have been recorded (Gasperetti 1988; Soorae et al. 2006; Gardner 2013; Buzás et al. 2018). Three of the species are abundant, five are rarely encountered and one is known from a single specimen. Beaked Sea Snakes are known from only a few specimens, of which most are from strandings. The Viperine Sea Snake from the Arabian Gulf is known from a single museum specimen collected from near Sir Bu Nair (alt. spelling: Sir Abu Nu'ayr), by the crew of the HMS Dalrymple (British Royal Navy) around 1963 (Gasperetti 1988). Sea snakes may be rare or overlooked during surveys, thus the known recorded species for the UAE should be considered the minimal number of species (see Box 19.2).

Box 19.2 Sea Snake Adaptations for Life at Sea

Sea snakes have developed several adaptations for life in a marine environment. To facilitate swimming, sea snakes have laterally compressed bodies (in comparison with the cylindrical bodies of their terrestrial snake relatives) with paddle-like tails. The ventral (i.e. belly) scales of sea snakes are reduced in size, as they no longer require land movement and are of little benefit for swimming; this is one reason why sea snakes cannot freely move on land.

Sea snakes have an enlarged lung which allows for increased air supply and improved oxygen supply into the blood. The lung further aids in buoyancy control to facilitate movement in the water while diving or surfacing for air. Respiration through the skin (cutaneous respiration) allows the absorption of oxygen and elimination of carbon dioxide, which combined with the saccular lung increase diving capacity (Heatwole 1999). Apart from respiration, the skin allows water through but resists the inward flow of salts.

The eyes of sea snakes, in comparison with terrestrial snakes, have changes in the visual pigments which improves vision under water and combined with their well-developed olfactory capability can help locate prey (Kutsuma et al. 2018). The nostrils of sea snakes are positioned upwards and regulated by valves to keep air in and avoid seawater from entering. They have a sublingual gland (modified salivary gland) in the mouth, located under the tongue sheath and which empties salt brine. The salt brine is expelled when the tongue protrudes.

Despite these adaptations to survive in a marine environment, sea snakes can dehydrate and infrequently still require freshwater. Freshwater is consumed when it rains and, on calm seas, a layer of freshwater may float on the heavier seawater which provides an additional source. The patchiness of sea snakes at different spatial scales might be related to the spatiotemporal distribution of rainfall (Lillywhite et al. 2012).

19.3.2.1 Arabian Gulf Sea Snake (*Hydrophis lapemoides*)

A smaller species, which reach lengths of up to 96 centimeters. The dorsal color between different snakes can be highly variable ranging from light brown or yellowish with dark bars across the dorsal surface (Fig. 19.5). Youngsters are light gray or yellow with prominent thick black bars across the body (Fig. 19.6). The Arabian Gulf Sea Snake is widely distributed from the Malay Archipelago westwards into the Gulf of Oman and Arabian Gulf (Sindaco et al. 2013; Ganesh et al. 2019; Chowdhury et al. 2021). It is abundant in the Arabian Gulf and Gulf of Oman. It prefers shallow marine waters and is often encountered near to the shore. They feed on small fish such as gobies and eels. Regularly encountered during the day and after dusk. Females will give birth (viviparity) to 1–5 young.

Fig. 19.5 Arabian Gulf Sea Snake, adult, female, from the Arabian Gulf, UAE. Photo: Johannes Els

Fig. 19.6 Arabian Gulf Sea Snake, youngster, from the Arabian Gulf, UAE, to illustrate the variability in color and patterns observed during different life stages. Photo: Johannes Els

19.3.2.2 Ornate Reef Sea Snake (*Hydrophis ornatus*)

A medium-sized species which reach lengths of up to 1.2 meters. Variable in color, the dorsal (i.e. back) is light brown or yellowish with dark bars or oval-rhomboidal spots close to each other (Fig. 19.7). The Ornate Reef Sea Snake is widely distributed from northern Australia westwards into the Gulf of Oman and Arabian Gulf (Bauer and Sadlier 2000; Cogger 2000; Jongbloed 2000, Kanta et al. 2021). The species is abundant in the Arabian Gulf and Gulf of Oman. It is often found in coastal waters during the day and after dusk. They eat a variety of fish species. Females will give birth to 2–5 young.

Fig. 19.7 An adult Ornate Reef Sea Snake stranded on a beach along the Arabian Gulf, UAE. Photo: Johannes Els

Fig. 19.8 Typical Yellow-bellied Sea Snake (Left; Photo: Johannes Els); Melanistic Yellow-bellied Sea Snake found stranded on Saadiyat Beach, Abu Dhabi on October 2022. (Right; Photo: Nick Cochrane-Dyet)

19.3.2.3 Yellow-Bellied Sea Snake (*Hydrophis platurus*)

A smaller species in comparison with the Arabian Gulf Sea Snake, reaching a total length of 88 centimeters. The Yellow-bellied Sea Snake is visibly distinct from all other species with a dark brown or black dorsal with a dark- or light-yellow ventral and flanks. The tail has vertical bands and blotches on a whitish background. The head is distinct from the body with a very narrow elongated snout. Rarely, other color variations are observed such as one melanistic Yellow-bellied Sea Snake found stranded on Saadiyat Beach, Abu Dhabi on the 21st of October 2022. (Fig. 19.8).

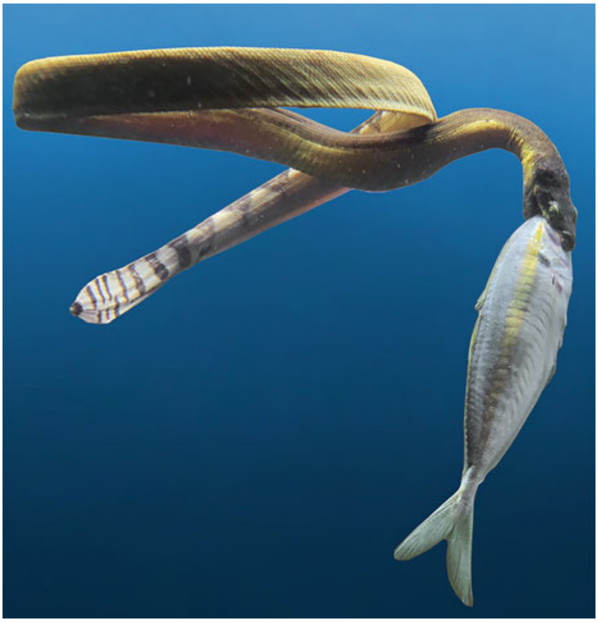


Fig. 19.9 Yellow-bellied Sea Snake feeding on a fish, Gulf of Oman, UAE. Photo: Johannes Els

Melanism is characterized by the excessive development of the dark-colored pigment melanin.

Yellow-bellied Sea Snakes are the most widely distributed species of all sea snakes, extending from the western shores of America, across the Pacific and Indian Oceans entering the Gulf of Oman and Arabian Gulf, and further westwards along the eastern coastline of Africa. It is abundant in the Gulf of Oman and often prefers clear, shallow waters with weak surf and currents. It is a pelagic species and has been observed to aggregate in large numbers of up to 1000 individuals per hectare on marine slicks. These aggregations are not related to breeding, but feeding gatherings and it is suggested that it may help individuals to increase their feeding opportunity due to fishes seeking shelter beneath the floating debris (Kropach 1971; Lillywhite et al. 2010). Yellow-bellied Sea Snakes predate on a variety of fish species (Fig. 19.9). Females give birth to 1–6 young.

19.3.2.4 Graceful Small-Headed Sea Snake (*Hydrophis gracilis*)

A medium-sized species reaching lengths of just over 1 m. It is distinguishable from all other species by having a small pointed head, a slender anterior body which thickens posteriorly four or five times in diameter compared to the neck. The species vary in color from light gray dorsally and paler on the ventral side which darkens posteriorly. Dark broad dorsal bands on the dorsal side of the anterior part of the body. It is widely distributed from northern Australia and New Guinea westwards to the Gulf of Oman and Arabian Gulf (Volsøe 1939; Sindaco et al. 2013;

Rezaie-Atagholipour et al. 2016). In the Arabian Gulf and Gulf of Oman the species appear to prefer coastal water and is rarely encountered. Graceful Small-headed Sea Snakes are specialists, feeding on slender bottom dwelling fish species such as gobies and eels that are hunted from within their burrows. Females give birth to 1–16 young.

19.3.2.5 Yellow Sea Snake (*Hydrophis spiralis*)

The largest sized species in Arabia, reaching a length of 2.75 meters. The dorsal color is yellow or brownish with narrow black rings encircling the body, which are narrower than the yellowish interspaces (Fig. 19.10). The head is yellow and the tail tip is usually black. Yellow Sea Snakes are widely distributed from New Caledonia westwards to the Gulf of Oman and Arabian Gulf (Volsøe 1939; Sindaco et al. 2013). Within the Arabian Gulf and Gulf of Oman, the species is less abundant in comparison with the Arabian Gulf Sea Snake or Ornate Reef Sea Snake. It prefers shallow coastal waters and has been found on the sea surface during the day and after dusk. Yellow Sea Snakes feed mainly on eels and other slender fish species. Females give birth to 5–14 young.

19.3.2.6 Spine-Bellied Sea Snake (*Hydrophis curtus*)

A medium-sized species reaching a length of 1 m. It has a large, robust, blunt head that is not distinct from the neck. Body scales each have a single sharp keel in the

Fig. 19.10 Yellow Sea Snake, adult, from the Gulf of Oman, UAE. Photo: Fadi Yaghmour

middle and the keels increases in size towards the flanks. The species is variable in color ranging from light brown, gray or yellowish, with darker head and tail with incomplete dark bars across the body. Spine-bellied Sea Snakes are widely distributed from northern Australia, New Caledonia, Asia and westwards into the Gulf of Oman and Arabian Gulf (Gardner 2013; Sindaco et al. 2013; Rezaie-Atagholipour et al. 2016). Relatively abundant in the Gulf of Oman, it lives in shallow marine habitats. It feeds on a variety of fish species, amphipods and cuttlefish (de Silva et al. 2011a, b; Rezaie-Atagholipour 2012). Reproductive females measure 53–91 cm (de Silva et al. 2011a, b) and give birth to four to ten young.

19.3.2.7 Annulated Sea Snake (*Hydrophis cyanocinctus*)

A long and slender species, reaching lengths of 1.5 m, with a small elongated head which can be distinguished from the neck. The species is variable in colour, with the dorsal light brown or yellowish, with dark bars across the body that are broader dorsally and fade away as they reach sexual maturity. The young are olive or yellowish in base color, ringed with bold black (Buzás et al. 2018) Widely distributed from Japan, westwards into the Gulf of Oman and Arabian Gulf (Gardner 2013; Sindaco et al. 2013; Carranza et al. 2021). In the Arabian Gulf and Gulf of Oman the species is relatively abundant in shallow marine waters over reefs, seagrass beds or sand. It has been observed both during the day and after dusk. The species feeds mainly on small fishes such as mudskippers and gobies (Rezaie-Atagholipour et al. 2013). Females give birth to 3–16 young.

19.3.2.8 Beaked Sea Snake (*Hydrophis schistosus*)

A large and robust species reaching lengths of 1.2 meters with a large, blunt head with the tip of snout beak-shaped (Fig. 19.11). The species are variable in colour, ranging from light grey or bluish, with dark bands across the body that fade away or disappear in sexually mature individuals. It is widely distributed from northern Australia westwards to the Gulf of Oman and Arabian Gulf (Gardner 2013; Sindaco et al. 2013; Carranza et al. 2021). It is more frequently encountered in the Gulf of Oman, but is overall less abundant compared to other species found in the region. Beaked Sea Snakes prefer shallow waters near the shore with sandy or muddy substrate and are observed both during the days and after dusk. In parts of the species range it is also found in mangrove and lagoon habitats. It feeds on a variety of fish species, but prefers gobies. Reproductive females measure 1–1.8 m in length (de Silva et al. 2011a, b) and give birth to 4–18 young.

Fig. 19.11 Beaked Sea Snake, adult, from the Gulf of Mannar, Sri Lanka. Photo: Johannes Els

19.3.2.9 Viperine Sea Snake (*Hydrophis viperinus*)

A smaller species that reaches 95 cm length. The species is variable in color, from dark gray or bluish dorsally, with dark rhomboid spots. The flanks and ventral are contrasting a lighter shade of the dorsal coloration; the tail tip is often black. The Viperine Sea Snake is widely distributed from the Malay Archipelago and Southern China westwards into the Gulf of Oman and Arabian Gulf (Anderson 1872; Gardner 2013; Carranza et al. 2021). Within the Arabian Gulf the species is known from a single specimen collected in 1963 near Sir Abu Nu'ayr, by the crew of the HMS Dalrymple (British Royal Navy) around 1963 (Gasperetti 1988). The Viperine Sea Snake is a very rare species in the Gulf of Oman, and is only known from the one specimen in the Arabian Gulf. It preys on small fishes, including gobies. Reproductive females measured 59–77 centimeters in length (de Silva et al. 2011a, b) and give birth to 2–6 young.

19.4 Ecological Importance of Sea Turtles and Sea Snakes

Evidence from numerous archeological sites in the vicinity of Dibba and Khor Fakkan strongly suggest the occurrence of sea turtle egg shells and the remains of turtle hatchlings dating back to the Iron I era (1200 to 1000 B.C.) (Potts 2001). These findings strongly suggest the historic occurrence of turtle nesting on the eastern coast of the UAE, and allude to their social importance as a source of sustenance for coastal communities (Pilcher et al. 2014). Town elders and community members in Kalba also reported as many as 50 turtles nesting annually on the beach of Khor Kalba in the 1960s. They report that these numbers gradually diminished until they were no longer observed in the 1980s. It is believed that turtles may have been inadvertently driven away by the disturbances of human activities in the area (Hebbelmann et al. 2016).

The decline of sea turtles from their historic abundance has received considerable attention from policy makers, the scientific community and the wider public, both in the UAE and internationally. This issue is often framed in the context of animal wellbeing or conservation status. The decrease in turtle abundance is rarely contextualized with the corresponding losses of ecosystem health and functionality of the world's most essential marine habitats (Wilson 2010).

Along with dugongs, Green Sea Turtles are the only large herbivores in UAE waters. Through grazing, green sea turtles maintain the functional composition and increase the productivity and nutrient content of seagrass beds (Bjorndal 1980; Thayer et al. 1984). Without grazing, seagrass blades can become overgrown, causing excess shade and stagnation that result in seagrasses being overwhelmed by invertebrates and algae (Zieman et al. 1999; Jackson et al. 2001; Jackson 2001). Green Sea Turtles also graze on algae that grow on hard rock substrates. Similarly, Hawksbills consume sponges that also grow on rocky substrates. In doing so, these turtles create opportunities for other species like corals to proliferate (Meylan 1988; León and Bjorndal 2002). Through their contributions to local fisheries, seagrass beds and coral reefs are significant for the economic stability and food security of arid coastal nations like the UAE (McClenachan et al. 2006).

Beach dunes are nutrient deficient habitats, especially in arid environments like the UAE. Eggshells and unhatched sea turtle eggs from turtle nests provide an important source of nitrogen, phosphorus and potassium that support vegetation growth (Hannan et al. 2007). This, in turn, increases the stability of beach dunes and also provides food for terrestrial grazers (Bouchard and Bjorndal 2000; Hannan et al. 2007). Furthermore, turtle eggs and hatchlings are also an important source of food for predators such as Arabian Red Fox (*Vulpes vulpes arabica*), ghost crabs and sea birds.

The ecological importance of sea snakes and the niche they occupy within the marine environment is still largely unknown. Apart from being predators who feed on various species of fish, sea snakes are also preyed upon by sharks, teleost fish and birds (Heatwole 1975). Sea snakes are often a host for fouling organisms, and may widen the distribution of these organisms within the marine environment. These may include organisms which are specialized and found only on sea snakes, such as the sea snake barnacle (*Platylepas ophiophilus*). Some species were reported to host bryozoans, which are not restricted to sea snakes only. Solitary fish species have been observed using sea snakes for possible shelter or protection, a behavior termed 'endoecism' (Zann et al. 1975).

19.5 Knowledge Gaps for Sea Turtles and Sea Snakes

19.5.1 Sea Turtles

Although great advances have been made in recent years to describe population connectivity and identify habitat use by Green and Hawksbill Sea Turtles, allowing the identification of Important Turtle Areas (ITAs) for conservation, further research is required to identify metapopulation dynamics (dispersal of other life stages such hatchlings and juveniles) along with key demographic parameters (population size, mortality and survival rates) derived from long term monitoring programmes.

Further work is also needed to understand the population status of Loggerhead and Olive Ridley Sea Turtles in the UAE. In order to facilitate adequate assessments of population trends, detailed and systematically collected information on population abundance across turtle nesting sites, females' reproductive biology (nesting success rate, clutch size, nest's success) and demographic features (annual clutch frequency, and remigration intervals) is also needed. Finally, better understanding of the extent of impact of identified threats to sea turtles in the UAE (pollution, boat strikes, impact of fishing practices that may result in entanglement and bycatch), and less known threats like the effects by climate change on turtle populations and their habitat remain as a priority for sea turtles in the UAE. Research is also required to determine causes for seasonal sea turtle strandings in the Arabian Gulf.

19.5.2 Sea Snakes

Due to the lack of information from within UAE waters, five species of sea snakes were categorized by IUCN as Data Deficient on a national level. With overall limited information available among the various species, their population status and causes for decline, if any, are unknown which might hinder conservation management in the future. Research is required to gain an improved understanding of the behavior and ecology of sea snakes in the region. What is known about sea snakes in the region is largely based on the work from Gasperetti (1988) for Arabia, with very few recent studies in UAE waters and those are confined to smaller geographical areas such as Buzás et al. (2018) and Soorae et al. (2006). Research focus to date has mainly been along the mainland coast of the UAE, species diversity around islands are overlooked, especially in the Arabian Gulf. Seasonal strandings of sea snakes and the potential causes for this event in the Arabian Gulf and Gulf of Oman, requires long term monitoring.

19.6 Threats to Marine Reptiles in the UAE

Sea turtles struggle for survival in the face of a variety of anthropogenic threats. The UAE is a rapidly developing nation with a long maritime history. Consequently, much of the urbanization and industrialization involves transformation of coastal areas through reclamation or other forms of coastal engineering (see Chap. 23), all in direct competition with sea turtle survival. This can take many forms including dredging, landfilling, rock piling or water current disruption, and may result in unintended additional pressures for turtles, including beach erosion, pollution, siltation, thermal stagnation, hypersaline plumes and habitat loss (Al Ameri et al. 2022). In the UAE, coastal development has resulted in the degradation of coral reefs, mangrove forests, seagrass beds, oyster beds, salt marshes and sandy beaches (Burt and Bartholomew 2019). Many of these habitats include areas used by sea turtles to forage and nest.

The development of coastal areas also introduces other threats to sea turtle hatchlings. Light is a crucial orientation stimulus for sea turtle hatchlings navigating from their nest into the sea. The introduction of artificial lighting on or near nesting beaches can attract and disorient sea turtle hatchlings, delaying their route to the water, thereby increasing their exposure to potential terrestrial predators, or causing hatchlings to get lost entirely. Light pollution is considered a significant threat for sea turtle hatchlings in many countries across the northwestern Indian Ocean, including the United Arab Emirates region (Pilcher and Al-Merghani 2000; Hanafy 2012; Ghassemi-Khademi 2014; Al Ameri et al. 2022) (see also Chap. 8).

Industrialization and urbanization of coastal areas also increases marine traffic, escalating the sea turtles' risk of boat strikes. An investigation of sea turtle strandings from the UAE's east coast reported boat-related traumas on 10.8% of stranded sea turtles (Yaghmour 2020). On the west coast, 20% of sea turtle strandings in Abu Dhabi had injuries consistent with boat strikes (EAD 2016). Another threat extensively investigated in recent years is marine pollutants, particularly marine debris entanglement and ingestion. Marine debris is defined as any manufactured and/or processed solid waste product that is discarded, lost or abandoned into the marine environment (Coe and Rogers 2012; Galgani et al. 2013).

An investigation of sea turtle strandings from the UAE's east coast documented marine debris entanglement among 5.9% of stranded sea turtles (Yaghmour 2020). Another examination of stranding from the UAE's west coast along the Abu Dhabi emirate reports 52% of stranded sea turtles entangled in marine debris (EAD 2016). Large quantities of marine debris were observed in the gastrointestinal tracts of 75.0–85.7% of green sea turtles, 83.3% of Hawksbill Sea Turtles, 57.1% of Loggerhead Sea Turtles and 28.6% of Olive Ridley Sea Turtles from the Gulf of Oman (Yaghmour et al. 2018a, 2021b, 2021a). These results are especially concerning when compared to those from a similar study that reports no marine debris was observed in the gastrointestinal tract of green turtles sampled in Oman between 1977 and 1979 (Ross 1985; Schuyler et al. 2014). The majority of ingested debris items consist of white or transparent, threadlike or sheetlike plastics that are mostly composed of polypropylene and polyethylene (Yaghmour et al. 2022a). The findings of those studies also suggest that most ingested debris items were likely to pass through the gastrointestinal tract suggesting that the main risks caused by marine debris ingestion are sub-lethal harms and not instantaneous death (Campani et al. 2013), although several cases were documented to result with lethal effects through obstruction or puncturing of the gastrointestinal tract. Obstruction was mainly caused by ingestion of plastic sheets such as plastic bags or plastic wrapping (Yaghmour et al. 2018a, 2021b, 2021a). Green Sea Turtles, particularly younger individuals, were at greatest risk of this threat as they ingest the greatest quantities of marine debris and also have the longest and narrowest gastrointestinal tracts. Puncturing of the gastrointestinal tract was mainly due to the ingestion of sharp metallic fishing gear such as fishing hooks and rusty fragments of traditional baited basket fishing traps known locally as '*gargoors*' (Yaghmour et al. 2018b).

Gargoors are dome-shaped basket traps with a funnel-like entrance and a sturdy circular supporting base (Weizhong et al. 2012; Al-Abdulrazzak and Pauly 2013). Traditionally, gargoors were made by weaving fronds from date palms (*Phoenix dactylifera*), whereas now they are made from galvanized steel (Grandcourt et al. 2008). The circumstances that lead sea turtles to consume metallic gargoor fragments are not entirely clear. It has been observed that the surface of lost and discarded gargoors are often colonized by epibiotic growth including algae, barnacles, molluscs and bryozoa. It is, therefore, believed that sea turtles may attempt to feed on this growth, and in doing so inadvertently consume gargoor fragments that become increasingly brittle through decay and rust (Yaghmour et al. 2018b). Furthermore, decayed gargoors, particularly those with dislodged funnel entrances, were observed to trap and drown sea turtles that happen to wander into them (Yaghmour et al. 2018b; Yaghmour 2020).

With the exception of the Gulf War spill of 1991, oil pollution has largely been overlooked as a threat to marine fauna in the UAE. However, upon closer examination, recent studies reported severe impacts that oil spills have on marine reptiles in the UAE. In one study, 71% of examined Green Sea Turtles contained harmful, petrogenically sourced Polycyclic Aromatic Hydrocarbons (PAHs) in their tissues (Yaghmour et al. 2020). That same study also reports alarming levels of harmful and illegal Organo-Chlorine Pesticides (OCPs), including DDTs, in 25% of examined Green Sea Turtles. Another study from the same area found that marine turtle strandings and mortalities sharply increase in frequency during periods that follow oil spills (Yaghmour 2019b). Finally, one study examined strandings related to an oil spill that took place in November 2021 along the East coast of Sharjah, on the beaches of Kalba (Yaghmour et al. 2022b). During that study, 39 sea snakes of four species (Yellow-bellied Sea Snake, Arabian Gulf Sea Snake, Yellow Sea Snake, Ornate Reef Sea Snake) were investigated. Most (84.6%) of these sea snakes had oil covering most (75–100%) of their bodies. Nearly all (91.4%) sea snakes also had oil covering their eyes and snouts. Furthermore, 25.8% were observed with oil in their mouth, 41.4% had oil residue in their esophagus and over a third (34.5%) had oil inside their stomachs. Overall, the study suggests that the viscosity and stickiness of this oil slick was the main cause of sea snake mortalities. Apart from oil spills sea

Fig. 19.12 Marine reptile threats: Green Sea Turtle with partially ingested thread-like marine debris in its mouth (**a**); marine debris items found in the gastrointestinal tract of a Loggerhead (**b1**) and Green Sea Turtle (**b2**); Green Sea Turtle trapped and drowned inside a gargoor (**c**); Arabian Red Fox pup with a Hawksbill Sea Turtle egg in its mouth (**d**); Arabian Gulf Coral Reef Sea Snake stranding coated with oil (**e**); bycatch of a dozen Green Sea Turtles during drag-net fishing (Photo credits: John Periera (**a**), Fadi Yaghmour (**b**–**e**) and Paul Rivers (**f**))

snakes are also negatively impacted by marine debris and unintentional fishing activities. While the potential negative impact on sea snakes due rising oceanic water temperatures due to climate change and how they will adapt to these changes is uncertain (Fig. 19.12).

19.7 Management and Conservation Efforts

19.7.1 National Policies and Management Actions

In the UAE, several national policies and management actions have been taken to conserve sea turtles. This includes the designation of wetlands, under the Ramsar Convention that includes habitats used by marine turtles. The UAE has also designated two sites in the UAE (Bu Tinah Shoal in Abu Dhabi and Sir Bu Nair Island and Protected Area in Sharjah) as sites of regional importance within the Indian Ocean and South-East Asia (IOSEA) Marine Turtle Memorandum of Understanding. The

Ministry of Climate Change and Environment (MOCCAE), in collaboration with local authorities, also developed the UAE's National Plan of Action for Turtles to guide priority conservation actions. Furthermore, the UAE is a signatory to the Convention of International Trade in Endangered Species in Wild Fauna and Flora (CITES) and the Convention of Biological Biodiversity (CBD) which ban turtle hunting, as well as the importing and exporting of bekko. Furthermore, the UAE is also a signatory to the Convention on the Conservation of Migratory Species of Wild Animals (CMS) which confers protection for migratory species like turtles throughout their range. Finally, several marine protected areas have been established to conserve identified sea turtle feeding and nesting habitats.

19.7.2 Monitoring Programmes

To assess the status of local turtle populations several monitoring programmes were established at key nesting sites in Sharjah, Dubai and Abu Dhabi over the last decade. Other programmes focused on feeding areas are run in Abu Dhabi, by the Environment Agency of Abu Dhabi (EAD) and recently an in-water conservation programme was established by the Environment and Protected Areas Authority (EPAA) in a newly discovered juvenile green turtle feeding aggregation in Sharjahs's east coast. Biennial aerial surveys conducted by EAD indicate that green and hawksbill turtle populations have remained stable. Furthermore, monitoring via satellite tracking has supported the assessment of Marine Protected Areas (MPAs) effectiveness for the conservation of sea turtles, indicating a great deal of overlap between them and the identified Important Turtle Areas (ITAs) for green turtles in the Emirate of Abu Dhabi. The overlap is less comprehensive in the Northern Emirates followed by the eastern coast where there is a great urgency for the establishment of MPAs.

Stranding monitoring and research conducted by the EPAA's Sharjah Strandings Response Program (SSRP), has filled the gaps regarding biodiversity, ecology and threats of marine reptiles, marine mammals and seabirds in the Emirate of Sharjah. Through this, the program aims to support the development of evidence-based conservation action and policy in the region as well as educate the wider public on the importance of conserving species and other emerging issues. Additionally, this program acts as an important tool for the response and rescue of live strandings In Sharjah.

19.7.3 Rescue and Rehabilitation

Several entities in the UAE provide stranded marine reptiles with medical support and care in order to reintroduce them to the sea. The Dubai Turtle Rehabilitation Project (DTRP) was established in Burj Al Arab Jumeirah in 2004 (Fig. 19.13). The

Fig. 19.13 Release of rescued and rehabilitated Green, Hawksbill and Olive Ridley Sea Turtle (clockwise order from top left) by the Dubai Turtle Rehabilitation Project (Photos: Michael Rall)

DTRP was the first marine turtle rehabilitation center in the UAE and the wider Arabian region. It is run in collaboration with Dubai's Wildlife Protection Office, with veterinary support provided by the Dubai Falcon Hospital and post mortem examinations conducted in the Central Veterinary Research Laboratory (CVRL). At the time this chapter was written the DTRP had successfully rehabilitated and released 2050 turtles, 69 of them with satellite tags (Barbara Lang-Lenton, pers. comm.).

Despite being a center that is mostly focused on terrestrial fauna, the Breeding Centre of Endangered Arabian Wildlife (BCEAW), located in the Sharjah Desert Park, receives and rehabilitates stranded sea snakes collected via the SSRP in Sharjah. The BCEAW is currently the only active center in the UAE where sea snakes are rehabilitated. Another center from the Sharjah Emirate is the Khor Kalba Mangrove Center, located in the Alqurm Wa Lehhaffaiiah Protected Area. The Khor Kalba Mangrove Center includes a turtle rehabilitation pond that receives and rehabilitates turtles rescued via the SSRP. It is the only sea turtle rehabilitation center on the eastern coast of the UAE.

In Abu Dhabi, the Wildlife Rescue Program was established as a collaboration between the Environment Agency of Abu Dhabi (EAD), Abu Dahbi's environment regulatory authority and the National Aquarium (TNA), the largest aquarium in the Middle East. The Wildlife Rescue Program aims to rescue, rehabilitate and release sea turtles as well as other wildlife of the Abu Dhabi Emirate (Himansu Das, pers. comm.).

Though not open at the time this chapter was written, the Yas SeaWorld Research and Rescue Center (YSWRRC) aims to provide expert care for the local marine wildlife, including both sea turtles and sea snakes, through the development of a strong rescue network and the establishment of cutting-edge rescue and rehabilitation facilities. Though the YSWRRC is established in the Emirate of Abu Dhabi, it has ambitions to support wildlife on a national and regional scale (Elise Marquis, pers. comm.).

19.7.4 Regulation Gaps

Despite the enormous efforts and progress made in marine reptile conservation in the UAE, there still remain several gaps in the current regulatory framework, particularly for sea snakes. Policy and management actions to conserve sea snakes globally is limited to species with restricted distribution ranges, nationally there are no conservation measures in place for any sea snake species. In fact sea snakes are often not included in conservation management plans. Lack of research interest has also led to lack of sufficient data, which hinders appropriate conservation actions.

19.8 The Future of Sea Turtles and Sea Snakes in the UAE

In light of our current knowledge, derived from monitoring efforts focusing on both green and hawksbill turtles, marine turtle populations in the country are relatively stable thus we believe that there is merit in having a cautious but optimistic view on the future of sea turtles in the UAE. Nonetheless, the increased exposure of marine turtles to marine debris, as demonstrated by the increase in frequency of marine debris ingestion among green sea turtles from 0% in the late 1970s to 75–87% in the late 2010s and early 2020s is a cause of great concern. However, since the UAE Cabinet's approval of the formation of the UAE Circular Economy Council in January of 2021 (www.moccae.gov.ae), we have observed a series of bold legislative actions that are gradually phasing out single-use plastics. It remains to be seen if these, and future measures will be enough to turn the rising tide of plastics in the UAE waters. To that end we recommended the continued monitoring of marine debris ingestion by sea turtles.

Despite the threats many of the UAE's coastal industrial, commercial, and recreational developments impose on turtles, these species have demonstrated a degree of behavioral adaptation and population resilience. The integrity, rigor and integration of the Environmental Impact Assessment process into design conceptualization, construction and operational planning can prove critical in reducing or nullifying future harm. In some scenarios, with careful consideration or impact offset implementation, some developments may be able to enhance the productivity of depleted marine zones to the benefit of adult, juvenile and hatchling turtles.

Furthermore there exists uncertainty about consequences of changes in environmental conditions and sea level in light of climate change that could have an important impact on turtle populations and their habitats. Further research efforts on this topic is desirable to facilitate the integration of climate-change adaptation solutions by monitoring programmes. In addition, we recommend the standardization of data collection across established monitoring programmes to understand trends over time.

When considering the lack of data regarding the current and historic status of sea snakes in the UAE, we can only conclude that the future of sea snakes in UAE waters is ambiguous. We can speculate that the dearth of research and conservation efforts focused on sea snakes may result in sustained and unaddressed anthropogenic threats. For example, oil spills, a frequent issue in UAE waters, were only recently observed to have serious impacts on sea snakes. Unpublished ongoing studies are also demonstrating that these species are exposed to harmful chemical residues such as heavy metals, PAHs and OCPs (Fadi Yaghmour, unpubl. data). It is also not known what impact the degradation of feeding habitats such as coral reefs, has on sea snake populations. However, some solace can be gained when considering that, to our knowledge, the nature of sea snakes does not collide directly with the interests of human development, as do sea turtles with their nesting habits. Furthermore, the resources sea snakes rely on are small fish of little or no commercial value for human consumption or exploitation. Additionally, sea snakes were not directly exploited historically as were sea turtles. We highly recommend the establishment of long-term monitoring programs to gain knowledge on how to best ensure the conservation of sea snakes.

19.9 Conclusion

Marine reptiles are ectothermic, air-breathing vertebrates found in tropical and subtropical waters, with the exception of one species that thrives in colder Atlantic waters. The waters of the UAE are recognized as important sea turtle habitats (Pilcher et al. 2014). In the UAE Green and Hawksbill Sea Turtles are abundant, Loggerhead and Olive Ridley Sea Turtles are observed occasionally, mostly along the eastern coast, while Leatherback Sea Turtles are rare. Sea snakes are the most diverse group of marine reptiles, which includes ten species occurring in the waters of the Arabian Gulf and the Gulf of Oman. Despite declining population levels globally, Green and Hawksbill Sea Turtle populations are considered stable within UAE waters and conservation management actions encouraged to continue. However, the population status of other sea turtle species along with all sea snakes remain understudied and ambiguous. Several challenges and threats face marine reptiles including habitat destruction through coastal development, marine pollution, bycatch and climate change.

19.10 Recommended Reading

For additional information on the conservation of marine turtles see Al Ameri et al. (2022), Pilcher et al. (2014). Detailed information for marine turtle species read Pilcher (2000). For additional information on marine turtle threats see Yaghmour et al. (2018a, b, 2019b, 2020c, 2021b). For additional details on sea snake biodiversity see Buzás et al. (2018).

References

Abreu-Grobois A, Plotkin P (2008) Lepidochelys olivacea. The international union for conservation of nature red list of threatened species 2008. http://www.iucnredlist.org/

Al Ameri HM, Himansu HS, Rodriguez-Zarate CJ, Antonopoulou M (2020) United Arab Emirates. In: Phillott AD, Rees AF (eds) Sea turtles in the Middle East and South Asia region: MTSG annual regional report 2020. Report of the IUCN-SSC Marine Turtle Specialist Group, 2020. www.iucn-mtsg.org/s/MTSG-Regional-Report_Middle-East-South-Asia_2020.pdf

Al Ameri HM, Al Harthi S, Al Kiyumi A, Al Sariri TS, Al-Zaidan ASY, Antonopoulou M et al (2022) Biology and conservation of marine turtles in the northwestern Indian Ocean: a review. Endange Species Res 48:67–86

Al Ameri HM, Al Harthi S, Al Kiyumi A, Al Sariri TS, Al-Zaidan ASY, Antonopoulou M, Godley BJ et al (2022) Biology and conservation of marine turtles in the northwestern Indian Ocean: a review. Endanger Species Res 48:67–86

Al-Abdulrazzak D, Pauly D (2013) From dhows to trawlers: a recent history of fisheries in the Gulf countries, 1950 to 2010, vol 21. Fisheries Centre Research Reports, Vancouver, p 2

Aspinall S (1995) United Arab Emirates. In: Scott DA (ed) A directory of the wetlands in the Middle East. IUCN, Gland, and IWRB, Slimbridge

Anderson J (1872) On some Persian, Himalayan, and other reptiles. Proc Zool Soc Lond 1872:371–404

Bauer AM, Sadlier RA (eds) (2000) The herpetofauna of New Caledonia, Contributions to herpetology, vol 17. Society for Study Amphibians and Reptiles, Ithaca

Bishop JM, Deshti T, Al-Ayoub S (2007) The Arabian Gulf's first record of the olive ridley, Lepidochelys olivacea, from Kuwait. Zool Middle East 42(1):102–103

Bjorndal KA (1980) Nutrition and grazing behavior of the green turtle *Chelonia mydas*. Mar Biol 56(2):147–154

Bostrom BL, Jones TT, Hastings M, Jones DR (2010) Behaviour and physiology: the thermal strategy of leatherback turtles. PLoS One 5(11):e13925

Bouchard SS, Bjorndal KA (2000) Sea turtles as biological transporters of nutrients and energy from marine to terrestrial ecosystems. Ecology 81(8):2305–2313

Burt JA, Bartholomew A (2019) Towards more sustainable coastal development in the Arabian Gulf: opportunities for ecological engineering in an urbanized seascape. Mar Pollut Bull 142:93–102

Buzás B, Farkas B, Gulyás E, Géczy C (2018) The sea snakes (Elapidae: Hydrophiinae) of Fujairah. Tribulus 26:1–31

Campani T, Baini M, Giannetti M, Cancelli F, Mancusi C, Serena F, Fossi MC et al (2013) Presence of plastic debris in loggerhead turtle stranded along the Tuscany coasts of the Pelagos sanctuary for Mediterranean marine mammals (Italy). Mar Pollut Bull 74(1):225–230

Carranza S, Els J, Burriel-Carranza B (2021) A field guide to the reptiles of Oman. Consejo Superior de Investigaciones Científicas, Madrid, p 223

Chowdhury MAW, Islam MR, Auawal A, Uddin H, Hasan N, Haidar IKA (2021) On the occurrence of Persian Gulf Sea Snake, *Hydrophis lapemoides* (Gray, 1849) (Reptilia, Squamata, Elapidae, Hydrophiinae), along the coast of Bangladesh. Check List 17(4):1075–1080

Coe JM, Rogers D (eds) (2012) Marine debris: sources, impacts, and solutions. Springer, New York

Cogger HG (2000) Reptiles and amphibians of Australia, 6th edn. Ralph Curtis Publishing, Sanibel Island, p 808

Crane J (1937) The Templeton Crocker Expedition. III. Brachygnathous crabs from the Gulf of California and the west coast of Lower California. Zoologica 22(3):47–78

de Silva A, Ukuwela KDB, Sivaruban A, Sanders KL (2011a) Preliminary observations on the reproductive biology of six species of Sri Lankan Sea snakes (Elapidae: Hydrophiinae). Salamandra 47(4):193–198

de Silva A, Sivaruban A, Ukuwela KDB, Rasmussen AR, Sanders KL (2011b) First record of a sea snake (*Lapemis curtus*) feeding on a gastropod. Herpetol Notes 4:373–375

Dunson WA (1975) The biology of sea snakes. University Park Press, Baltimore, MD, p 530

EAD (2016) Biodiversity annual report 2016: status of marine turtle conservation in Abu Dhabi Emirate. Environment Agency Abu Dhabi, Abu Dhabi

Egan D (2007) Snakes of Arabia: a field guide to the snakes of the Arabian Peninsula and its shores. Motivate Publishing, Dubai, p 208

Ferrara CR, Vogt RC, Sousa-Lima RS (2013) Turtle vocalizations as the first evidence of posthatching parental care in chelonians. J Comp Psychol 127(1):24–32

Ficetola GF (2008) Impacts of human activities and predators on the nest success of the hawksbill turtle, *Eretmochelys imbricata*, in the Arabian Gulf. Chelonian Conserv Biol 7(2):255–257

Frick MG, Williams KL, Bolten AB, Bjorndal KA, Martins HR (2004) Diet and fecundity of Columbus crabs, *Planes minutus*, associated with oceanic-stage loggerhead sea turtles, Caretta caretta, and inanimate flotsam. J Crustac Biol 24(2):350–355

Fuentes MM, Hamann M, Lukoschek V (2012) Marine reptiles. CSIRO Marine and Atmospheric Research

Galgani F, Hanke G, Werner SDVL, De Vrees L (2013) Marine litter within the European marine strategy framework directive. ICES J Mar Sci 70(6):1055–1064

Ganesh S, Nandhini T, Samuel V, Sreeraj C, Abhilash K, Purvaja R, Ramesh R (2019) Marine snakes of Indian coasts: historical resume, systematic checklist, toxinology, status, and identification key. J Threat Taxa 11(1):13132–13150

Gardner AS (2013) The amphibians and reptiles of Oman and the UAE. Chimaira, Frankfurt, p 480

Gasperetti J (1988) Snakes of Arabia. Fauna Saudi Arabia 9:169–450

Ghassemi-Khademi T (2014) Study the biological status of two species of endangered turtles of Iran: Euphrates softshell turtle (Refetus euphraticus) and hawksbill sea turtle (*Eretmochelys imbricata*). J Middle East Appl Sci Technol 12:350–354

Gladstone W, Krupp F, Younis M (2003) Development and management of a network of marine protected areas in the Red Sea and Gulf of Aden region. Ocean Coast Manag 46(8):741–761

Grandcourt E, Loughland R, Siddiqui K, Al-Cibahy A, Das H, Brown G, Soorae P et al (2008) Marine and coastal environments of Abu Dhabi Emirate, United Arab Emirates. Environment Agency - Abu Dhabi, Abu Dhabi

Hanafy M (2012) Nesting of marine turtles on the Egyptian beaches of the Red Sea. Egypt J Aquat Biol Fish 16(2):59–71

Hannan LB, Roth JD, Ehrhart LM, Weishampel JF (2007) Dune vegetation fertilization by nesting sea turtles. Ecology 88(4):1053–1058

Heatwole H (1975) Predation on sea snakes. In: Dunson WA (ed) The biology of sea snakes. University Park Press, Baltimore, MD, pp 233–249

Heatwole H (1999) Sea snakes. Krieger Publishing, Malabar, p 148

Hebbelmann L, Pereira J, Yagmour F, Al Ali A (2016) New records of sea turtle nesting at Al Qurm Wa Lehhfaiiah protected area beach after a 30-year absence. Mar Turtle Newsl 150:7–9

Hirth HF, Abdel Latif EM (1980) A nesting colony of the hawks bill turtle Eretmochelys imbricata on Seil Ada Kebir Island, Suakin Archipelago, Sudan. Biol Conserv 17:125–130

Jackson JB (2001) What was natural in the coastal oceans? PNAS 98(10):5411–5418
Jackson JB, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Warner RR et al (2001) Historical overfishing and the recent collapse of coastal ecosystems. Science 293(5530): 629–637
Jongbloed M (2000) Field guide to the reptiles and amphibians of the UAE - wild about reptiles. Barkers Trident Communications, p 116
Kanta F, Sasai T, Hibino Y, Nishizawa H (2021) Morphology, diet, and reproduction of coastal hydrophis sea snakes (Elapidae: Hydrophiinae) at their northern distribution limit. Zool Sci 38(5):405–415
Kropach C (1971) Sea snake (*Pelamis platurus*) aggregations on slicks in Panama. Herpetologica 29(2):131–135
Kutsuma R, Takahide S, Takushi K (2018) How snakes find prey underwater: sea snakes use visual and chemical cues for foraging. Zool Sci 35(6):483–486
León YM, Bjorndal KA (2002) Selective feeding in the hawksbill turtle, an important predator in coral reef ecosystems. Mar Ecol Prog Ser 245:249–258
Lillywhite HB, Solórzano A, Sheehy CM III, Ingley S, Sasa M (2010) New perspectives on the ecology and natural history of the sea snake, *Pelamis platurus*, in Costa Rica: does precipitation influence distribution? Reptil Amphib 17(2):69–72
Lillywhite HB, Brischoux F, Sheehy CM III, Pfaller JB (2012) Dehydration and drinking responses in a pelagic sea snake. Integr Comp Biol 52(2):227–234
Manire CA, Norton TM, Stacy BA, Innis CJ, Harms CA (2017) Sea turtle health and rehabilitation. J. Ross Publishing, Plantation, FL, p 1045
McClenachan L, Jackson JB, Newman MJ (2006) Conservation implications of historic sea turtle nesting beach loss. Front Ecol Environ 4(6):290–296
McClellan F, Catherine M, Braun-McNeill J, Avens L, Wallace BP, Read AJ (2010) Stable isotopes confirm a foraging dichotomy in juvenile loggerhead sea turtles. J Exp Mar Biol Ecol 387(1–2):44–51
Meylan A (1988) Spongivory in hawksbill turtles: a diet of glass. Science 239(4838):393–395
Minton SA (1975) Geographic distribution of sea snakes. In: Dunson WA (ed) The biology of sea snakes. University Park Press, Baltimore, MD, pp 21–31
Mobaraki A (2004) Marine turtles in Iran: results from 2002. Turtle News 104:13
Mortimer JA, Donnelly M (2008) Eretmochelys imbricata. In: IUCN Red List of Threatened Species IUCN SSC Marine Turtle Specialist Group Version 2014.1
Musick JA, Limpus CJ (1997) Habitat utilization and migration in juvenile sea turtles. In: Lutz PL, Musick JA (eds) The biology of sea turtles. CRC Press, Boca Raton, FL, pp 137–164
Nasher AK, Al Jumaily M (2013) Initial steps to building long term sea turtle conservation program on Soqotra. TAYF, the Soqotra Newsletter 10:14
Natoli A, Phillips KP, Richardson DS, Jabado RW (2017) Low genetic diversity after a bottleneck in a population of a critically endangered migratory marine turtle species. J Exp Mar Biol Ecol 491:9–18
Paladino FV, O'Connor MP, Spotila JR (1990) Metabolism of leatherback turtles, gigantothermy, and thermoregulation of dinosaurs. Nature 344(6269):858–860
PERSGA (Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden) (2006) State of the marine environment, report for the Red Sea and Gulf of Aden. PERSGA, Jeddah
Pilcher NJ (2000) The green turtle, *Chelonia mydas* in the Saudi Arabian Gulf. Chelonian Conserv Biol 3:730–735
Pilcher NJ, Al-Merghani M (2000) Reproductive biology of green turtles at Ras Baridi, Saudi Arabia. Herpetol Rev 31(3):142
Pilcher NJ, Saad M (2006) Status of leatherback turtles in Yemen. Assessment of the conservation status of the leatherback turtle in the Indian Ocean and South-East Asia. IOSEA Species Assessment 1:164–166

Pilcher N, Perry L, Antonopoulou M, Abdel-Moati M (2014) Short-term behavioural responses to thermal stress by hawksbill turtles in the Arabian region. J Exp Mar Biol Ecol 457:190–198

Pilcher NJ, Rodriguez-Zarate CJ, Antonopoulou MA, Mateos-Molina D, Das HS, Bugla IA (2020) Combining laparoscopy and satellite tracking: successful round-trip tracking of female green turtles from feeding areas to nesting grounds and back. Glob Ecol Conserv 23:e01169

Pilcher NJ, Antonopoulou MA, Rodriguez-Zarate CJ, Al-Sareeria TS, Baldwin R, Willson A, Willson MS (2021) Wide-scale population connectivity revealed by postnesting migrations of green sea turtles from Ras Al Hadd, Oman. chelonian conservation and biology: celebrating 25. Years as the World's Turtle and Tortoise Journal 20(1):10–17

Potts DT (2001) Before the Emirates: an archaeological and historical account of developments in the region c. 5000 BC to 676 AD. United Arab Emirates: a new perspective, pp 28–69

Rasmussen AR, Murphy JC, Ompi M, Gibbons JW, Uetz P (2011) Marine reptiles. PLoS One 6(11):e27373

Rees AF, Baker SL (2006) Hawksbill and olive ridley nesting on Masirah Island, Sultanate of Oman: an update. Mar Turt Newsl 113:2–5

Rees A, Al-Kiyumi A, Broderick A, Papathanasopoulou N, Godley B (2012) Each to their own: inter-specific differences in migrations of Masirah Island turtles. Chelonian Conserv Biol 11:243–248

Rees AF, Papathanasopoulou N, Godley BJ (2018) Tracking hawksbill and green sea turtles in Kuwait reveals variability in migratory and residency strategies. Indian Ocean Turt Newsl 28:23–26. https://www.iotn.org/ iotn28-08-tracking-hawksbill-and-green-sea-turtles-inkuwait-reveals-variability-in-migratory-and-residencystrategies/

Rezaie-Atagholipour M (2012) *Lapemis curtus* (short sea snake) diet. Herpetol Rev 43:494

Rezaie-Atagholipour M, Riyahi-Bakhtiari A, Sajjadi M (2013) Feeding habits of the annulated sea snake, *Hydrophis cyanocinctus*, in the Persian Gulf. J Herpetol 47(2):328–330

Rezaie-Atagholipour M, Ghezellou P, Hesni MA, Dakhteh SMH, Ahmadian H, Vidal N (2016) Sea snakes (Elapidae, Hydrophiinae) in their westernmost extent: an updated and illustrated checklist and key to the species in the Persian Gulf and the Gulf of Oman. ZooKeys 622:129–164

Ross JP (1985) Biology of the green turtle, *Chelonia mydas*, on an Arabian feeding ground. J Herpetol 19:459–468

Ross JP, Barwani MA (1982) Review of the sea turtles in the Arabian area. In: Bjorndal KA (ed) The biology and conservation of sea turtles. Smithsonian Institution Press, Washington, DC, pp 373–383

Sanders KL, Michael SY, Mumpuni L, Bertozzi T, Rasmussen AR (2012) Multilocus phylogeny and recent rapid radiation of the viviparous sea snakes (Elapidae: Hydrophiinae). Mol Phylogenet Evol 66(3):575–591

Schuyler Q, Hardesty BD, Wilcox C, Townsend K (2014) Global analysis of anthropogenic debris ingestion by sea turtles. Conserv Biol 28(1):129–139

Sherratt E, Rasmussen AR, Sanders KL (2018) Trophic specialization drives morphological evolution in sea snakes. R Soc Open Sci 5:172141

Sindaco R, Venchi A, Grieco C (2013) The reptiles of the Western Palearctic, Volume 2: annotated checklist and distributional atlas of the snakes of Europe, North Africa, Middle East and Central Asia, with an update to Volume 1. Edizioni Belvedere, Latina (Italy), p 543

Soorae PS, Das HS, Al Mazrouei H (2006) Records of sea snakes (subfamily Hydrophiinae) from the coastal waters of the Abu Dhabi emirate, United Arab Emirates. Zool Middle East 39:109–110

Thayer GW, Bjorndal KA, Ogden JC, Williams SL, Zieman JC (1984) Role of larger herbivores in seagrass communities. Estuaries 7(4):351–376

Tuxbury SM, Salmon M (2005) Competitive interactions between artificial lighting and natural cues during seafinding by hatchling marine turtles. Biol Conserv 121:311–316

Van de Elst R (2006) Status of leatherback turtles in Somalia. In: Hamann M, Limpus C, Hughes G, Mortimer L, Pilcher NJ (eds) Assessment of the conservation status of the leatherback turtle in the Indian Ocean and South-East Asia. IOSEA species assessment, Volume 1. Bangkok, IOSEA Marine Turtle MoU Secretariat, pp 122–124

Vergne AL, Mathevon N (2008) Crocodile egg sounds signal hatching time. Curr Biol 18(12): R513–R514

Volsøe H (1939) The sea-snakes of the Iranian gulf and the Gulf of Oman. In: Danish scientific investigation in Iran, vol 1. E. Munksgaard, Copenhagen, pp 9–45

Wallace BP, Avens L, Braun-McNeill J, McClellan CM (2009) The diet composition of immature loggerheads: insights on trophic niche, growth rates, and fisheries interactions. J Exp Mar Biol Ecol 373(1):50–57

Weizhong C, Al-Baz A, Bishop JM, Al-Husaini M (2012) Field experiments to improve the efficacy of gargoor (fish trap) fishery in Kuwait's waters. Chin J Oceanol Limnol 30(4):535–546

Wilson EG (2010) Why healthy oceans need sea turtles: the importance of sea turtles to marine ecosystems. Oceana

Witherington BE, Salmon M (1992) Predation on loggerhead turtle hatchlings after entering the sea. J Herpetol 26(2):226–228

Yaghmour F (2019a) Strandings of olive ridley sea turtle, *Lepidochelys olivacea* Eschscholtz, 1829 from the coastal waters of the United Arab Emirates. Mar Turt Newsl 158:27–29

Yaghmour F (2019b) Are oil spills a key mortality factor for marine turtles from the eastern coast of the United Arab Emirates? Mar Pollut Bull 149:110624

Yaghmour F (2020) Anthropogenic mortality and morbidity of marine turtles resulting from marine debris entanglement and boat strikes along the eastern coast of the United Arab Emirates. Mar Pollut Bull 153:111031–111031

Yaghmour F, Al Naqbi H (2020) First record of Columbus crab Planes minutus (Crustacea: Decapoda: Brachyura: Grapsidae) Linnaeus, 1758 for the northwestern Indian Ocean. Mar Biodivers Rec 13(1):7

Yaghmour F, Jarwan M (2020) Rare observation of Hawksbill Turtle (Eretmochelys imbricata) nesting activity in Khor Fakkan, Eastern Coast of Sharjah, United Arab Emirates. Mar Turtle Newsl 161:31–32

Yaghmour FA, Rodríguez-Zárate CJ (2021) First record of Olive Ridley Sea Turtle Lepidochelys olivacea (Eschscholtz, 1829) nesting in the United Arab Emirates. Herpetol Notes 14:353–356

Yaghmour F, Al Bousi M, Whittington-Jones B, Pereira J, García-Nuñez S, Budd J (2018a) Marine debris ingestion of green sea turtles, *Chelonia mydas*,(Linnaeus, 1758) from the eastern coast of the United Arab Emirates. Mar Pollut Bull 135:55–61

Yaghmour F, Al Bousi M, Whittington-Jones B, Pereira J, García-Nuñez S, Budd J (2018b) Impacts of the traditional baited basket fishing trap "gargoor" on green sea turtles *Chelonia mydas* (Testudines: Cheloniidae) Linnaeus, 1758 from two case reports in the United Arab Emirates. Mar Pollut Bull 135:521–524

Yaghmour F, Samara F, Alam I (2020) Analysis of polychlorinated biphenyls, polycyclic aromatic hydrocarbons and organochlorine pesticides in the tissues of green sea turtles, *Chelonia mydas*, (Linnaeus, 1758) from the eastern coast of the United Arab Emirates. Mar Pollut Bull 160: 111574

Yaghmour F, Al Bousi M, Al Naqbi H, Whittington-Jones B, Rodríguez-Zarate CJ (2021a) Junk food: interspecific and intraspecific distinctions in marine debris ingestion by marine turtles. Mar Pollut Bull 173:113009

Yaghmour F, Al Bousi M, Al Naqbi H, Samara F, Ghalayini T (2021b) Junk food: a preliminary analysis of ingested marine debris by hawksbill *Eretmochelys imbricata* and olive ridley *Lepidochelys olivacea* sea turtles (Testudines: Cheloniidae) from the eastern coast of the United Arab Emirates. Mar Pollut Bull 173:113073

Yaghmour F, Samara F, Ghalayini T, Kanan SM, Elsayed Y, Al Bousi M, Al Naqbi H (2022a) Junk food: polymer composition of macroplastic marine debris ingested by green and loggerhead sea turtles from the Gulf of Oman. Sci Total Environ 828:154373

Yaghmour F, Els J, Maio E, Whittington-Jones B, Samara F, El Sayed Y, Mupandawana M et al (2022b) Oil spill causes mass mortality of sea snakes in the Gulf of Oman. Sci Total Environ 825:154072

Zann LP (1975) Biology of a barnacle (*Platylepas ophiophilus* Lachester) symbiotic with sea snakes. In: Dunson WA (ed) The biology of sea snakes. University Park Press, Baltimore, pp 267–286

Zann L, Cuffey RJ, Kropach C (1975) Fouling organisms and parasites associated with the skin of sea snakes. In: Dunson WA (ed) The biology of sea snakes. University Park Press, Baltimore, pp 251–265

Zieman JC, Fourqurean JW, Frankovich TA (1999) Seagrass die-off in Florida bay: long-term trends in abundance and growth of turtle grass, *Thalassia testudinum*. Estuaries 22(2):460–470

Chapter 20
Sharks and Rays of the United Arab Emirates

Aaron C. Henderson and Shamsa Al Hameli

20.1 What Exactly Are 'Sharks' and 'Rays'?

The term 'sharks and rays' refers to a diverse group of aquatic vertebrates known scientifically as the elasmobranch fishes (Elasmobranchii). They differ from other fish groups in a variety of ways, but most notably in the possession of a skeleton that is composed entirely of cartilage (Klimley 2013). It is because of this trait that they are sometimes referred to as the 'cartilaginous fishes', while all other fish groups are collectively known as the 'bony fishes' (due to the presence of bone, to varying degrees, in their skeletons). However, the elasmobranchs differ from bony fish in a variety of other ways as well, which is hardly surprising given that this group has been evolving independently for over 400 million years. Indeed, the modern elasmobranchs are the living descendants of one of the earliest vertebrate lineages and, consequently, they have retained many ancestral characteristics (Grogan and Lund 2004).

Although a detailed exploration of elasmobranch anatomy and physiology is beyond the scope of this chapter, some of their distinguishing traits are worth emphasising. Externally, the most obvious difference is that elasmobranchs do not possess the relatively large, flexible, scales that are typical of most bony fish. Instead, their skin is covered with tiny placoid scales known as denticles, which give elasmobranch skin its characteristic sandpaper-like texture (Fig. 20.1). However,

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-031-37397-8_20.

A. C. Henderson (✉)
Biology Department, College of Science, UAE University, Al Ain, United Arab Emirates
e-mail: ahenderson@uaeu.ac.ae

S. Al Hameli
Environment Agency – Abu Dhabi, Abu Dhabi, United Arab Emirates

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_20

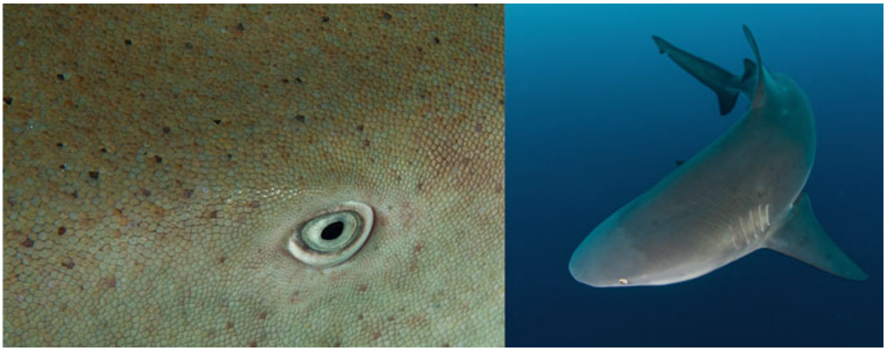


Fig. 20.1 From a distance, sharks might appear to possess smooth skin, but on closer inspection their placoid scales are clearly evident (left). Another key difference between elasmobranchs and other fish groups is that they possess multiple, paired gill openings. These are typically found on the side of the head in sharks, as seen here (right), but on the underside of the head in batoids. Image credit: Aspas/shutterstock.com (left) and Stefan Pircher/shutterstock.com (right), used under license to S. Al Hamali

in some species the skin is largely devoid of scales, while in others the denticles are enlarged to form prominent thorn-like structures (Meyer and Seegers 2012). It is notable from an evolutionary perspective that denticles have the same basic structure as teeth, consisting of an interior pulp cavity surrounded by a hard mineralised material called dentine which, in turn, is overlain with enamel.

Also evident externally is the fact that elasmobranchs have multiple paired gill openings, as compared to the single pair of gill openings found on a bony fish. These paired gill openings range in number from five to seven, with the vast majority of species having five (Fig. 20.1). Species with six or seven pairs of gill openings represent more ancient branches of the elasmobranch evolutionary tree and are largely confined to the deeper regions of the ocean (Ebert et al. 2021; Last et al. 2016).

Perhaps the most notable difference between elasmobranchs and the vast majority of other fishes, is that they reproduce via internal fertilisation. Whereas most bony fish release their eggs and sperm into the surrounding water for fertilisation to take place outside the body, the elasmobranchs undergo a physical copulation, whereby the male deposits his sperm inside the female's body (Pratt and Carrier 2011). This is achieved with copulatory organs known as claspers, which are scroll-like extensions of the pelvic fins. As claspers are only found on males, their presence or absence allows the gender of any elasmobranch to be ascertained easily.

Following copulation, the sperm that have been deposited in the female's reproductive tract must undertake a lengthy trip through the uterus until they reach the oviducal gland; a structure that is unique to elasmobranchs and which performs a variety of tasks (Hamlett et al. 2005a). It acts initially as a receptacle for the sperm, where they can be stored for periods of days, months, or even years, until the female ovulates (Pratt 1993). It is thought that the oviducal gland is also the site of fertilisation, after which it secretes a protective covering around the egg (Hamlett and Koob 1999). The nature of this protective covering varies according to the reproductive strategy of the species in question, for the females of some species release the fertilised egg from the body and embryonic development is completed externally, while others retain the fertilised egg in the uterus for embryonic development to be completed within the female's body (Carrier et al. 2004). In the case of the former, egg-laying species, the egg covering is usually tough and leathery (commonly called a "mermaid's purse"), while in the latter, live-bearing species, it is thin and membranous. The reproductive output of egg-laying species is not constrained by the size of the female's body, as she can continue to lay eggs for as long as there are viable sperm stored in the oviducal gland. However, these embryos will rely entirely on the yolk reserves in the egg to fuel their development until they hatch from the egg-case a number of months later. Consequently, they tend to be small in size and vulnerable to predation at the time of hatching. The females of live-bearing species can produce only as many embryos as their body can physically accommodate for the duration of the pregnancy. However, a variety of strategies have evolved by which the mother can pass additional nutrients to her embryos, so that they are not solely reliant on their yolk reserves (Hamlett et al. 2005b). So, although far fewer embryos are produced, they tend to be larger and less prone to predation at the time of birth. These aspects of elasmobranch reproductive biology have a large bearing on their varying abilities to withstand fishing pressure and habitat loss, and we will revisit this topic later in this chapter.

Returning to the question posed at the beginning of this section, why do we distinguish between two distinct groups of elasmobranchs, namely 'sharks' and 'rays'? As in all matters related to taxonomy, the answer is complicated but, in essence, sharks have gill openings placed on the sides of the head, whereas rays have gill openings that are positioned on the underside of the head. While this might seem like an arbitrary difference, it does appear to reflect a clear genetic division within the elasmobranchs (Naylor et al. 2005). The sharks form a lineage that is usually referred to as the Selachii while the rays form a lineage known as the Batoidea. Although sharks vary in colouration and range in size from the diminutive dwarf lanternshark (*Etmopterus perryi*) that reaches a length of only 21 cm, to the gigantic whale shark (*Rhincodon typus*) that reaches a length of almost 20 m, their body form is relatively well conserved (with a few exceptions) (Ebert et al. 2021). On the other hand, rays are a much more diverse group that encompasses a variety of body forms, including the egg-laying skates, the live-bearing stingrays, guitarfishes and sawfishes, among others (Last et al. 2016).

20.2 Ecological Importance

Elasmobranchs are found throughout the marine environment, ranging from shallow inshore areas to the deepest depths of the ocean. The bull shark (*Carcharhinus leucas*), is famous for being able to move between marine and freshwater environments (Thorson 1971), but a number of other shark and ray species are also euryhaline (capable of withstanding wide fluctuations in salinity), while a small number of ray species are restricted to freshwater (Lucifora et al. 2015). Regardless of the environment in which they are found, all elasmobranch species are predatory in nature (Wetherbee and Cortés 2004). Prey preferences vary from species to species and are largely informed by lifestyle. Demersal species, i.e. those that live close to the seabed, tend to have diets dominated by a variety of bottom-dwelling invertebrates such as crabs and polychaete worms, although fish, squid and octopuses may also be consumed. Pelagic species, i.e. those that live higher in the water column, usually have diets that are dominated by fish; although, it is worth pointing out that the two largest shark species in the world, the whale shark and the basking shark, are filter-feeders whose diets consists mostly of zooplankton (Wetherbee and Cortés 2004). The routine consumption of marine mammals, sea turtles and seabirds is the preserve of a small number of shark species, such as the great white shark (*Carcharodon carcharias*) and the tiger shark (*Galeocerdo cuvier*).

It is common to see elasmobranchs referred to as ‘apex predators’, meaning that they occupy the highest trophic (i.e. feeding) level of the food web that they are part of (Wallach et al. 2015). However, this is a somewhat simplistic and misleading representation of their ecological role. After all, we are talking about a diverse group of animals of varying sizes, lifestyles and dietary preferences. For example, the Arabian carpetshark (*Chiloscyllium arabicum*) is a common demersal shark in the coastal waters of the UAE that feeds mostly on small invertebrates and grows to a maximum size of around 90 cm (Ebert et al. 2021). An animal of this size is incapable of feeding on large fish, marine reptiles or mammals, but is itself likely to be an important prey item for larger predators (Fig. 20.2). On the other hand, the tiger shark can reach lengths well in excess of 500 cm and is unlikely to be a common prey for any other species—at least by the time it reaches adult size. It also feeds on a wide variety of species, including other sharks, sea turtles and marine mammals (Heithaus 2001). So, whereas the latter can truly be considered an apex predator, the former is most certainly not. Indeed, it is a relatively small number of large-bodied shark species that deserve the apex predator moniker, while most other sharks and batoids are more accurately described as ‘mesopredators’, i.e. they occupy intermediate trophic levels.

Nonetheless, both apex predators and mesopredators play important roles in the structuring and functioning of food webs, and, as such, factors that impact their abundance in an ecosystem can have far reaching consequences (Pauly et al. 1998). The most publicised of these is the so-called ‘trophic cascade’, whereby changes in the abundance of a species in one trophic level cascades through all trophic levels down to the primary producers (e.g. marine plants and algae) (Terborgh et al. 2010). It is hardly surprising then, that numerous studies have linked wide-ranging negative ecological consequences to the overfishing of elasmobranch species (Barley et al. 2017; Myers et al. 2007).

The importance of elasmobranchs to food web dynamics can also extend across multiple ecosystems. As we will see later in this chapter, some shark and batoid species inhabit what are termed ‘nursery grounds’ during the early stages of life, and these are typically shallow, inshore areas where food is abundant and potential

Fig. 20.2 The Arabian carpetshark is one of the more common shark species in the UAE. Given its size and lifestyle, it should be considered a mesopredator rather than an apex predator. Photographer: Shamsa Al Hameli

predators are less common (Heupel et al. 2007). The fact that they are feeding in these productive inshore areas during their early years, before moving out to deeper coastal areas or the open ocean, where they may fall prey to larger predators, means that they are effectively transferring nutrients and energy from one place to another. In other words, they form a trophic link between what might otherwise be largely distinct ecosystems (Osgood and Baum 2015; Sievers et al. 2019). While such a role is not limited to elasmobranchs, their sheer size elevates their importance in the process.

20.3 Sharks of the UAE

It would be reasonable to expect that this section of the chapter might begin with a straightforward statement declaring the number of shark species that have been recorded in UAE waters. Alas, there are two major complicating factors in this regard. The first is that, compared to many other parts of the world, relatively little scientific research was undertaken around the Arabian Peninsula until a few decades ago. Consequently, the field of marine research in the region is still quite young and there is a distinct lack of historical data to consider in the construction of local species checklists. The second complicating factor is that the world of taxonomic research in general has undergone something of a revolution in recent times, thanks to the advent of DNA barcoding (Savolainen et al. 2005). This has resulted in a huge increase in scientific publications that challenge pre-existing notions on species' identities and relationships (DeSalle and Goldstein 2019)—particularly in geographic regions or with taxa that had already received limited taxonomic attention. Elasmobranchs in the Arabian region tick both of these boxes.

Keeping these caveats in mind, the most recent global checklist of shark species shows 47 (from 15 families) as possibly occurring in UAE waters (Ebert et al. 2021). These range in size from the Arabian carpetshark at 90 cm in length, to the world's largest fish, the whale shark, that reaches up to 20 m in length. Of course, not all of these species can be considered common in UAE waters; indeed, definitive evidence for the local occurrence of a number of these species is lacking. To date, some 31 species have actually been confirmed in UAE waters, including zebra sharks (Stegastomatidae), whale sharks (Rhincodontidae), houndsharks (Triakidae), weasel sharks (Hemigalidae), requiem sharks (Carcharhinidae) and hammerhead sharks (Sphyrnidae). Of these, it is the requiem sharks that are by far the most common, with this family including large-bodied species such as the blacktip shark (*Carcharhinus limbatus*) and bull shark, and a wide variety of small-bodied species such as the milk shark (*Rhizoprionodon acutus*) and sliteye shark (*Loxodon macrorhinus*) (Box 20.1). A tentative checklist of shark species in UAE waters is provided at the end of this chapter.

Box 20.1 Commonly Misidentified Species in the UAE

When most people think of a shark, what they usually picture is grey and torpedo shaped, with the characteristic triangular dorsal fin. This is the typical appearance of a particular family of sharks—the requiem sharks (Carcharhinidae). This is one of the largest shark families and many of the species that it contains look very similar to each other.

This is particularly true of those species that commonly exhibit dark fin tips. To the uninitiated, it might seem reasonable to assume that a grey-coloured shark with dark fin tips is a 'blacktip shark'. Alas, the situation is more complicated than this. A number of different species fit this general description including, of course, the actual blacktip shark. To complicate the matter further, the darkness of some or all fin tips can fade with age in some species. In UAE waters, the species that are most likely to be confused in this regard are the aforementioned blacktip shark, the spinner shark (*Carcharhinus brevipinna*) and the graceful shark (*Carcharhinus amblyrhinchoides*). Another species, the blacktip reef shark also has very prominent dark markings on its fins; however, whereas the former three species are all large-bodied and predominantly grey in colour, the latter doesn't grow much larger than 1.5 m in length and its skin has more of a brownish-grey hue.

(continued)

Box 20.1 (continued)

Other local elasmobranch species that look very similar to each other are the bull shark and pigeye shark (*Carcharhinus amboinensis*); the hooktooth shark (*Chaenogaleus macrostoma*) and the slender weasel shark (*Paragaleus randalli*); the cowtail ray (*Pastinachus ater*) and the broad cowtail ray (*Pastinachus sephen*); the leopard whipray (*Himantura leoparda*) and the coach whipray (*Himantura uarnak*).

The shark species that are most likely to be encountered by SCUBA divers and snorkelers in the UAE are the zebra shark (*Stegostoma fasciatum*) and the blacktip reef shark (*Carcharhinus melanopterus*), both of which associate with coral reefs and rocky outcrops (Fig. 20.3). Neither species poses a threat to humans as long as they are given a wide berth and not harassed. Zebra sharks will spend time lying on the seabed and can sometimes be easily approached, leading to a temptation to touch and stroke them. However, this type of behaviour is to be avoided as it can cause stress to the animal and, despite their generally docile nature, they can bite when provoked (Compagno 1984).

Fig. 20.3 The blacktip reef shark is one of the shark species that divers and snorkelers in the UAE are most likely to encounter. Photographer: Shamsa Al Hameli

20.4 Rays of the UAE

As mentioned previously, 'rays' is the common term applied to the Batoidea, and this includes a wide variety of what are mostly dorso-ventrally depressed (i.e. they possess relatively wide, flat bodies) lineages. It is because of this body shape that they have come to be referred to as 'flat sharks' in recent parlance. The waters of the UAE are home to a diverse array of batoid species including sawfishes (Pristidae), wedgefishes (Rhinidae), guitarfishes (Rhinobatidae), giant guitarfishes (Glaucostegidae), butterfly rays (Gymnuridae), stingrays (Dasyatidae), eagle rays (Myliobatidae), pelagic eagle rays (Aetobatidae), cownose rays (Rhinopteridae) and devil rays (Mobulidae) (Last et al. 2016). Estimating the number of individual batoid species that occur in UAE waters is even more difficult than for sharks, as there is a great deal of uncertainty around the identities of numerous species (Naylor et al. 2012) (Box 20.2). In fact, it seems likely that many of the batoids that occur in UAE waters are either cryptic species (i.e. they look very similar to a well-known species from elsewhere but are in fact genetically distinct) or are a species complex (i.e. what appears to be a single species is actually two or more genetically distinct species). Unravelling this taxonomic tangle is a work in progress, but a tentative list of batoids in UAE waters is also provided at the end of this chapter.

Whereas the majority of shark species found in UAE waters are at least reasonably active swimmers, batoids more commonly spend extended periods lying on the seabed. This is particularly true of the guitarfishes, stingrays and butterfly rays, and it is species from these families that SCUBA divers and snorkelers in the UAE are most likely to encounter. However, the eagle rays, pelagic eagle rays, cownose rays and devil rays are all active swimmers, and it is species from these families that are most likely to be encountered near the surface (Fig. 20.4).

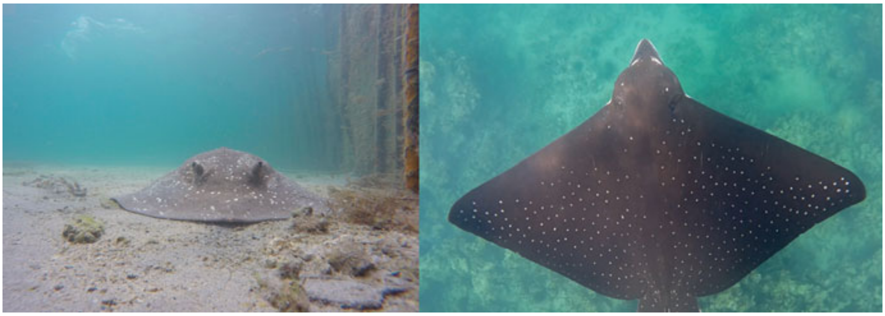


Fig. 20.4 Although rays are mostly likely to be encountered resting on the seabed as in the case of this porcupine ray (left), some species are active swimmers and may be found closer to the surface, such as this eagle ray (right). Photo credits: Shamsa Al Hameli

Box 20.2 When one species becomes four

If you were to consult a species guide from only a few years ago, you would likely find among its pages a species of stingray with white spots on its skin and black and white bands along its tail, known as the whitespotted whipray (*Himantura gerrardi*). Researchers had long thought that this might by a species complex consisting of two or more distinct species, and with the help of genetic analyses these suspicions turned out to be correct. The erstwhile *H. gerrardi* is now known to be four distinct species, namely *Maculabatis gerrardi*, *Maculabatis bineeshi*, *Maculabatis arabica* and *Maculabatis randalli* (Last et al. 2016).

Whenever a new species is described, it can take some time to determine the extent of its geographic distribution, and such is the case with these whiprays. Although they can all be found within what was *H. gerrardi*'s reported distribution (Indo-West Pacific), they don't each necessarily occupy that whole range. *Maculabatis gerrardi* seems to have the broadest distribution of the four, occurring throughout the Indo-West Pacific including the Gulf of Oman. *Maculabatis bineeshi* has so far only been recorded from Indian waters and does not appear to occur in the Gulf of Oman or Arabian Gulf. *Maculabatis randalli* appears to be limited to the Arabian Gulf, possibly including the UAE's Arabian Gulf coast, while *Maculabatis arabica* had, until recently, been limited to the west coast of India. However, it has since been documented from the UAE's Arabian Gulf (Alhameli et al. unpublished data) and Gulf of Oman (Henderson 2020) coasts.

20.5 A Need for Nurseries: The Importance of Shallow, Inshore Habitats to Newborn Sharks and Rays

A nursery habitat, as the name suggests, is one that is utilised by newborn and juvenile sharks and rays. However, there is more to the concept than simply identifying an area where the young animals happen to occur. It is generally accepted that, in order to be considered a nursery area, it must meet the following criteria: Newborns and young juveniles are more common in the area under consideration than in other areas; they remain in, or return to, the area for extended periods; the area is repeatedly used across years (Heupel et al. 2007).

Nurseries tend to occur in productive, inshore areas, thereby providing the young sharks and rays with abundant feeding opportunities. Clearly, they play an extremely important role in the life cycles of species that use them, and anything that impacts the health and integrity of these areas can disrupt the populations that depend on them (Courrat et al. 2009).

In order to visualise how nurseries are used by elasmobranchs, we can look at the classic example of the lemon shark (*Negaprion brevirostris*), the reproductive biology and ecology of which has been studied in detail by researchers in the western

Fig. 20.5 Inshore nursery grounds are incredibly important in the life-cycle of many elasmobranch species. This newborn halavi guitarfish (*Glaucostegus halavi*) is in water only a few centimetres deep. Photographer: Aaron Henderson

Atlantic Ocean for a number of decades (e.g. Chapman et al. 2009; Correa et al. 1995; Feldheim et al. 2002; Gruber et al. 1988; Kessel et al. 2013). Pregnant females move into shallow coastal areas adjacent to mangrove forests in early summer, where they each proceed to give birth to between 4 and 17 pups, depending on the size of the female. Once birthing is complete, the female leaves the area and moves back out to deeper waters. The neonates, which measure around 60 cm in length, will remain in these very shallow waters for the first few years of their life. As they grow, they gradually increase the area that they utilise, eventually moving away from the mangroves into deeper sand flats and seagrass areas, eventually joining the adult population offshore or around coral reefs (Morrissey and Gruber 1993).

Many of the elasmobranchs that occur in UAE waters follow a similar life cycle as the lemon shark, including the closely related and almost identical sicklefin lemon shark (*Negaprion acutidens*). Archive footage from the BBC filmed during the early 1970s and available online shows Emirati fishers following large schools of these juveniles around the mangrove forests in Khor Faridah, Abu Dhabi. Alas, this species has been heavily fished and the population has declined to the extent that these large aggregations of juveniles are no longer common; however, the nurseries remain important for many other shark and ray species (Fig. 20.5). Moreover, scientists are still uncovering new and fascinating aspects of elasmobranch reproductive biology, some of which have dramatically altered our understanding of how these animals respond to adverse conditions (Box 20.3).

Box 20.3 Zebedee's Virgin Births

In 2007, a zebra shark in the Burj Al Arab aquarium in Dubai laid 30 eggs, of which three contained embryos (Robinson et al. 2011). This, in itself, is not particularly unusual, as captive egg-laying species commonly produce unfertilised eggs (possibly as a means of preventing oocyte accumulation in

(continued)

Box 20.3 (continued)
the ovary). The interesting aspect of this story is that the shark, named Zebedee, had never been in contact with a male of her species during her adult life. Sharks, like all vertebrates, reproduce sexually, whereby a male sperm unites with a female ovum to produce a zygote that divides to become an embryo. So, without access to sperm from a male zebra shark, how could Zebedee have produced these embryos? What's more, she went on to do the same thing in subsequent years!

The aquarium staff compared Zebedee's DNA with that of the embryos and concluded that she had given birth through a process known as parthenogenesis, i.e. virgin birth. Although producing offspring in this manner is not unknown among vertebrates, it is extremely rare. The process has also been documented elsewhere in other elasmobranch species, including the bonnethead shark (*Sphyrna tiburo*), blacktip shark, white-spotted bamboo shark (*Chiloscyllium plagiosum*), smalltooth sawfish (*Pristis pectinata*) and whitespotted eagle ray (*Aetobatus narinari*) suggesting that it may not be all that uncommon in elasmobranchs. Indeed, it seems likely that at least some temporally unusual elasmobranch births in captivity that were originally attributed to female sperm storage, may have been due to parthenogenesis (Fig. 20.6).

20.6 Movements and Migrations: Lessons Learned from Tagging, Tracking and Genetic Studies

The most extensive elasmobranch tagging/tracking study in the region to date has been on whale sharks, using a combination of satellite-linked tags and photo-identification of individuals based on skin spot patterns (Robinson et al. 2017). Despite the fact that whale sharks are known to be a wide-roaming species, those in the Arabian Gulf were observed to remain there for extended periods, although movement between the Arabian Gulf and Gulf of Oman was also evident. Interestingly, the sharks aggregated at specific feeding sites during the summer but became more dispersed during winter, indicating seasonality in their habitat preference. Moreover, specific individuals were noted to return to the same feeding sites during each of the 5 years for which the study ran.

The movements of one shark in the study were particularly impressive, having travelled from the Al Shaheen gas field off Qatar to the coast of Somalia over the course of 37 days, a trip of some 2644 km. This was the only shark in the study to have moved beyond the Gulf of Oman. It was also one of the largest sharks to be tagged during the study, and is thought to have been a pregnant female. Although further studies are required to investigate whale shark movements over a longer timeframe, this points to the possibility that the sharks may utilise the Arabian Gulf and Gulf of Oman during specific life stages. It is further supported by the fact that

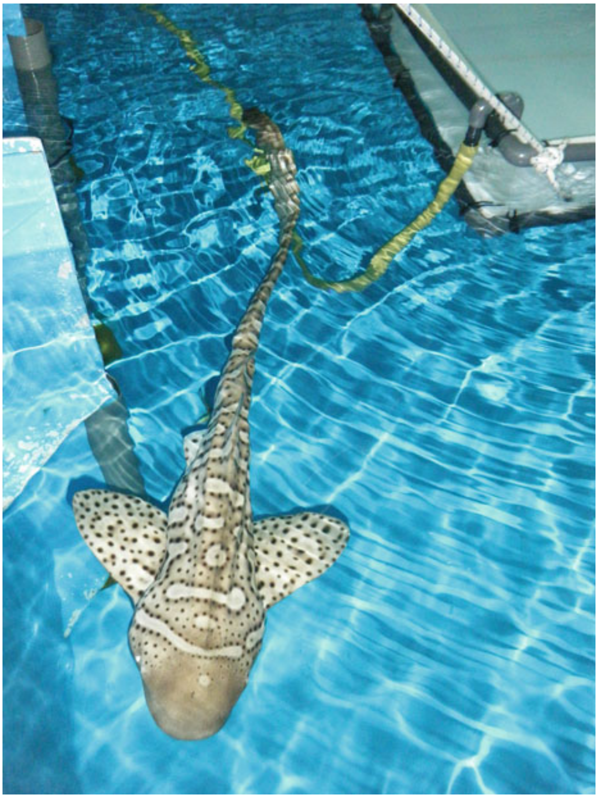


Fig. 20.6 One of Zebedee's parthenogenic 'virgin birth' offspring, behind the scenes at the Burj Al Arab Aquarium. Photographer: Aaron Henderson

small juveniles (<4 m in length) and large adults (>10 m in length) have not been observed in the region.

One other study has deployed satellite tags on sharks in the Gulf of Oman, with mixed results (Henderson and Reeve 2014). A bignose shark (*Carcharhinus altimus*) tagged off Muscat in 2011 moved approximately 97 km southward along the coastline over a period of 5 days. Unfortunately, the satellite track after this period is basically a straight line to the port of Al Quriyyat, indicating the shark was captured by fishermen and taken ashore. However, a sicklefin lemon shark tagged during the same study provided more extensive data. This shark was tagged off the Gulf of Oman coast of the Musandam peninsula in February 2011 and transmitted its archived data in May 2011. During this three-month period, it moved through the Strait of Hormuz into Iranian waters before moving westward through UAE waters, eventually ending up near Das Island. The total distance travelled by the shark was 578 km, in just 89 days (Fig. 20.7).

A more recent investigation into elasmobranch habitat use along the coast of Abu Dhabi has found an area near Ras Ghurab Island that seems to be of particular importance to two critically endangered batoids—the Pakistan whipray and the halavi guitarfish (Al Hameli et al. unpublished data). These species were

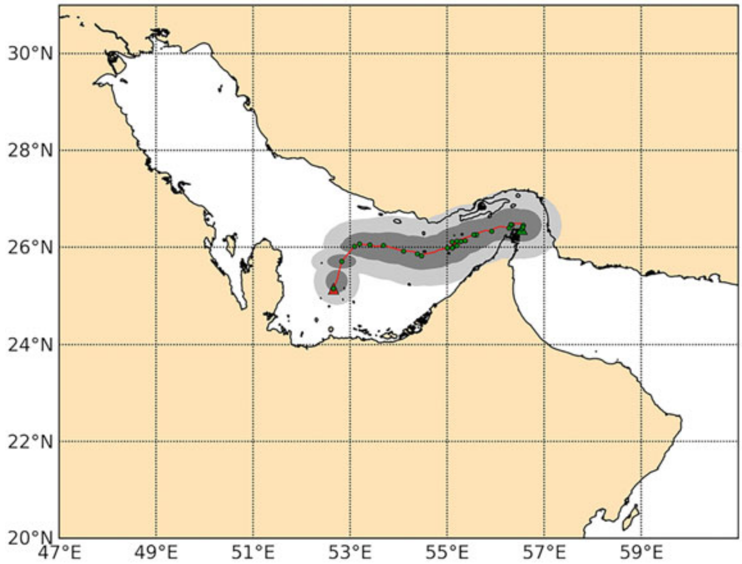


Fig. 20.7 This map shows the path followed by a sicklefin lemon shark that was tagged with a pop-up satellite archival tag (PSAT) outside the Arabian Gulf, off the Musandam peninsula in 2011. The tag transmitted its data 3 months and 578 km later, when the shark was close to Das Island, Abu Dhabi (Source: A. Henderson, unpubl. data)

considerably more abundant in this area than in the surrounding waters, and satellite tags that were deployed on some individuals indicate that they remain in the area for periods of at least several months.

While physically tagging and tracking marine animals has, historically, been the mainstay of understanding their movement patterns, advances in genetic analyses now facilitate researchers in the investigation of population structure and connectivity using DNA sequences. One such study assessed the population genetics of four shark species that occur around the Arabian Peninsula, from the Arabian Gulf to the Red Sea (Spaet et al. 2015). This included large-bodied species (blacktip shark and scalloped hammerhead shark), a medium-bodied species (spottail shark) and a small-bodied species (milk shark). At the outset of the study, it was assumed that each of the large-bodied species most likely formed a continuous population around the Arabian Peninsula, given their size and mobility, while the medium- and small-bodied species would be more likely to form multiple, smaller, discreet populations. What the study actually found is that there are no contemporary barriers to gene flow around the Arabian Peninsula in any of the study species. In other words, there are no population divisions around the Arabian Peninsula in any of the four species; they are each a pan-regional population.

Taken together, these studies tell us two important things. Firstly, the fact that individual animals commonly move across international boundaries and that populations are spread across multiple national territories complicates conservation efforts. Individual animals will be exposed to different fisheries and levels of protection as they move from one jurisdiction to another, and high levels of exploitation in one area are likely to impact whole populations. Consequently, there is a need for cooperative fisheries management in the region—after all, there is no point in one country have highly effective management measures in place if activities in other countries have a detrimental impact on those same populations. Secondly, the fact that some species, or particular life stages, might be highly dependent on habitats in specific locations, means that there is an onus on each country to identify and protect these areas.

20.7 Sharks and Rays in Emirati Culture

Traditionally, there are a number of gears and techniques used by Emirati fishers to target elasmobranchs, depending on the fishing area. In inshore shallow waters, particularly around islands, large meshed gill nets (*leikh*) 2–4 m deep and 100 m long with a mesh size of up to 30 cm were used to target sharks. Fishers usually deployed the nets overnight around particular areas where sharks were known to occur. Another gear type used in shallow waters is *al sakkar*, a temporary tidal barrier net usually 2 m deep and 500–1000 m long. Although based on the location and season, lemon sharks and rays can be commonly caught with this technique. Larger sharks, guitarfish and wedgefish were hunted using traditional wooden spears (*oumlah*) tied to a float that would tire the wounded fish and help in retrieving the catch. For offshore waters, longlines (*manshallah*) are usually deployed to target sharks from commercially registered dhows locally known as *lanj* (12–20 m long traditional vessels made from wood or fiberglass, that spend up to 10 days at sea).

Emirati fishers have traditional names for many local shark and ray species, with this sometimes extending to having multiple names for the same species depending on its size. Although fishers interviewed by the authors have expressed a preference for juvenile sharks, as the flesh becomes tougher with age, a wide variety of species and sizes have traditionally been caught. Accordingly, they have witnessed a great decline in some shark and ray populations within the areas they have historically fished, leading many to stop targeting elasmobranchs. One fisher pointed out that, in the past, he would encounter or catch between 7 and 10 elasmobranchs every other day, including juvenile blacktip sharks, whitecheek sharks, wedgefish, guitarfish and hammerhead sharks, but this is no longer the case. Of particular concern is that less than 20 years ago, wedgefish could be encountered on a daily basis, whereas now they might be seen only once or twice per year. When asked to quantify the decrease in local elasmobranch populations, the general consensus was a drop of approximately 50%, beginning in the early 2000s.

The traditional local utilisation of sharks and rays has been primarily for their meat. Dried and salted meat (*ouwal*) is consumed throughout the year, while fresh meat is used in a number of specific dishes such as *jsheed*. Liver oil from sharks and rays was also a valuable commodity at one time, as it was used to waterproof the hulls of wooden vessels. However, although still occasionally used in this manner, the advent of fibreglass vessels and synthetic sealants for wood, means that this is no longer common practice.

20.8 Threats to Shark and Ray Populations

There are two broad anthropogenic threats to shark and ray populations—indeed, to marine life in general. The first is overfishing, i.e. the removal of too many individuals from the population. The second is through habitat destruction or degradation.

Unfortunately, elasmobranchs have been heavily fished throughout the region and many species have experienced notable declines (Henderson et al. 2008; Jabado et al. 2014a; Jabado and Spaet 2017; Moore 2012). Shark and ray flesh has been utilised in local dishes for generations and this has resulted in targeted fisheries throughout the Arabian Gulf and neighbouring bodies of water. However, the level of exploitation underwent a dramatic increase in recent decades due to the demand for shark fin in the Far East and advances in fishing technology. Whereas the animals were once caught for their flesh and landed whole, the high value of shark fin meant that it became more profitable to remove the fins at sea and dump the rest of the carcass, so that the boat could be filled with the more valuable fins (Fig. 20.8). Thankfully, many countries eventually introduced legislation that prohibited the

Fig. 20.8 Even fins from small sharks are valuable to the shark fin market. Here, fins from small species such as the milk shark and slit-eye shark, as well as from juveniles of larger species such as the blacktip shark and scalloped hammerhead shark are being sun-dried prior to export to the Far East. Photographer: Aaron Henderson

practice of finning at sea and required the animals to be landed whole. However, considerable damage was already done by that stage, and the on-going fisheries depleted the populations further (Box 20.4).

Box 20.4 Where Did All the Sawfish Go?
The sawfishes (Pristidae) are large, shark-like batoids (Fig. 20.9). Although they possess an elongate body, the head is notably flattened and the gill slits are located on the underside—a defining feature of batoids. However, it is the long, toothed rostrum that is the most characteristic feature of the sawfishes and, of course, this is what gives them their name.

Written and photographic evidence indicates that sawfishes were abundant and widespread in the Arabian region up to the 1960s, but records thereafter are sparse, especially since the 1980s (Moore 2015). Although they have been a valuable commodity since the mid-nineteenth century, it seems that their precipitous decline coincided with the widespread availability of nylon gillets, in which their rostra become easily entangled. Although there are occasional, anecdotal reports of encounters with sawfish by UAE fishers, it seems that these animals are now incredibly rare, not just in the UAE but throughout the region.

Whereas the impacts of fisheries on shark and ray populations are straightforward, human activities that alter habitat quality can be less obvious. It is easy to see why coastal development and construction projects might not be commonly thought of as a threat to mobile marine animals such as sharks—after all, there is a whole ocean there for them to use. However, as mentioned previously, many species rely on shallow, inshore habitats for their nursery grounds, and the loss of these areas can impact the reproductive ecology of the species in question. The knock-on effect is that recruitment—the addition of new juvenile individuals to the population—is

Fig. 20.9 Sawfish were once common in UAE waters but are now extremely rare throughout the region. Image credit: Shaun Wilkinson/shutterstock.com, used under license to S. Al Hameli

reduced, further limiting the ability of these species to withstand any level of fishing pressure.

Of course, it is not just the complete loss of habitat that is of concern. Anything that influences water quality can alter ecosystem functioning and throw food webs out of kilter, thereby impacting all species that depend on these ecosystems (Palumbi et al. 2009). Eutrophication and the accumulation of pollutants can be particularly pronounced in coastal areas due to effluent discharge and surface run-off, further threatening the viability of inshore nursery grounds (Paerl 2006). Moreover, the Arabian Gulf is a semi-enclosed sea with a slow rate of water turnover, and this promotes the accumulation of pollutants on a broader scale (Naser 2013). As in the case of fisheries management, the management of water quality within the Arabian Gulf requires a collaborative approach.

Lastly, we must consider the potential impacts of climate change on local elasmobranchs. The Arabian Gulf is already the hottest sea in the world, and anything that might drive temperatures up is a matter for concern (see Chap. 4). Apart from the potential effects of temperature on elasmobranch physiology (Osgood et al. 2021), there is an inverse relationship between water temperature and dissolved oxygen. In other words, as water heats up, it contains less oxygen and, as with most marine animals, elasmobranchs depend on dissolved oxygen for respiration. This is cause for concern, as studies have already shown that low oxygen conditions are occurring around inshore reefs during summer (de Verneil et al. 2021).

However, there is another aspect of climate change that is of major concern in the marine environment: ocean acidification. Although a description of the process itself is beyond the scope of this chapter, ocean acidification is the term ascribed to the gradual decrease in ocean pH associated with the increase in atmospheric carbon dioxide. Its impact on marine life is far reaching, having consequences that are both direct and indirect, acute and gradual. Of immediate concern are the potential impacts of ocean acidification on the developmental biology of elasmobranchs, particularly in egg-laying species, where the developing embryo is exposed directly to environmental conditions (Johnson et al. 2016).

20.9 Data Requirements for the Effective Management of Shark and Ray Populations

There are three main groups of data that are of use in the management and conservation of exploited marine species. These consist of a species' inherent biological traits (growth rate, size at maturity, reproductive output etc), its ecological characteristics (distribution, habitat requirements, movement patterns etc), and data relating to the exploitation of the species (capture data, landings data, fishery operational data etc). Where all of these data are available, they can be combined to model the population under various scenarios and levels of exploitation, thereby allowing policy makers to implement the most effective management and conservation measures. Typically, these consist of closed fishing seasons, areas in which fishing is temporarily or permanently prohibited, gear restrictions, catch limits, size limits, and so on (Hart and Reynolds 2002). However, if the data on which the management decisions are based are incomplete or inaccurate, the value of the management measures will be limited, and possibly even detrimental to the management goals.

The UAE, like most countries in the region, suffers from a paucity of biological, ecological and fisheries data regarding local elasmobranchs, and this creates numerous barriers to the formulation and implementation of effective management and conservation measures. As in many parts of the world, elasmobranch landings in the UAE are not identified to species; instead, they are broadly categorised as ‘shark’ or ‘ray’. Critically, this means that there is no reliable information available regarding the extent to which fishing activities are impacting any one species. On top of this, locally-derived biological and ecological data are few and far between, even for common species. Although there are published data for many of the UAE’s elasmobranch species from elsewhere in their respective ranges, these must be treated with caution. Elasmobranch growth rates, sizes at maturity, reproductive cycles, migration patterns etc. can vary with geographic location (Bradley et al. 2017), as most of these traits are intricately tied to the prevailing environmental conditions. Hence, data collected from the population under consideration are infinitely more valuable to policy makers than comparable data from a population that is far removed (Fig. 20.10).

Fig. 20.10 Understanding movement patterns and habitat requirements is essential to formulating effective fishery management and conservation strategies. Here, the authors are tagging a female sicklefin lemon shark off the coast of Abu Dhabi. Photographer: Maitha Al Hameli

20.10 Current National Management Measures

Under the UAE Ministerial Decree No. 43 for the Year 2019 on Regulating the Fishing and Trading of Sharks, there are nine articles aimed at the conservation and sustainable fishing of sharks and rays. The legislation states that registered *lanj* boats are permitted to fish for sharks and rays between July to February, with fishing banned between March and June. During the permitted fishing season there are limitations on the number and size of hooks that can be used (no more than 100 non-stainless steel circle hooks with a maximum size of 12/0), as well as the type of fishing nets that can be used (those constructed from nylon threads are banned).

The legislation also prohibits the capture of species listed on Appendix I or II of the Convention on the International Trade in Endangered Species of Wildlife and Flora (CITES) or on Appendix I of the Convention on the Conservation of Migratory Species of Wild Animals (CMS) at any time. Similarly, Federal Law No. 23 (and its Executive By-Laws) for the Year 1999 on the Exploitation, Protection and Development of Living Aquatic Resources also affords some species complete protection. In all of these cases, where a prohibited species is caught, or a permitted species is caught during the closed season, it should be released alive. When this is not possible, the carcass should be handed over to the competent local authority.

In addition to enacting specific legislation to protect elasmobranchs in UAE waters, the government has also followed the advice of the Food and Agricultural Organisation of the United Nations (FAO) in developing a National Plan of Action for the Conservation of Sharks (NPOA-Sharks). This document outlines the knowledge gaps and data requirements pertinent to the sustainable exploitation of shark and ray species and, therefore, provides guidance to researchers and policy makers in their efforts to ensure that the nation's shark and ray populations are effectively managed and conserved (Anon 2018).

20.11 Conclusions

A diverse array of elasmobranchs species have been recorded in UAE waters, but years of heavy exploitation and habitat loss have impacted these populations, and many species are now extremely rare. However, all is not lost. Scientific interest in elasmobranchs is at an all-time high, and conservation concerns have been acknowledged by relevant authorities through the development of stronger fishing and trade regulations. It is important that this momentum is not allowed to fade. More research is required to better understand the biology, ecology and status of local elasmobranchs, while additional conservation regulations are required to help these populations to recover and ensure a bright future for this natural, and national, treasure.

20.12 Recommended Readings

For readers interested in learning more about the biology of sharks and rays, The Biology of Sharks and Their Relatives (Vol. 1 and 2), edited by J. C. Carrier et al. and published by CRC Press, is a good starting point. Those with a particular interest in elasmobranch taxonomy can access the extensive (and free) online Chondrichthyan Tree of Life at https://sharksrays.org.

References

Anon (2018) The UAE National Plan of action for the Conservation & Management of sharks. UAE Ministry of Climate Change & Environment

Barley SC, Meekan MG, Meeuwig JJ (2017) Species diversity, abundance, biomass, size and trophic structure of fish on coral reefs in relation to shark abundance. Mar Ecol Prog Ser 565: 163–179. https://doi.org/10.3354/meps1198

Bradley D, Conklin E, Papastamatiou YP, McCauley DJ, Pollock K, Kendall BE, Gaines SD, Caselle JE (2017) Growth and life history variability of the grey reef shark (*Carcharhinus amblyrhynchos*) across its range. PLoS One 12:e0172370. https://doi.org/10.1371/journal.pone.0172370

Brown JNB (1992) Whale shark *Rhincodon Typus* (Smith, 1929). Tribulus 2:22

Carrier JC, Pratt HL, Castro JI (2004) Reproductive biology of elasmobranchs. In: Carrier JC, Musick JA, Heithaus MR (eds) Biology of sharks and their relatives. CRC Press, Baton Rouge, pp 269–286

Chapman DD, Babcock EA, Gruber SH, Dibattista JD, Franks BR, Kessel SA, Guttridge T, Pikitch EK, Feldheim KA (2009) Long-term natal site-fidelity by immature lemon sharks (Negaprion brevirostris) at a subtropical island. Mol Ecol 18:3500–3507. https://doi.org/10.1111/j.1365-294X.2009.04289.x

Compagno LJV (1984) Part 1: Hexanchiformes to Lamniformes. In: Sharks of the world: an annotated and illustrated catalogue of shark species known to date, FAO species catalogue, vol 4. FAO, Rome

Correa J, De Marignac J, Gruber S (1995) Young lemon shark behaviour in Bimini lagoon. Bahamas J Sci 3:2–8

Courrat A, Lobry J, Nicolas D, Laffargue P, Amara R, Lepage M, Girardin M, Le Pape O (2009) Anthropogenic disturbance on nursery function of estuarine areas for marine species. Estuar Coast Shelf Sci 81:179–190. https://doi.org/10.1016/j.ecss.2008.10.017

de Verneil A, Burt JA, Mitchell M, Paparella F (2021) Summer oxygen dynamics on a southern Arabian Gulf coral reef. Front Mar Sci 8:1676. https://doi.org/10.3389/fmars.2021.781428

DeSalle R, Goldstein P (2019) Review and interpretation of trends in DNA barcoding. Front Ecol Evol 7:302. https://doi.org/10.3389/fevo.2019.00302

Ebert DA, Dando M, Fowler S (2021) Sharks of the world: a complete guide. Princeton University Press, Princeton, NJ

Feldheim KA, Gruber SH, Ashley MV (2002) The breeding biology of lemon sharks at a tropical nursery lagoon. Proc R Soc Lond Ser B 269:1655–1661. https://doi.org/10.1098/rspb.2002.2051

Grogan ED, Lund R (2004) The origin and relationships of early chondrichthyes. In: Carrier JC, Musick JA, Heithaus MR (eds) Biology of sharks and their relatives. CRC Press, Baton Rouge, pp 3–32

Gruber SH, Nelson DR, Morrissey JF (1988) Patterns of activity and space utilization of lemon sharks, Negaprion brevirostris, in a shallow Bahamian lagoon. Bull Mar Sci 43:61–76

Hamlett WC, Koob TJ (1999) Female reproductive system. In: Hamlett WC (ed) Sharks, skates, and rays: the biology of elasmobranch fishes. John Hopkins University Press, Baltimore, pp 398–443

Hamlett WC, Knight DP, Pereira FTV, Steele J, Sever DM (2005a) Oviducal glands in chondrichthyans. In: Hamlett WC (ed) Reproductive biology and phylogeny of Chondrichthyes: sharks, Batoids and chimaeras. Science Publishers, Enfield, pp 301–335

Hamlett WC, Kormanik G, Storrie M, Stevens B, Walker TI (2005b) Chondrichthyan parity, lecithotrophy and matrotrophy. In: Hamlett WC (ed) Reproductive biology and phylogeny of chondrichthyes: sharks, batoids and chimaeras. Science Publishers Inc, Enfield, pp 395–434

Hart PJB, Reynolds JD (2002) Handbook of fish biology and fisheries: Volume 2 Fisheries. Blackwell, London

Heithaus MR (2001) The biology of tiger sharks, *Galeocerdo cuvier*, in Shark Bay, Western Australia: sex ratio, size distribution, diet and seasonal changes in catch rates. Environ Biol Fish 61:25–36. https://doi.org/10.1023/A:1011021210685

Henderson AC (2020) A review of potential taxonomic barriers to the effective management of gulf elasmobranch fisheries. Aquat Ecosyst Health Manage 23:210–219. https://doi.org/10.1080/14634988.2020.1800327

Henderson AC, Reeve AJ (2014) Assessment of shark population movements, delineations and breeding grounds in the Sultanate of Oman. Ministry of Agriculture and Fisheries, Muscat, p 63

Henderson AC, Al-Oufi H, McIlwain JL (2008) Survey, status and utilization of the Elasmobranch Fishery Resources of the Sultanate of Oman. Ministry of Agriculture and Fisheries, Muscat, p 136

Henderson AC, Reeve AJ, Jabado RW, Naylor GJP (2016) Taxonomic assessment of sharks, rays and guitarfishes (Chondrichthyes: Elasmobranchii) from South-Eastern Arabia, using the NADH dehydrogenase subunit 2 (NADH2) gene. Zool J Linnean Soc 176:399–442. https://doi.org/10.1111/zoj.12309

Heupel MR, Carlson JK, Simpfendorfer CA (2007) Shark nursery areas: concepts, definition, characterization and assumptions. Mar Ecol Prog Ser 337:287–297. https://doi.org/10.3354/meps337287

Jabado RW (2018) The fate of the most threatened order of elasmobranchs: shark-like batoids (Rhinopristiformes) in the Arabian Sea and adjacent waters. Fish Res 204:448–457. https://doi.org/10.1016/j.fishres.2018.03.022

Jabado RW, Spaet JLY (2017) Elasmobranch fisheries in the Arabian seas region: characteristics, trade and management. Fish Fish 18:1096–1118. https://doi.org/10.1111/faf.12227

Jabado RW, Al Ghais SM, Hamsa W, Henderson AC, Ahmad MA (2013) First record of the sand tiger shark, Carcharias taurus, from United Arab Emirates waters. Mar Biodivers Rec 6:e27. https://doi.org/10.1017/S1755267213000043

Jabado RW, Al Ghais SM, Hamza W, Henderson AC (2014a) The shark fishery in The United Arab Emirates: an interview based approach to assess the status of sharks. Aquat Conserv Mar Freshwat Ecosyst 25:800–816. https://doi.org/10.1002/aqc.2477

Jabado RW, Al Ghais SM, Hamza W, Shivji MS, Henderson AC (2014b) Shark diversity in the Arabian/Persian Gulf higher than previously thought: insights based on species composition of shark landings in the United Arab Emirates. Mar Biodivers 45:719–731. https://doi.org/10.1007/s12526-014-0275-7

Jabado RW, Al Hameli SM, Grandcourt EM, Al Dhaheri SS (2018) Low abundance of sharks and rays in baited remote underwater video surveys in the Arabian Gulf. Sci Rep 8:15597. https://doi.org/10.1038/s41598-018-33611-8

Jabado RW, Ebert DA, Al Dhaheri SS (2022) Resolution of the Aetomylaeus nichofii species complex, with the description of a new eagle ray species from the Northwest Indian Ocean and a key to the genus Aetomylaeus (Myliobatiformes: Myliobatidae). Mar Biodivers 52:1–13. https://doi.org/10.1007/s12526-021-01234-4

Johnson MS, Kraver DW, Renshaw GM, Rummer JL (2016) Will ocean acidification affect the early ontogeny of a tropical oviparous elasmobranch (Hemiscyllium ocellatum)? Conserv Physiol 4:1–11. https://doi.org/10.1093/conphys/cow003

Kessel ST, Gruber SH, Gledhill KS, Bond ME, Perkins RG (2013) Aerial survey as a tool to estimate abundance and describe distribution of a carcharhinid species, the lemon shark, Negaprion brevirostris. J Mar Biol 2013:1–10. https://doi.org/10.1155/2013/597383

Klimley AP (2013) The biology of sharks and rays. The University of Chicago Press, Chicago

Last PR, Naylor GJP, Séret B, White WT, de Carvalho MR, Stehmann MFW (2016) Rays of the world. CSIRO Publishing, Clayton South

Lucifora LO, de Carvalho MR, Kyne PM, White WT (2015) Freshwater sharks and rays. Curr Biol 25:R971–R973. https://doi.org/10.1016/j.cub.2015.09.004

Meyer W, Seegers U (2012) Basics of skin structure and function in elasmobranchs: a review. J Fish Biol 80:1940–1967. https://doi.org/10.1111/j.1095-8649.2011.03207.x

Moore ABM (2012) Elasmobranchs of the Persian (Arabian) Gulf: ecology, human aspects and research priorities for their improved management. Rev Fish Biol 22:35–61. https://doi.org/10.1007/s11160-011-9222-x

Moore ABM (2015) A review of sawfishes (Pristidae) in the Arabian region: diversity, distribution, and functional extinction of large and historically abundant marine vertebrates. Aquat Conserv Mar Freshwat Ecosyst 25:656–677. https://doi.org/10.1002/aqc.2441

Moore ABM, McCarthy ID, Carvalho GR, Peirce R (2012a) Species, sex, size and male maturity composition of previously unreported elasmobranch landings in Kuwait, Qatar and Abu Dhabi Emirate. J Fish Biol 80:1619–1642. https://doi.org/10.1111/j.1095-8649.2011.03210.x

Moore ABM, Ward RD, Peirce R (2012b) Sharks of the Persian (Arabian) Gulf: a first annotated checklist (Chondrichthyes: Elasmobranchii). Zootaxa 3167:1–16. https://doi.org/10.11646/zootaxa.3167.1.1

Moore AB, Almojil D, Harris M, Jabado RW, White WT (2013) New biological data on the rare, threatened shark Carcharhinus leiodon (Carcharhinidae) from the Persian Gulf and Arabian Sea. Mar Freshw Res 65:327–332. https://doi.org/10.1071/MF13160

Morrissey JF, Gruber SH (1993) Home range of juvenile lemon sharks, *Negaprion brevirostris*. Copeia 1993:425–434. https://doi.org/10.2307/1447141

Myers RA, Baum JK, Shepherd TD, Powers SP, Peterson CH (2007) Cascading effects of the loss of apex predatory sharks from a coastal ocean. Science 315:1846–1850. https://doi.org/10.1126/science.113865

Naser HA (2013) Assessment and management of heavy metal pollution in the marine environment of the Arabian Gulf: a review. Mar Pollut Bull 72:6–13. https://doi.org/10.1016/j.marpolbul.2013.04.030

Naylor GJP, Ryburn JA, Fedrigo O, López JA (2005) Phylogenetic relationships among the major lineages of modern elasmobranchs. In: Hamlett WC (ed) Reproductive biology and phylogeny of chondrichthyes. Science Publishers, Enfield, pp 1–26

Naylor GJP, Caira JN, Jensen K, Rosana KAM, White WT, Last PR (2012) A DNA sequence-based approach to the identification of shark and ray species and its implications for global elasmobranch diversity and parasitology. Bull Am Mus Nat Hist 367:1–262

Osgood GJ, Baum JK (2015) Reef sharks: recent advances in ecological understanding to inform conservation. J Fish Biol 87:1489–1523. https://doi.org/10.1111/jfb.12839

Osgood GJ, White ER, Baum JK (2021) Effects of climate-change-driven gradual and acute temperature changes on shark and ray species. J Anim Ecol 90:2547–2559. https://doi.org/10.1111/1365-2656.13560

Paerl HW (2006) Assessing and managing nutrient-enhanced eutrophication in estuarine and coastal waters: interactive effects of human and climatic perturbations. Ecol Eng 26:40–54. https://doi.org/10.1016/j.ecoleng.2005.09.006

Palumbi SR, Sandifer PA, Allan JD, Beck MW, Fautin DG, Fogarty MJ, Halpern BS, Incze LS, Leong JA, Norse E, Stachowicz JJ, Wall DH (2009) Managing for ocean biodiversity to sustain marine ecosystem services. Front Ecol Environ 7:204–211. https://doi.org/10.1890/070135

Pauly D, Christensen V, Dalsgaard J, Froese R, Torres F (1998) Fishing down marine food webs. Science 279:860–863. https://doi.org/10.1126/science.279.5352.860

Pratt HL (1993) The storage of spermatozoa in the oviducal glands of western North Atlantic sharks. Environ Biol Fish 38:139–149. https://doi.org/10.1007/978-94-017-3450-9_12

Pratt HL Jr, Carrier JC (2011) Elasmobranch courtship and mating behavior. In: Hamlett WC (ed) Reproductive biology and phylogeny of chondrichthyes: sharks, batoids and chimaeras. CRC Press, Baton Rouge, pp 139–175

Robinson DP, Braverstock W, Al-Jura A, Hyland K, Khazanehdari KA (2011) Annually recurring parthenogenesis in a zebra shark *Stegostoma fasciatum*. J Fish Biol 79:1376–1382. https://doi.org/10.1111/j.1095-8649.2011.03110.x

Robinson DP, Jaidah MY, Bach SS, Rohner CA, Jabado RW, Ormond R, Pierce SJ (2017) Some like it hot: repeat migration and residency of whale sharks within an extreme natural environment. PLoS One 12:e0185360. https://doi.org/10.1371/journal.pone.0185360

Savolainen V, Cowan RS, Vogler AP, Roderick GK, Lane R (2005) Towards writing the encyclopaedia of life: an introduction to DNA barcoding. Philos Trans R Soc B Biol Sci 360:1805–1811. https://doi.org/10.1098/rstb.2005.1730

Sievers M, Brown CJ, Tulloch VJD, Pearson RM, Haig JA, Turschwell MP, Connolly RM (2019) The role of vegetated coastal wetlands for marine megafauna conservation. Trends Ecol Evol 34:807–817. https://doi.org/10.1016/j.tree.2019.04.004

Spaet JLY, Jabado RW, Henderson AC, Moore ABM, Berumen ML (2015) Population genetics of four heavily exploited shark species around the Arabian peninsula. Ecol Evol 5:2317–2332. https://doi.org/10.1002/ece3.1515

Terborgh J, Holt RD, Estes JA (2010) Trophic cascades: what they are, how they work, and why they matter. In: Terborgh J, Estes JA (eds) Trophic cascades: predators, prey, and the changing dynamics of nature. Island Press, Washington, pp 1–18

Thorson TB (1971) Movement of bull sharks, *Carcharhinus leucas*, between Caribbean Sea and Lake Nicaragua demonstrated by tagging. Copeia 1971:336–338. https://doi.org/10.2307/1442846

Wallach AD, Izhaki I, Toms JD, Ripple WJ, Shanas U (2015) What is an apex predator? Oikos 124:1453–1461. https://doi.org/10.1111/oik.01977

Wetherbee BM, Cortés E (2004) Food consumption and feeding habits. In: Carrier JC, Musick JA, Heithaus MR (eds) Biology of sharks and their relatives. CRC Press, Baton Rouge, pp 225–246

Chapter 21
Fishes of the Emirates

Matthew D. Mitchell, Johannes Els, and Marie Seraphim

21.1 Diversity and Abundance of Fishes

Fishes are the most diverse vertebrate group with around 36,000 species, compared with 11,000 species of birds and 6500 species of mammals (IUCN 2021). Having evolved several hundred million years ago, fishes have diversified to the point they can be found in almost all major aquatic habitats on earth, from mountain to lakes to the depths of the oceans, under the ice of the polar seas, intertidal mudflats, the darkest caves, and everything in between. Indeed, fishes are ecologically dominant in most aquatic habitats where they are found and play a central role in maintaining the functioning and health of their various ecosystems (Helfman et al. 2009). Fishes also represent a valuable resource for humanity, providing 178 million tonnes of food globally at a value of USD 406 billion (2020 data; FAO 2022). It is of little surprise that fishes are an important economic and ecological resource in the United Arab Emirates (UAE), second only to oil in terms of economic value as a resource sector (van Lavieren et al. 2011).

The UAE is predominantly a desert, yet freshwater habitats do exist and consist of pools and streams in the wadis of the Hajar Mountains as well as in various

M. D. Mitchell (✉)
Marine Biology Laboratory, New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
e-mail: mdm18@nyu.edu

J. Els
Environment and Protected Areas Authority, Breeding Centre for Endangered Arabian Wildlife, Sharjah, United Arab Emirates

M. Seraphim
Marine Biology Laboratory, New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

Scottish Seabird Centre, The Harbour, North Berwick, UK

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_21

man-made dams, wells and related structures. However, most of the UAE's aquatic environments are marine, and encompass 58,000 km^2 across the national exclusive economic zone, including both the Arabian Gulf and the Gulf of Oman. Overall, approximately 479 species of fish from 95 families are reported to inhabit the marine and brackish waters of the UAE (Froese and Pauly 2022), with an additional 3 species being freshwater (Freyhof et al. 2020) ('fish' refer here to 'bony fishes', not cartilaginous fishes (e.g. sharks and rays) which are discussed separately in Chap. 20). Freshwater fishes are discussed separately in Box 21.1, with the remainder of the chapter focused on marine fish assemblages.

Several fish families dominate in terms of the number of species and total abundance in the UAE, with the trevallys and jacks (Carangidae), tuna (Scombridae), snapper (Lutjanidae), and seabreams (Nemipteridae) families being particularly diverse and abundant, along with some families of smaller fishes that are closely associated with coral reef systems, including wrasses (Labridae), blennies (Blenniidae), gobies (Gobiidae) and cardinal fish (Apogonidae). Among this diverse group are species that highlight the marked variety of fishes, with members of the Gobiidae family being just a few centimetres in length while ocean sunfish (Fig. 21.1c; *Mola mola*) are the largest bony fish in the world. Some species, on the other hand, such as the spotted seahorse (*Hippocampus kuda*), the stonefish (*Synanceia verrucosa*) and humpback turretfish (Fig. 21.1f; *Tetrosomus gibbosus*) defy expectations of what a fish should look like.

When compared to other regions at similar latitudes within the Indo-Pacific, the diversity of UAE fishes is lower than expected and several taxonomic groups that are common elsewhere are missing from this region (Carpenter et al. 1997; Coles and Tarr 1990). This lower diversity reflects the biogeographic isolation of the UAE and extreme environments found in its waters (Burt et al. 2011; Grandcourt 2012; Sheppard 1993). The UAE is situated in the far northwest corner of the Indian Ocean and is isolated by a range of environmental and oceanographic barriers that minimise the influx of new species from the adjacent Red Sea, western Indian Ocean, and Indo-Pacific regions (Burt et al. 2011; Grandcourt 2012). Consequently, the Gulf of Oman and Arabian Gulf fish communities represent distinct biogeographic subregions, home to progressively more depauperate fish communities. The diversity and abundance of fishes is highest in the Gulf of Oman. This is due to its proximity to the Arabian Sea, from where the majority of the UAE fishes originated, but also due its high productivity due to upwelling of deep, nutrient rich waters during the summer monsoon, and the relatively benign environment, where temperatures range from 22 °C in the winter to 32 °C in the summer, while salinity hovers around 36 PSU which is typical of open ocean systems (Reynolds 1993; Sheppard et al. 1992). In contrast, the Arabian Gulf is young, only forming around 16,000 years ago following the last ice age, and only reaching its current shorelines 6000 years ago (Sheppard et al. 1992) (see Chap. 4 for further details on the Gulf's origin and environment). Due to being formed only recently, endemic species have had little time to evolve and there are no species endemic to the Arabian Gulf alone (Froese and Pauly 2022), although a few Gulf species are endemic to the broader Arabian region (DiBattista et al. 2020). Consequently, the diversity of fishes in the

Fig. 21.1 The UAE is home to diverse array of fish species. (**a**) Broomtail wrasse (*Cheilinus lunulatus*), (**b**) Arabian butterflyfish (*Chaetodon melapterus*), (**c**) Ocean sunfish (*Mola mola*), (**d**) Sailfish (*Istiophorus platypterus*), (**e**) Yellowtail tang (*Zebrasoma xanthurum*), (**f**) Humphead turretfish (*Tetrosomus gibbosus*), (**g**) Moon wrasse (*Thalassoma lunare*), (**h**) Flathead grey mullet (*Mugil cephalus*), (**i**) Picasso triggerfish (*Rhinecanthus assasi*), (**j**) Yellowfin tuna (*Thunnus albacares*), (**k**) Dory snapper (*Lujanus fluviflamma*), (**l**) Painted sweetlips (*Diagramma pictum*). Photo credits: (**a**) Cheilinus_lunulatus...DSCF8074BE.jpg by Kora27 (CC BY-SA 4.0); (**b**) IMG_3683.JPG by Parviz Tavakoli Kolour (CC-BY 3.0); (**c**) modified from Mola mola géant Bali.JPG by Franck Fauvel (CC BY-SA 3.0); (**d**) 8063763187_f18b7f7e96_o by CFoceanimages (CC BY-ND 2.0); (**e**) Zebrasoma xanthurum2.JPG by Gdiggers (CC BY-SA 3.0); (**f**) Humpback Turretfish – Tetrasomus gibbosus.jpg by Bernd (CC BY 2.0); (**g**) Thalasoma lunare 1.jpg by Leonard Low (CC BY 2.0); (**h**) Mújol (Mugil cephalus), Parque natural de la Arrábida, Portugal, 2020-07-23, DD 19.jpg by Diego Delso (CC BY-SA 4.0); (**i**) Picassofish_(a_triggerfish),_Rhinecanthus_assasi_(35735682754).jpg by Derek Keats (CC BY 2.0); (**j**) Al mcglashan tuna.jpg by Al McGlashan (CC BY-SA 4.0); (**k**) Lutjanus_fulviflamma.jpg by Erics (CC BY-SA 4.0); (**l**) Painted_Sweetlips_(Diagramma _pictum)_subadult_(8501952361).jpg by Bernard Dupont (CC BY-SA 2.0)

Arabian Gulf has been dependent on the colonisation of species from the Gulf of Oman via the narrow Strait of Hormuz. Furthermore, those species that made it into the Arabian Gulf must be able to survive the extreme environmental conditions of the southern Arabian Gulf where most of the UAEs marine area occurs. The southern

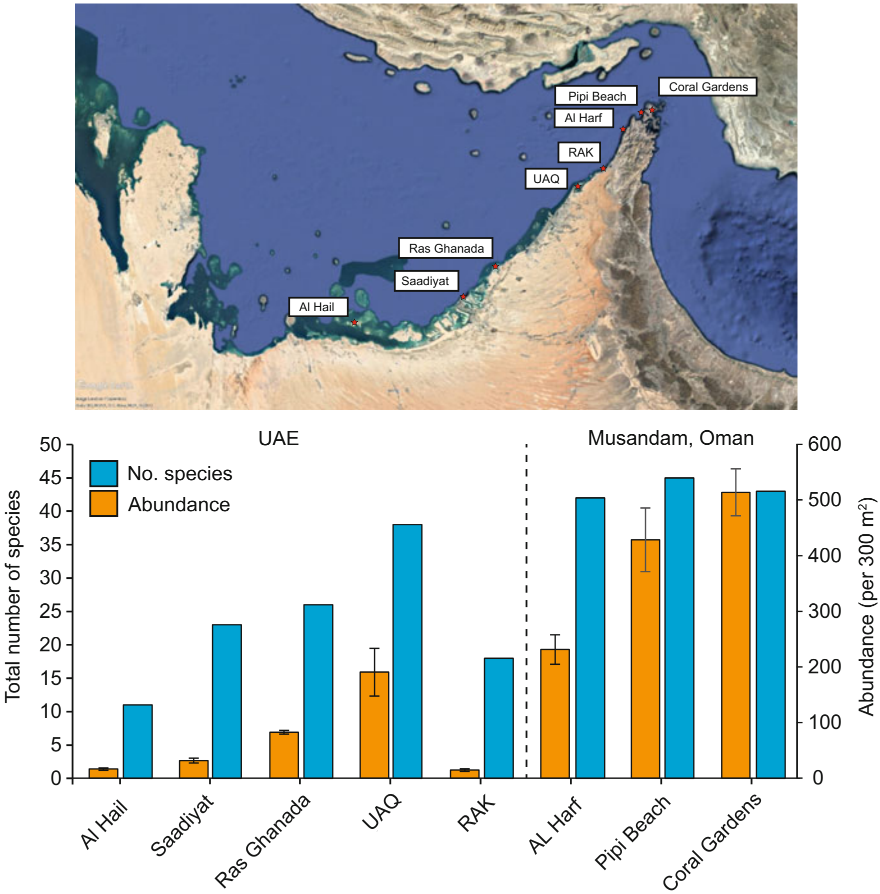


Fig. 21.2 A 2019 survey of fishes in the southern Arabian Gulf shows both the diversity and abundance of fish clearly declines from the Strait of Hormuz moving into the more environmentally extreme southern Arabian Gulf. The location of the reef surveyed are shown on the map while the total number of species recorded (blue bars) and the average abundance of fish (orange bars) are shown in the graph. Image credit: Google Earth Pro version 7.3, (2017) UAE coastline 25°27′ 15.61″N, 54°41′18.09″E . 3D buildings data layer. [Online] Available at: http://www.google.com/earth/index.html [accessed 10/07/2022]; Data Source: Matthew Mitchell, unpubl. Data.)

Arabian Gulf is very shallow (<30 m deep) and experiences extreme environmental conditions, with temperatures ranging from 12 °C in winter to >36 °C in summer, hyper-saline conditions (~44 PSU) and periods of low oxygen (hypoxia) and near-absence of oxygen (anoxia) during summer months (Sheppard et al. 1992; de Verneil et al. 2021). As a result, as shown in Fig. 21.2, the diversity and abundance of fish declines as you move into the Arabian Gulf and environmental conditions get progressively more challenging towards the southwest (Burt et al. 2011; Feary et al. 2010).

Box 21.1 The Freshwater Fishes of the Hajar Mountains and Coastal Systems

Three species of freshwater fishes are native to the UAE. Two species, the Hajar Lotak (*Cyprinion muscatense*) and Orange-ear Garra (*Garra barreimiae*) are within the family Cyprinidae (barbels and carps) and are restricted to the freshwater streams and pools of the Hajar Mountains. A single salt-tolerant species, Arabian killifish (*Aphaniops stoliczkanus*) from the family Aphanniidae (Eurasian killifish) is found in both coastal and freshwater bodies.

Hajar Lotak—endemic to the Hajar Mountains, which are shared between Oman and UAE, with the latter being the most northern distribution range for the species globally. Within the UAE, the species is restricted to a small geographical area near Hatta (Dubai). It is found within larger pools with seasonal fluctuations in discharge. A fast-moving and mid-water dweller which form small schools, the Hajar Lotak feeds on periphyton as well as aquatic and terrestrial invertebrates. Adult fish are 134 mm in size and spawn for the first time at 8–13 months of age. There is no specific spawning season, but is likely triggered by the rain season. During the spawning season, adults develop a prominent light blue colour on the head, lips and pectoral fin.

Box Fig. 21.1 Hajar Lotak (*Cyprinion muscatense*) from the Hajar Mountains. Photo credit: Johannes Els

Orange-ear Garra—endemic to the Hajar Mountains within Oman and United Arab Emirates. It is found within pools, streams, falaj systems and springs with fresh or brackish waters along both flanks of the northern Hajar Mountains, extending southwards from the southern edge of the Ru'us al-Jibal

(continued)

Box 21.1 (continued)
range (Musandam peninsula) to the Sultanate of Oman border. The species distribution range extends into the Sultanate of Oman to Wadi Hawasina on the Gulf of Oman coast. Adult fish are 70 mm in size. Orange-ear Garra are opportunistic feeders consuming periphyton, dead insects and decaying plant materials. The Orange-ear Garra can survive under extreme conditions and can withstand very high temperatures, fluctuating salinities and seasonal flash floods. Unique adaptations include a reduced air bladder to lessen buoyancy and an adhesive structure (mental disc) which with the assistance of their large, paired fins maintain their position in fast flowing waters.

Box Fig. 21.2 Right: Orange-ear Garra (*Garra barreimiae*) from Wadi Shawka. Left: Ventral view of the adhesive structure behind the lower jaw of the Orange-ear Garra. Photo credit: Johannes Els

Arabian killifish—A widespread coastal species from the shores of north-West India, Iran, Iraq, Kuwait, eastern Saudi Arabia, UAE and Gulf of Oman. It is found in lagoons, estuaries, lower parts of streams and in a variety of inland water bodies. Within the Hajar Mountains they are restricted to lower pools and streams and are absent from the uppermost mountain pools where only Orange-ear Garra are present. Arabian killifish were widely introduced into water bodies throughout the country, most likely to aid in the control mosquito larvae. Adult fishes are 53 mm in size. Females, juveniles and non-reproductive males form shoals in open water. Adult and reproductive males are territorial and during spawning season defend spawning sites. Males grow larger than females with a lifespan of 2–3 years. A male and female will pair up for spawning on plants, algae and in rock fissures. The species can tolerate salinities up to 14.5‰ and for short periods up to 25.0‰. Arabian killifish feed on algae, detritus and a variety of aquatic invertebrates.

(continued)

Box 21.1 (continued)

Box Fig. 21.3 Arabian killifish (*Aphaniops stoliczkanus*). Photo credit: Barbara Nicca

21.2 Fish Habitats of the Emirates

21.2.1 Natural Habitats

The benthic (i.e., sea bottom) environment of the UAE primarily consists of soft sediments with little to no structural complexity on either coast. Yet this structurally benign environment supports a matrix of interconnected habitats that provide critical resources for fishes throughout their lives. Many of these habitats are located within the intertidal and subtidal areas adjacent to the coast (Fig. 21.3a, b; Mateos-Molina et al. 2020, 2021; Vaughan et al. 2019). These habitats are highly productive and support a greater diversity and abundance of fishes in coastal waters than in offshore regions, particularly in the Arabian Gulf (Egerton et al. 2018; Lin et al. 2021), and are far more diverse than the neighbouring terrestrial environment (Van Lavieren et al. 2011).

Fringing the coastline, intertidal habitats, which include salt flats (*sabkha* in Arabic), mangrove forests, and mudflats are particularly productive and provide important feeding grounds for fish. These intertidal habitats have a very shallow gradient (in the UAE), cover large areas, and provide substrate for extensive algae mats (Barth and Böer. 2002; Burt 2014). In turn, the algae support a diverse invertebrate community on which fish can feed during high tides. As these sites are only accessible periodically during high tide and provide shelter via mangrove root systems and in the pools and drainage channels during low tides, they provide important nursery grounds for a range of fishes such as juvenile sweetlips, snappers, and mojarras (Fig. 21.4; Barth and Böer 2002; Burt 2014). The only fish able to live

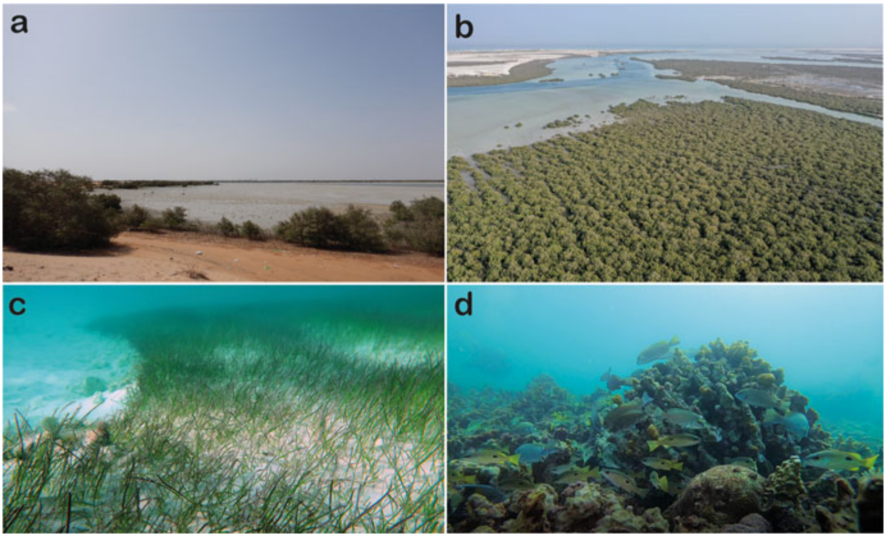


Fig. 21.3 Fish have colonised all marine habitats in the UAE including intertidal (**a**) mudflats and (**b**) mangroves which they access during high tide, as well as subtidal (**c**) seagrass beds and (**d**) coral reefs. Photo credits: (**a**, **d**) Matthew Mitchell and (**b**, **c**) Noura Al-Mansoori

permanently in these habitats are Walton's mudskippers (*Periopthalmus waltoni*) which even inhabit mangrove areas during low tide when water is out (Feulner and Roobas 2013). These unusual fish are amphibious and can survive for extended periods out of the water by breathing through their skin.

Adjacent to these habitats, subtidal habitats are dominated by extensive seagrass beds, seasonal macroalgal beds and coral reefs (see Chaps. 9, 10, and 11, respectively) (Fig. 21.3c, d; Vaughan et al. 2019). Coral reefs are by far the most productive and important habitat for fishes in the UAE. The complex structure provided by corals support highly biodiverse fish communities, including most species found in the UAE. For example, 280–300 of the 540 species (incl. sharks and rays) in the Gulf of Oman (ca. 55%) are reef-associated fishes (Bento 2009). Indeed, the abundance of fish on coral reefs is such that reef-associated fish contribute 70% of fisheries catches within the Arabian Gulf (Grandcourt 2012). Seagrass beds cover an area of 5500 km^2 in the UAE representing 4% of the total seagrass habitat in the world. They are also considered to be the second most diverse habitat in the UAE following coral reefs, and they support a range of commercially important fish species (Basson et al. 1977). Macroalgal beds are seasonally abundant and reach their peak during spring where they can cover up to 85% of available hard substrate, creating a complex new habitat for fishes (John 2012). Yet, while it is thought they provide important spawning and nursery habitats for fishes (Sheppard et al. 1992), macroalgae is a poor food source for most fishes and is eaten by only a few species (Sheppard et al. 2010). It has also been suggested that the proliferation of macroalgae on reefs during the winter and spring period may have a negative effect

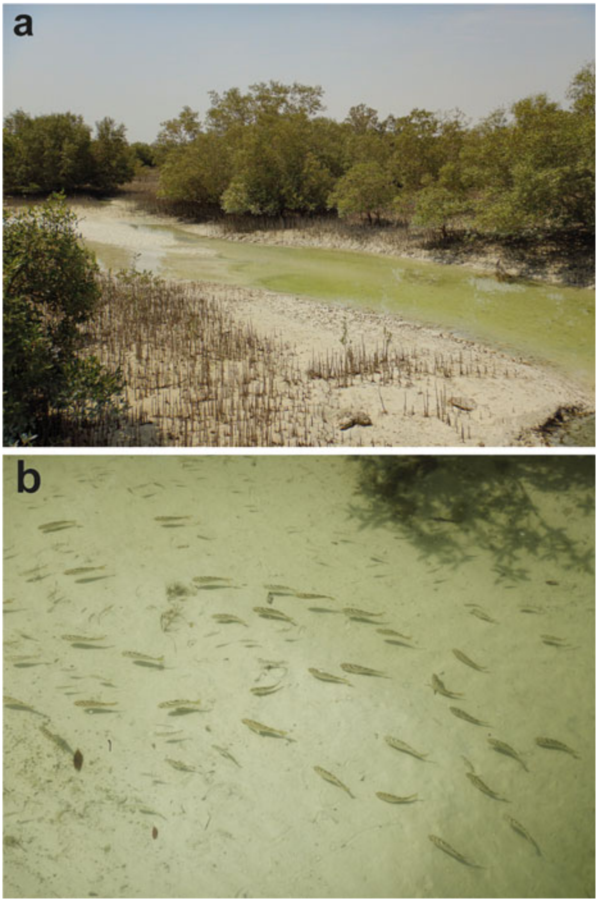


Fig. 21.4 Intertidal habitats provide shelter for juvenile fish from larger predators. (**a**) shallow pools and channels in mangroves allow juveniles to avoid predators during low tide, while at high tide the above ground roots provide shelter. (**b**) Juvenile sweetlips hide in a shallow mangrove pool. Photo credits: Matthew Mitchell

on reef fish abundance (Coles and Tarr 1990; Grandcourt 2012), a pattern seen on reefs in Australia where fish actively avoid dense algae patches (Hoey and Bellwood 2011).

Offshore pelagic (i.e., deep) waters, while less diverse in terms of habitats compared to coastal waters, are by far the largest in terms of area and include limestone mounds and salt domes which can form islands with fringing coral reefs. While these offshore waters support a lower diversity and abundance of fishes, they still maintain important fisheries and provide critical support for a range of species (Egerton et al. 2018; Lin et al. 2021). Recent studies have shown that for several pelagic species, adults tend to be more abundant offshore and some species such as sailfish (*Istiophorus platypterus*) and mackerel tuna (*Euthynnus affinis*) migrate from inshore to offshore waters in the spring to breed (Hoolihan 2003, 2004; Hoolihan and Luo 2007; Robinson et al. 2013). As with inshore habitats, fishes tend to be associated with the more complex habitats such as oyster beds and coral reefs (Egerton et al. 2018; Lin et al. 2021). This is particularly true around offshore islands such as Sir Abu Nu'Ayr, where extensive coral reefs host a higher abundance and diversity of fishes due to being surrounded by cooler deeper waters compared to their inshore equivalents (Burt et al. 2016; Sheppard et al. 1992).

Beyond these broad gradients in fish abundance resulting from environmental and biogeographic conditions, there is little information as to how and why fishes are distributed across the various habitats of the UAE. Most fish species are highly mobile and move between different habitats depending on their resources requirements or to avoid deleterious environments. This is done over temporal scales including diurnal, seasonal or at critical junctions in their life-histories (e.g., for spawning, or transitioning from juvenile to adult habitats) (Clark et al. 2009; Dahlgren and Egglestone 2000; Mumby and Hastings 2007). In doing so, they act as important vectors for transporting nutrients and energy between these different habitats (Clark et al. 2009; Sheaves 2009). In tropical coastal systems mangrove forests, seagrass beds and coral reefs have been shown to be highly connected due to fish movements, where juveniles recruit to seagrass beds and mangrove forests before moving to coral reefs as adults (McMahon et al. 2012; Mumby et al. 2004). Yet the ecological value of the UAE aquatic habitats for fish and the connectivity between them is still to be determined. However, many fishes in the UAE do appear to move between different habitats, e.g., pelagic species like sailfish (*Istiophorus platypterus*) are thought to migrate offshore to breed (Hoolihan 2003; Hoolihan and Luo 2007). Coastal habitats appear to be important nursery grounds (Burt 2014; Vaughan et al. 2019), but their relative value as such remains unknown, and knowledge of where fish go once they leave these habitats is also unknown. Possibly the most striking movement of fishes between habitats occurs on coral reefs, where seasonal abundance of fish can vary by 40%, with fish numbers peaking during the hottest summer months (Vaughan et al. 2021). Again, where and why these fishes leave the reefs during the winter months has still to be determined. Studies have suggested fishes move offshore to avoid colder waters in the shallows (Coles and Tarr 1990), while others argue that fish may not leave at all and are just less active and therefore less visible during cold spells (Vaughan et al. 2021).

21.2.2 Artificial Habitats

Following the discovery of oil and gas in the region, the human population has expanded rapidly over the last few decades with an increasing amount of people moving to coastal cities in the UAE. Consequently, there has been a rapid acceleration of coastal development to the point where breakwaters and seawalls form extensive marine habitats in urban areas (see Chap. 23) (Burt et al. 2012, 2013b; Burt 2014). Further offshore, structures pertaining to the oil and gas industry provide complex, novel habitats in what is mainly a low complexity, sand-bottom environment. These structures rapidly develop marine assemblages, and act as large-scale unplanned artificial reefs. Similarly, more typical planned artificial reefs have been built with the aim of attracting species for fisheries and tourism (Feary et al. 2011),

Fig. 21.5 With the rapid increase in coastal development and the petroleum industry, fishes have learned to use these artificial habitats as novel homes. (**a**) underwater structures of oil rigs are home to many fishes, (**b**) seawalls are common along the UAE coastline, (**c**) fishes including snapper and seabreams are regularly seen along these structures. Photo credits: (**a**) Mubarek Offshore Platformes.jpg by Crescent Petrolium/Icethorn (CC BY-SA 3.0); (**b**, **c**) Matthew Mitchell

and diverse communities rapidly develop around them as well (Burt et al. 2009; Feary et al. 2011). Surveys of fish communities in these habitats have revealed that densities of fish can exceed those on local reefs, including commercially important species such as snappers, groupers, jacks, and barracudas (Al-Cibahy et al. 2009; Burt et al. 2010). While these various human-made structures support large communities of fishes, their ecological value and role towards population productivity are poorly understood (Feary et al. 2011). A study of breakwater fish communities in Dubai showed that fish species composition differed from those on local coral reefs (Burt et al. 2009). Furthermore, seasonal changes in abundance and diversity did not match natural fluctuations observed on coral reefs (Burt et al. 2010), suggesting that artificial habitats are not surrogates for natural habitats. However, there is evidence that human-made reefs can maintain key ecological roles, as juvenile fish colonise breakwaters in similar numbers as they do on coral reefs (Burt et al. 2010) and mackerel tuna (*Euthynnus affinis*) aggregate under oil rigs during spring and possibly use them as spawning sites (Robinson et al. 2013) (Fig. 21.5).

21.3 Ecology of Fishes on the World's Hottest Reefs

Fishes are central to the ecological functioning of marine habitats, and through their various behaviours and activities, they maintain ecosystem health and support marine food webs. Our understanding of the ecology and demography of fishes in the waters of the UAE is rather rudimentary. Few studies over the years have directly examined fish ecology and much of what we know is based on fisheries trawls, which are subject to bias from gear selectivity that targets commercial species (Grandcourt 2012). However, over the last 15 years or so, there has been a significant increase in ecological studies focusing on the impacts of the extreme environment in the southern Arabian Gulf on coral reef fish communities. Extremes in temperature, dissolved oxygen, and salinity pose significant physiological challenges to fish, impacting neurological function, inducing deleterious stress effects, and impacting energy budgets which in turn can impact growth, reproduction, survival, population dynamics and, ultimately, the structure and functioning of communities (Munday et al. 2008; Pankhurst and Munday 2011). The variation in environmental conditions within the UAE, and particularly between the two Gulf regions, provides a unique 'natural laboratory' for comparative studies on how fish communities persist under the extreme environmental conditions seen in the southern Arabian Gulf.

Studies into the life-history traits of fishes in the UAE have largely focused on commercially important species such as orange-spot grouper (*Epinephelus coioides*), Spangled emperor (*Lethrinus nebulosus*), Painted sweetlips (*Diagramma pictum*), and the Dory snapper (*Lutjanus fulviflamma*) (Grandcourt et al. 2011a; Grandcourt 2012). Such studies show that fishes within the UAE vary greatly in their age and growth characteristics, but certain global life-history trends persist e.g., shorter lived species tend to grow much faster than the more long-lived species (Grandcourt 2012). What is also apparent is that fishes in the southern Arabian Gulf along the Abu Dhabi coast tend to be smaller at a given age, reach smaller maximum size, and are younger than individuals from other locations in the Arabian Gulf and Gulf of Oman (Grandcourt et al. 2011a; Grandcourt 2012; Priest et al. 2016). For example, the maximum size of Yellowfin hind (*Cephalopholis hemistiktos*) caught in Abu Dhabi was just 288 cm compared to 443 cm in the Gulf of Oman (Priest et al. 2016). These differences in life-history traits conform to those of stocks that are overfished, which tend consist of smaller fish that reproduce earlier (Grandcourt et al. 2011a; Grandcourt 2012). However, recent studies on non-commercial species suggest that environmental conditions may also be having an effect on fish life-histories (Brandl et al. 2020; D'Agostino et al. 2020, 2021). These studies have shown that in the southern Arabian Gulf, fishes, including tiny cryptobenthic fishes, are smaller than their counterparts in other regions of the UAE, although age does not seem to differ between locations (Fig. 21.6; Brandl et al. 2020; D'Agostino et al. 2021; Feary et al. 2010). The reduction in size of these fishes has generally been ascribed to the extreme summer temperatures of the southern Arabian Gulf limiting the energy available for growth (Brandl et al. 2020; Feary et al. 2010). Additionally, a recent study suggested that salinity was in fact the primary cause of smaller sized fishes, as osmoregulation can require up to 30% of a fish's daily energy production (D'Agostino et al. 2021). Indeed, there is growing evidence that despite exceeding the upper thermal limits of fishes elsewhere in the world, the extreme temperatures of the southern Arabian Gulf are within the range of tolaerance of many species from either of the UAE's coasts (Brandl et al. 2020; D'Agostino et al. 2021). Research investigating the impacts of the extreme environments on fish physiology and life-history are only in their infancy in the UAE, but it is likely that both environmental stressors (for all fishes) and overfishing (for larger fishes) contribute to changes seen in fish life-history traits.

Beyond the impacts on life-history traits, temperature appears to have a profound effect on the ecology of fishes in the southern Arabian Gulf. Observations of Paletail damsels (*Pomacentrus trichrourus*) on coral reefs around Abu Dhabi have shown that these fish modify behaviours to mitigate the effects of temperature (D'Agostino et al. 2020). Both laboratory and field studies demonstrated damsel foraging rates,

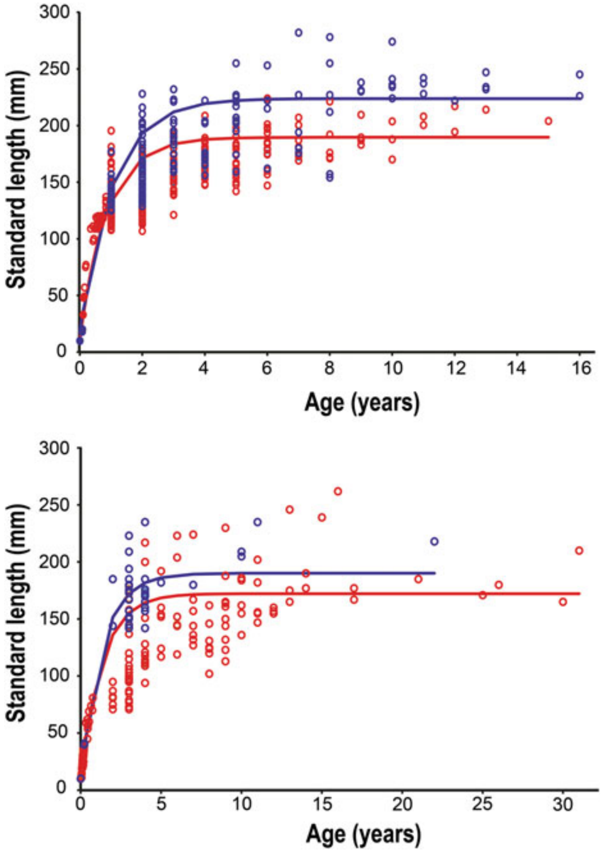


Fig. 21.6 Growth curves for Blackspot snapper (Lutjanus ehrenbergii) (upper graph) and Yellowbar angelfish (Pomacnthus maculosus) showing the greater sizes reached for fish populations in the Gulf of Oman (blue lines) compared to the hotter and more saline Arabian Gulf (red lines). Image credits: Modified from Fig. 3 in D'Agostino et al. (2021), reproduced under Creative Commons (CC-BY-4.0)

activity and distance moved were kept to a minimum when thermal stress was at its highest in both winter and summer, but feeding activity peaked during spring when thermal stress was minimal (D'Agostino et al. 2020). Such plasticity in behaviour is thought to reflect either the physiological constraints of temperature on the performance of ectotherms or behavioural optimisation of energy expenditure versus energy acquisition. Diet also appears to vary within species on geographical and seasonal scales. A range of fishes have distinct diets between Gulf of Oman populations and the southern Arabian Gulf populations, with Yellowbar angelfish (*Pomacanthus maculosus*) switching from primarily feeding on sponges and algae across most its global range to eating live coral on reefs around Abu Dhabi (Shraim et al. 2017), while cryptobenthic species eat a greater diversity of prey in the Gulf of Oman compared to Arabian Gulf populations (Brandl et al. 2020). This plasticity in diet choice also occurs across seasons, with Paletail damsels and Dark damsels (*Pomacentrus aquilus*) both consuming a diverse array of prey during the spring months of April and May before switching to feeding predominantly on corals during the hottest month of August (Shraim et al. 2017). It is unclear if these changes in diet reflect active selection for foods with different nutritional values in response

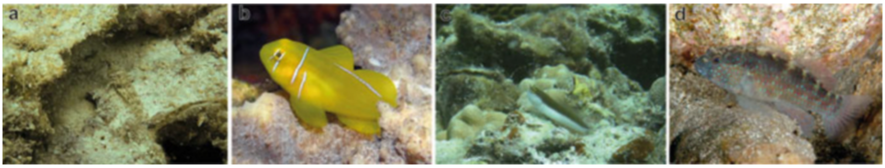


Fig. 21.7 Cryptobenthic fishes are small (<5 cm length), often camouflaged and with a tendency to hide, and consequently they are generally overlooked. Yet they actually make up around half the number of fish on coral reefs and play and important role in supporting reef communities. As they are fast growing and short lived, with several generation per year, it is thought they provide the major food source that sustain fish communities on coral reefs (Brandl et al. 2019); (**a**) Anomalous goby (*Coryogalops anomalus*), (**b**) Lemon goby (*Gobiodon citrinus*), (**c**) Gulf blenny (*Ecsenius pulcher*), (**d**) S tarry goby (*Asterropteryx semipunctata*) Photo credits: (**a**, **c**) Matthew Mitchell; (**b**) Lemon_Goby.jpg by Rob (CC BY 2.0); (**d**) HoshiHZro.jpg by Izuzuki (CC BY-SA 3.0)

to changing temperature, selection for food based on what is available across seasons, or simply what they are able to physically capture and consume during the hottest months (Shraim et al. 2017). What is clear, however, is that with increasing temperature, the quality and volume of food consumed by fishes declines (Brandl et al. 2020; D'Agostino et al. 2020; Shraim et al. 2017). Consequently, Arabian Gulf individuals tend to be of poorer body condition than their counterparts in cooler environments such as the Gulf of Oman, and the seasonal variation of food quality likely contributes to variable growth patterns seen in many fishes from the southern Gulf. Additionally, the lower productivity of these smaller fish will have a negative effect on the transfer of energy and nutrients through higher trophic levels (Brandl et al. 2020). This is particularly true for the cryptobenthic communities which are thought to be a major food source that support reef fish communities (Fig. 21.7; Brandl et al. 2019). Extreme temperatures may, therefore, act to constrain the ability of coral reef ecosystems to maintain abundant and diverse fish communities indirectly via declines in abundance and/or quality of food resources available on reefs.

These environmental effects on fishes appear to drive community level changes on coral reefs, as communities in the southern Arabian Gulf have low abundance of most trophic guilds (i.e. feeding groups, for example 'herbivores') compared to reefs in less extreme regions in the UAE (Burt et al. 2011; Feary et al. 2010). Reef fishes in the southern Arabian Gulf are predominantly made up of grazing herbivores, omnivores, and small generalist predators while several important groups such as large herbivores, corallivores, planktivores and species closely associated with coral are rare or missing entirely (Burt et al. 2011). Many of these important functional groups perform key services that maintain the diversity and functioning of reefs, none more so than large herbivores such as parrotfishes (Hoey et al. 2016). Parrotfishes are the most important guild of herbivores, making up the majority of 'scraper' and 'excavator' fishes that are responsible for removing algae from the reef, clearing ground for coral juveniles to settle and grow. In the absence of these herbivores, and with low abundance of sea urchins, it is not clear which processes control algal communities on these reefs (Hoey et al. 2016). Corallivores are also usually well represented within coral reef communities globally, but are rare throughout the UAE, where only five species are present, most of which are generalists rather than the specialists that are common elsewhere (Pratchett et al. 2013). In the southern Arabian Gulf, they are represented by just one species, the Black-spotted butterflyfish (*Chaetodon nigropunctatus*). That corallivores are rare here would suggest there is no link between corals and higher trophic groups on these reefs (Pratchett et al. 2011, 2013). However, recent studies on the diets of fishes in the southern Arabian suggest that the functional role of specialist corallivores might be fulfilled by other species switching to more generalist diets, as both damselfishes and angelfish have been shown to consume significant amounts of coral rather than their normal diets of plankton, algae and sponges (D'Agostino et al. 2020; Shraim et al. 2017).

21.4 Fisheries in the UAE

Fishes have played a central role in the history of coastal communities of southeast Arabia. With deserts covering much of the terrestrial environment, fishes have historically provided an important source of food and valuable commodity for trade (Beech 2003). The earliest records of fishing activity in the region date back to 8000 YBP, during the Neolithic period, when fishers predominantly caught species found in shallow waters associated with mangroves and seagrasses (Lidour and Beech 2019, 2020). The presence of stone sinkers in settlements suggests that beach seines and gill nets, along with *hadrah'*s (Fig. 21.8a; semi-permanent tidal

Fig. 21.8 The communities inhabiting the northeast Arabian Peninsula have been fishing since Neolithic times using many techniques still used today, including (**a**) *Hadra,* intertidal fence traps. Today fish are still caught using traditional boats (**b**) Dhow's and many of the species sold in (**c**) local markets have remained the same as caught by people during the Neolithic period , such as (**d**) *hammour* and (**e**) *jesh*. Photo credits: (**a**) Shamsa Al-Hameli; (**b**, **c**) Matthew Mitchell; (**d**) Noura Al-Mansoori; (**f**) 46864187155_7a7040181c_o Rickard Zerpe (CC BY 2.0)

barriers traps) were the main methods used to capture fish (Beech 2003; Lidour and Beech 2020). *Gargoor*'s (Fig. 21.8b; baited basket traps made from palm fronds) were also likely to have been employed, although being made from palm fronds there is little evidence for their use due to their poor preservation (Lidour and Beech 2019, 2020). Fish bones found at UAE archaeological sites have revealed that neolithic communities ate a diverse variety of fish species not too dissimilar from the species targeted by modern fisheries, with seabreams, emperors, anchovies, tuna, groupers and sweetlips being the main species caught, along with small sharks and sawfish commonly captured (Fig. 21.8d, e; Lidour and Beech 2020).

Today, fishes still represent an important source of nutrition and trade in the UAE. While revenues from commercial fisheries account for only a modest portion of the UAE's GDP (Wabnitz et al. 2018), it is nonetheless the country's second most valuable natural resource following oil and gas (Grandcourt 2012). In the emirate of Abu Dhabi alone, 1267 tonnes of fish were landed in 2020, generating a revenue of 24.4 million Dirhams (EAD 2020). Fishing is still an important part of the Emirati cultural heritage, cuisine and a popular sport, and healthy fish stocks are therefore of national importance. Typically, modern fisheries operate from traditional wooden dhow boats (Fig. 21.8c; *lansh*) fitted with engines, with fishing trip duration averaging around 3–5 days (Grandcourt et al. 2009). The current contribution of *lansh* (small boats launched from land) to total landings has however steadily decreased since the introduction of recent fishing restrictions (Environment Agency Abu Dhabi 2020). Some fishers hold privileged concession rights to fish in private areas (known as *buhoors*) and the right to use restricted fishing methods (Environment Agency Abu Dhabi 2020). These rights are passed on through generations in an effort to conserve cultural elements of the UAE maritime way of life.

Overall, fish catches are diverse, and reef-associated species form the bulk of all fish landings, with the key species encountered at fish markets dominated by emperors, groupers, sweetlips, jacks, trevallys, snappers, mackerels and seabreams (Grandcourt 2012). The total fish landing volume is largely represented by four valuable species: the Narrow-barred Spanish mackerel, the Orange-spotted grouper, the Blackspot snapper and the Orange-spotted trevally. Gargoors have traditionally been the most used technique to non-selectively target demersal (bottom-dwelling) species but were banned in 2019 in the emirate of Abu Dhabi due to concerns over declining fish stocks. Other techniques currently in use include *hadrah*, gill nets, barrier nets, beach seines and handlines (Grandcourt 2012; Grandcourt et al. 2009). Due to supply and demand imbalances, the UAE is an active seafood importer, with 72% of consumed seafood originating from other countries and the local fisheries and aquaculture operations supplying the remaining 28% of consumed seafood (Environment Agency Abu Dhabi 2019; Jawan and Waryani 2021).

21.5 Threats to the Persistence of Fishes in the UAE

As fishes are both ecologically and economically important to the UAE, they are susceptible to both changes in their environment and over-exploitation from commercial fisheries. Fishing practises, in particular, have led to significant declines in fish populations. In the Arabian Gulf 47% of marine bony fishes are impacted by extractive fishing and 8.2% of fish species are classified as 'threatened' as per the IUCN Red List standard (Buchanan et al. 2019). Fishing intensity has climbed over the last 30 years (Vaughan et al. 2019), with areas of low fish abundance converging with zones of high human population density, thus further highlighting the increasing strain on renewable but finite resources (Grandcourt et al. 2011b). Traditional inshore fisheries are thought to operate within sustainable levels owing to the use of non-destructive methods and the implementation of fish catching permits; however, very little data is available on actual recreational catches (Jawad and Waryani 2021). On the other hand, most commercial fisheries are currently classified as fully exploited or over-exploited, with declines in abundance seen across most fish stocks (Grandcourt 2012). Furthermore, by targeting specific size-classes of fish (typically the largest), fisheries can disproportionately impact demographics of fish populations reducing their capacity to reproduce and replenish stocks (Grandcourt 2012).

The rapid growth of the population of the UAE following the development of the petroleum industry has resulted in the urbanization of coastal regions, to the point that 40% of the Arabian Gulf's coastline has now been modified to accommodate these growing populations (Naser 2014). Processes such as dredging and land reclamation to build these projects has resulted in considerable damage to and loss of coastal habitats, which have either been built directly on or smothered by dredged material (Fig. 21.9; Burt 2014; Feary et al. 2011; Vaughan et al. 2019). The loss of these habitats places addition stress on what are productive but threatened habitats that support fish populations. Furthermore, to sustain the human population of the UAE in this arid environment, numerous desalinations plants have been built throughout the UAE to provide potable water (Sale et al. 2011). The production of this water results in over 1000 m^3/s of waste brine, water that is both higher in salinity and (often) temperature than the surround water, being pumped into coastal waters producing plumes that can extend several kilometres (Burt et al. 2013a; Hamza and Munawar 2009). These plumes not only represent a significant additional physiological challenge for fish osmoregulation in an already thermally and osmotically challenging environment (D'Agostino et al. 2021) but toxins in the form of heavy metals, chlorates and radioactive isotopes might, along with those from wastewater discharge explain the increasing levels heavy metals found in fish (Vaughan et al. 2019).

Climate change poses a significant threat to fishes throughout the UAE. While fishes in the Arabian Gulf already live at temperatures above those predicted to kill fishes elsewhere in the world by 2100, they are still susceptible to further increases in temperature and are likely living at the upper limits of what they can physiologically

Fig. 21.9 Coastal development has led to the destruction of significant areas of coastal habitat. (**a**) The Dubai coastline is heavily developed and consists of sea walls, harbours, and offshore developments such as the manmade islands of (**b**) the World Islands and (**c**) the Palm Jumeirah. Image credits: (**a**) Google Earth Pro version 7.3, (2017) *Dubai coastline 25°04′33°N, 55°13′38″E.* 3D buildings data layer. [Online] Available at: http://www.google.com/earth/index.html [accessed 13/07/2022]; (**b**) Google Earth Pro version 7.3, (2017) *The World Islands 25°13′30″N, 55°09′57″E.* 3D buildings data layer. [Online] Available at: http://www.google.com/earth/index.html [accessed 13/07/2022]; (**c**) Google Earth Pro version 7.3, (2017) *Palm Jumeirah 25°07′11″N, 55°07′50″E.* 3D buildings data layer. [Online] Available at: http://www.google.com/earth/index.html [accessed 13/07/2022]

tolerate. The frequent fish kills seen in coastal waters during the hottest periods in summer would certainly suggest this is the case (Al-Ansi et al. 2002). As discussed earlier, temperature is already impacting fishes living in the hotter areas of the UAE, and with temperatures increasing in the Arabian Gulf at twice the rate of global oceans (Al-Rashidi et al. 2009), we can expect to see these effects exacerbated in the future and extend to Gulf of Oman populations as well. Fishes will also be indirectly affected by climate change through habitat degradation and loss. Coral reefs, in particular, will be affected by climate change as corals, which build the structure of reefs and provide food for many species, experience ‘bleaching’ events and often die during periods of high temperatures (see Chap. 11). If not replaced by new corals, this can lead to the erosion of reef complexity as well as loss of food resources that supports fish communities (Munday et al. 2008; Pratchett et al. 2009). These bleaching events have already happened on UAE reefs in 1996 and 1998 when 90% of corals were killed, and in 2017 when 73% of corals were lost (Burt et al. 2019; Riegl 2002). As a result, important structure-forming corals like table corals (*Acropora*) are no longer found on inshore reefs in the southern Gulf and are becoming rare on the east coast of the UAE. Indeed, with continued habitat loss and fragmentation, along with the effects of climate change, most of the UAE's fishes will be vulnerable to extinction within the coming decades (Buchanan et al. 2019).

21.6 Management and Conservation

While it may seem that the future is bleak for the UAE's fishes, steps are being taken by the government to reduce the impacts on fishes and to protect them for future generations. Given the various pressures on fish populations, management effort are being applied through two main avenues: management of fisheries and the protection of key habitats. Regulation of fisheries has been steadily increasing since the turn of the century, with increased monitoring followed by progressively more stringent restrictions on fishing gear. Fisheries resource assessments, complemented with traditional knowledge surveys, are now regularly conducted by the relevant government and environmental agencies to assess the exploitation levels of commercially important species (Grandcourt et al. 2009). Alongside this increased monitoring, various restrictions on gear use are being promoted, with bans on trawling and fishing gear such as drift nets, gill nets and gargoors implemented to protect sensitive habitats. Similarly, seasonal closures and species-specific catch permits have been enacted to protect over-exploited species and species vulnerable at certain times of year (e.g., spawning periods) (EAD 2020).

Throughout the emirates a series of Marine Protected Area (MPA) networks have been developed to protect fishes and their habitats, including in the Arabian Gulf (10 MPAs) and Gulf of Oman (5 MPAs) (IUCN 2022). Around 12% of the UAEs marine environment is now protected in these areas, many of which are located in Abu Dhabi and are showing promising signs of ecological recovery (Grandcourt et al. 2011b; IUCN 2022). Reports have noted increased abundance, biomass and average size of commercially exploited species within MPAs when compared to areas without fishing restrictions (Grandcourt et al. 2011b). Additionally, access restrictions around oil and gas platforms also result in *de facto* MPAs, as permits are required to approach within 5 km of these areas and where fishing prohibitions are strictly enforced. With several hundred of these restricted zones in place within UAE waters (>800), this consequently offers undeniable benefits to marine ecosystems within their borders and to the fishes that inhabit them (Bouwmeester et al. 2020). Finally, efforts are also being made to restore and conserve certain habitats. Under the guidance of UAE's Ministry of Climate Change and Environment an extensive coral restoration project was announced in 2018 off the Fujairah coast. This project aims to build an artificial reef covering some 300,000 m^3 which they suggest will help to protect and replenish fish population in the area, although care should be taken to ensure that this reef is placed within an MPA so as not to exacerbate overfishing on these highly concentrated fish communities (Feary et al. 2011).

21.7 Conclusion

The UAE is home to a diverse and abundant array of fishes that have contributed over several thousand years, and continue to do so, to the success of communities living in the UAE. Their value has always been associated with fisheries, providing a key source of nutrition, and supporting the second largest economic resource in the UAE. Yet our understanding of the true diversity of fishes in the UAE and their ecological value is vastly understudied. Recent studies have started to highlight how the extreme environments of the UAE alter fish physiology, behaviour and ecology, and have attracted attention from the global scientific community who are looking to the fishes of the UAE as a valuable model system for understanding how climate change will impact the worlds fishes. Hence, the fishes of the UAE represent a unique and internationally critical resource to research addressing the impacts of climate change and their conservation should be a priority at the national level.

21.8 Recommended Readings

Additional information on the overall ecology of the Arabian Gulf can be found in Vaughan et al. (2019) while Burt et al. (2011) and Feary et al. (2010) discuss how local fish communities fit into the broader regional picture and their value to understanding climate change impacts on fishes. Finally, Grandcourt (2012) provides a concise overview of coral reef fishes and fisheries in the Gulf.

References

Al-Ansi M, Abdel-Moati M, Al-Ansari I (2002) Causes of fish mortality along the Qatari waters (Arabian Gulf). Int J Environ Stud 59:59–71

Al-Cibahy A, Grandcourt E, Bugla I (2009) Report on evaluation of eco-reefs installed in Marawah marine biosphere reserve, 17th edn. Environment Agency Abu Dhabi, Abu Dhabi

Al-Rashidi TB, El-Gamily HI, Amos CL, Rakha KA (2009) Sea surface temperature trends in Kuwait Bay, Arabian Gulf. Nat Hazards 50:73–82

Barth HJ, Böer B (2002) Sabkha ecosystems: volume I: the Arabian peninsula and adjacent countries, vol 1. Kluwer Academic Publisher, Dordrecht

Basson PW, Burchard JE, Price A, Bobrowski L (1977) Biotopes of the Western Arabian gulf: marine life and environments of Saudi Arabia. Aramco Department of Loss Prevention and Environmental Affairs, Dhahran

Beech MJ (2003) The development of fishing in the United Arab Emirates: a zooarchaeological perspective. In: Potts D, Naboodah H, Hellyer P (eds) Archaeology of the United Arab Emirates: proceedings of the first international conference on the archaeology of the UAE. Trident Press, London, pp 289–308

Bento R (2009) Proposed management plan for Rul Dibba-Al Faqeet marine protected area. Fujairah Emirate, Abu Dhabi

Bouwmeester J, Riera R, Range P, Ben-Hamadou R, Samimi-Namin K, Burt JA (2020) Coral and reef fish communities in the thermally extreme Persian/Arabian gulf: insights into potential climate change effects. In: Rossi S, Bramanti L (eds) Perspectives on the marine animal forests of the world. Springer, Cham, pp 63–86

Brandl SJ, Rasher DB, Côté IM, Casey JM, Darling ES, Lefcheck JS, Duffy JE (2019) Coral reef ecosystem functioning: eight core processes and the role of biodiversity. Front Ecol Environ 17: 445–454. https://doi.org/10.1002/fee.2088

Brandl SJ, Johansen JL, Casey JM, Tornabene L, Morais RA, Burt JA (2020) Extreme environmental conditions reduce coral reef fish biodiversity and productivity. Nat Commun 11:3832. https://doi.org/10.1038/s41467-020-17731-2

Buchanan JR, Ralph GM, Krupp F, Harwell H, Abdallah M, Abdulqader E, Al-Husaini M, Bishop JM, Burt JA, Choat JH, Collette BB, Feary DA, Hartmann SA, Iwatsuki Y, Kaymaram F, Larson HK, Matsuura K, Motomura H, Munroe T et al (2019) Regional extinction risks for marine bony fishes occurring in the Persian/Arabian Gulf. Biol Conserv 230:10–19. https://doi.org/10.1016/j.biocon.2018.11.027

Burt JA (2014) The environmental costs of coastal urbanization in the Arabian Gulf. City 18:760–770. https://doi.org/10.1080/13604813.2014.962889

Burt J, Bartholomew A, Usseglio P, Bauman A, Sale PF (2009) Are artificial reefs surrogates of natural habitats for corals and fish in Dubai, United Arab Emirates. Coral Reefs 28:663–675. https://doi.org/10.1007/s00338-009-0500-1

Burt J, Feary D, Usseglio P, Bauman A, Sale PF (2010) The influence of wave exposure on coral community development on man-made breakwater reefs, with a comparison to a natural reef. Bull Mar Sci 86:839–859. https://doi.org/10.5343/bms.2009.1013

Burt JA, Feary DA, Bauman AG, Usseglio P, Cavalcante GH, Sale PF (2011) Biogeographic patterns of reef fish community structure in the northeastern Arabian peninsula. ICES J Mar Sci 68:1875–1883. https://doi.org/10.1093/icesjms/fsr129

Burt JA, Bartholomew A, Feary DA (2012) Man-made structures as artificial reefs in the Gulf. In: Riegl BM, Purkis SJ (eds) Coral reefs of the Gulf. Coral reefs of the world, vol 3. Springer, Dordrecht, pp 171–186

Burt JA, Al-Khalifa K, Khalaf E, AlShuwaikh B, Abdulwahab A (2013a) The continuing decline of coral reefs in Bahrain. Mar Pollut Bull 72:357–363. https://doi.org/10.1016/j.marpolbul.2012.08.022

Burt JA, Feary DA, Cavalcante G, Bauman AG, Usseglio P (2013b) Urban breakwaters as reef fish habitat in the Persian Gulf. Mar Pollut Bull 72:342–350. https://doi.org/10.1016/j.marpolbul.2012.10.019

Burt JA, Smith EG, Warren C, Dupont J (2016) An assessment of Qatar's coral communities in a regional context. Mar Pollut Bull 105:473–479. https://doi.org/10.1016/j.marpolbul.2015.09.025

Burt JA, Paparella F, Al-Mansoori N, Al-Mansoori A, Al-Jailani H (2019) Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. Coral Reefs 38(4):567–589. https://doi.org/10.1007/s00338-019-01767-y

Carpenter KE, Krupp F, Jones DA, Zajonz U (1997) The living marine resources of Kuwait, eastern Saudi Arabia, Bahrain, Qatar, and The United Arab Emirates. Food and Agricultural Organization of the United Nations, Rome

Clark RD, Pittman S, Caldow C, Christensen J, Roque B, Appeldoorn RS, Monaco ME (2009) Nocturnal fish movement and trophic flow across habitat boundaries in a coral reef ecosystem (SW Puerto Rico). Caribb J Sci 45:282–303. https://doi.org/10.18475/cjos.v45i2.a15

Coles SL, Tarr BA (1990) Reef fish assemblages in the Western Arabian gulf: a geographically isolated population in an extreme environment. Bull Mar Sci 47(3):696–720

D'Agostino D, Burt JA, Reader T, Vaughan GO, Chapman BB, Santinelli V, Cavalcante GH, Feary DA (2020) The influence of thermal extremes on coral reef fish behaviour in the Arabian/Persian Gulf. Coral Reefs 39:733–744. https://doi.org/10.1007/s00338-019-01847-z

D'Agostino D, Burt JA, Santinelli V, Vaughan GO, Fowler AM, Reader T, Taylor BM, Hoey AS, Cavalcante GH, Bauman AG, Feary DA (2021) Growth impacts in a changing ocean: insights from two coral reef fishes in an extreme environment. Coral Reefs 40(2):433–446. https://doi.org/10.1007/s00338-021-02061-6

Dahlgren CP, Egglestone DB (2000) Ecological processes underlying ontogenetic habitat shifts in a coral reef fish. Ecology 81(8):2227–2240

de Verneil A, Burt JA, Mitchell M, Paparella F (2021) Summer oxygen dynamics on a southern Arabian Gulf coral reef. Front Mar Sci 8:781428. https://doi.org/10.3389/fmars.2021.781428

DiBattista JD, Saenz-Agudelo P, Piatek MJ, Cagua EF, Bowen BW, Choat JH, Rocha LA, Gaither MR, Hobbs JPA, Sinclair-Taylor TH, McIlwain JH, Priest MA, Braun CD, Hussey NE, Kessel ST, Berumen ML (2020) Population genomic response to geographic gradients by widespread and endemic fishes of the Arabian peninsula. Ecol Evol 10(10):4314–4330. https://doi.org/10.1002/ece3.6199

EAD (2020) Fisheries and Aquaculture Bulletin 2020

Egerton JP, Al-Ansi M, Abdallah M, Walton M, Hayes J, Turner J, Erisman B, Al-Maslamani I, Mohannadi M, Le Vay L (2018) Hydroacoustics to examine fish association with shallow offshore habitats in the Arabian Gulf. Fish Res 199:127–136. https://doi.org/10.1016/j.fishres.2017.12.002

Environment Agency Abu Dhabi (2019) The UAE national framework statement for sustainable fisheries (2019–2030)

FAO (2022) The state of world fisheries and aquaculture 2022. Towards blue transformation. FAO, Rome

Feary DA, Burt JA, Bauman AG, Usseglio P, Sale PF, Cavalcante GH (2010) Fish communities on the world's warmest reefs: what can they tell us about the effects of climate change in the future? J Fish Biol 77(8):1931–1947. https://doi.org/10.1111/j.1095-8649.2010.02777.x

Feary DA, Burt JA, Bartholomew A (2011) Artificial marine habitats in the Arabian Gulf: review of current use, benefits and management implications. Ocean Coast Manag 54(10):742–749. https://doi.org/10.1016/j.ocecoaman.2011.07.008

Feulner GR, Roobas B (2013) Re-discovery of the mudskipper periophthalmus Waltoni Koumans, 1941 in the United Arab Emirates. Tribulus 21:42–77

Freyhof J, Els J, Feulner GR, Hamidan NA, Krupp F (2020) The freshwater fishes of the Arabian Peninsula. Dubai, Motivate Media Group, p 272

Froese R, Pauly D (eds) (2022) FishBase. World Wide Web Electronic Publication. Version (02/2022)

Grandcourt E (2012) Reef fish and fisheries in the Gulf. In: Riegel BM, Purkis SJ (eds) Coral reefs of the Gulf. Coral reefs of the world, vol 3. Springer, Dordrecht, pp 127–161

Grandcourt E, Al-Cibahy A, Das HS, George D, Beech MJ, Javed S, Tourenq C, Barcelo I, Soorae P, Tamaei S, Hartmann S (2009) Marine and coastal environment of Abu Dhabi Emirate, United Arab Emirates. Aquat Ecosyst Health Manag 12(1):93–105. https://doi.org/10.1080/14634980902858823

Grandcourt E, Al Abdessalaam TZ, Francis F, Al Shamsi A (2011a) Demographic parameters and status assessments of Lutjanus ehrenbergii, Lethrinus lentjan, Plectorhinchus sordidus and Rhabdosargus sarba in the southern Arabian Gulf: southern Arabian Gulf demersal fish assessment. J Appl Ichthyol 27(5):1203–1211. https://doi.org/10.1111/j.1439-0426.2011.01776.x

Grandcourt E, Al-Cibahy A, Al-Harthi SS, Bugla I (2011b) The abundance status and bio-economic production potential of coral reef fisheries resources in Abu Dhabi

Hamza W, Munawar M (2009) Protecting and managing the Arabian Gulf: past, present and future. Aquat Ecosyst Health Manage 12(4):429–439. https://doi.org/10.1080/14634980903361580

Helfman GS, Collette BB, Facey DE, Bowen BW (eds) (2009) The diversity of fishes: biology, evolution, and ecology, 2nd edn. Blackwell, Hoboken, NJ

Hoey AS, Bellwood DR (2011) Suppression of herbivory by macroalgal density: a critical feedback on coral reefs? Ecol Lett 14:267–273. https://doi.org/10.1111/j.1461-0248.2010.01575.x

Hoey AS, Feary DA, Burt JA, Vaughan G, Pratchett MS, Berumen ML (2016) Regional variation in the structure and function of parrotfishes on Arabian reefs. Mar Pollut Bull 105(2):524–531. https://doi.org/10.1016/j.marpolbul.2015.11.035

Hoolihan J (2003) Sailfish movement in the Arabian Gulf: a summary of tagging efforts. Mar Freshw Res 54(4):509. https://doi.org/10.1071/MF01252

Hoolihan J (2004) Managing Arabian Gulf sailfish - issues of transboundary migration. In: Payne AIL, O'Brien CM, Rogers SI (eds) Management of shared fish stocks. Blackwell, Oxford, pp 339–347

Hoolihan JP, Luo J (2007) Determining summer residence status and vertical habitat use of sailfish (Istiophorus platypterus) in the Arabian Gulf. ICES J Mar Sci 64(9):1791–1799. https://doi.org/10.1093/icesjms/fsm148

IUCN (2021) The IUCN red list of threatened species. Version 2021-3

IUCN (2022) Protected planet: the world database on protected areas (WDPA) and world database on other effective area-based conservation measures (WD-OECM). UNEP-WCMC and IUCN, Cambridge

Jawad LA, Waryani B (2021) Monitoring the marine recreational fisheries in the Arabian Gulf and Sea of Oman. In: Jawad LA (ed) The Arabian Seas: biodiversity, environmental challenges and conservation measures. Springer, pp 907–915

John DM (2012) Marine algae (seaweeds) associated with coral reefs in the Gulf. In: Riegl BM, Purkis SJ (eds) Coral reefs of the Gulf. Coral reefs of the world, vol 3. Springer, Dordrecht, pp 309–335

Lidour K, Beech MJ (2020) At the Dawn of Arabian fisheries: fishing activities of the inhabitants of the Neolithic tripartite house of Marawah Island, Abu Dhabi Emirate (United Arab Emirates). Arab Archaeol Epigr 31(1):140–150. https://doi.org/10.1111/aae.12134

Lidour K, Beech MJ (2019) The numerous islands of Ichthyophagi: Neolithic fisheries of Delma Island, Abu Dhabi Emirate (UAE). Proc Semin Arab Stud 49:207–222

Lin YJ, Roa-Ureta RH, Kambrath Pulikkoden AR, Premlal P, Nazeer Z, Qurban MA, Rabaoui L (2021) Essential fish habitats of demersal fish in the Western Arabian Gulf. Mar Pollut Bull 173: 113013. https://doi.org/10.1016/j.marpolbul.2021.113013

Mateos-Molina D, Antonopoulou M, Baldwin R, Bejarano I, Burt JA, García-Charton JA, Al-Ghais SM, Walgamage J, Taylor OJS (2020) Applying an integrated approach to coastal marine habitat mapping in the North-Western United Arab Emirates. Mar Environ Res 161:105095. https://doi.org/10.1016/j.marenvres.2020.105095

Mateos-Molina D, Ben Lamine E, Antonopoulou M, Burt JA, Das HS, Javed S, Judas J, Khan SB, Muzaffar SB, Pilcher N, Rodriguez-Zarate CJ, Taylor OJS, Giakoumi S (2021) Synthesis and evaluation of coastal and marine biodiversity spatial information in the United Arab Emirates for ecosystem-based management. Mar Pollut Bull 167:112319. https://doi.org/10.1016/j.marpolbul.2021.112319

McMahon KW, Berumen ML, Thorrold SR (2012) Linking habitat mosaics and connectivity in a coral reef seascape. Proc Natl Acad Sci 109(38):15372–15376. https://doi.org/10.1073/pnas.1206378109

Mumby PJ, Hastings A (2007) The impact of ecosystem connectivity on coral reef resilience: coral reef resilience. J Appl Ecol 45(3):854–862. https://doi.org/10.1111/j.1365-2664.2008.01459.x

Mumby PJ, Edwards AJ, Arias-González JE, Lindeman KC, Blackwell PG, Gall A, Gorczynska MI, Harborne AR, Pescod CL, Renken H, Wabnitz CCC, Llewellyn G (2004) Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature 427(6974): 533–536. https://doi.org/10.1038/nature02286

Munday PL, Jones GP, Pratchett MS, Williams AJ (2008) Climate change and the future for coral reef fishes. Fish Fish 9(3):261–285. https://doi.org/10.1111/j.1467-2979.2008.00281.x

Naser HA (2014) Marine ecosystem diversity in the Arabian gulf: threats and conservation. In: Grillo O (ed) Biodiversity - the dynamic balance of the planet. InTech

Pankhurst NW, Munday P (2011) Effects of climate change on fish reproduction and early life history stages. Mar Freshw Res 62(9):1015. https://doi.org/10.1071/MF10269

Pratchett MS, Wilson SK, Graham NAJ, Munday PL, Jones GP, Polunin NVC (2009) Coral bleaching and consequences for motile reef organisms: past, present and uncertain future effects. In: van Oppen MJH, Lough JM (eds) Coral bleaching. Ecological studies, vol 205. Springer, Berlin, pp 139–158

Pratchett MS, Hoey AS, Wilson SK, Messmer V, Graham NAJ (2011) Changes in biodiversity and functioning of reef fish assemblages following coral bleaching and coral loss. Diversity 3(3): 424–452. https://doi.org/10.3390/d3030424

Pratchett MS, Hoey AS, Feary DA, Bauman AG, Burt JA, Riegl BM (2013) Functional composition of Chaetodon butterflyfishes at a peripheral and extreme coral reef location, the Persian Gulf. Mar Pollut Bull 72(2):333–341. https://doi.org/10.1016/j.marpolbul.2012.10.014

Priest MA, DiBattista JD, McIlwain JL, Taylor BM, Hussey NE, Berumen ML (2016) A bridge too far: dispersal barriers and cryptic speciation in an Arabian peninsula grouper (Cephalopholis hemistiktos). J Biogeogr 43(4):820–832. https://doi.org/10.1111/jbi.12681

Reynolds MR (1993) Physical oceanography of the Gulf, Strait of Hormuz, and the Gulf of Oman—results from the Mt Mitchell expedition. Mar Pollut Bull 27:35–59. https://doi.org/10.1016/0025-326X(93)90007-7

Riegl B (2002) Effects of the 1996 and 1998 positive sea-surface temperature anomalies on corals, coral diseases and fish in the Arabian Gulf (Dubai, UAE). Mar Biol 140(1):29–40. https://doi.org/10.1007/s002270100676

Robinson DP, Mohammed YJ, Jaidah RW, Jabado RW, Lee-Brooks K, Nour El-Din NM, Al Malki AA, Elmeer K, McCormick PA, Henderson AC, Pierce SJ, Ormond RFG (2013) Whale sharks, Rhincodon Typus, aggregate around offshore platforms in Qatari waters of the Arabian Gulf to feed on fish spawn. PLoS One 8(3):e58255. https://doi.org/10.1371/journal.pone.0058255

Sale PF, Feary DA, Burt JA, Bauman AG, Cavalcante GH, Drouillard KG, Kjerfve B, Marquis E, Trick CG, Usseglio P, Van Lavieren H (2011) The growing need for sustainable ecological management of marine communities of the Persian Gulf. Ambio 40(1):4–17. https://doi.org/10.1007/s13280-010-0092-6

Sheaves M (2009) Consequences of ecological connectivity: the coastal ecosystem mosaic. Mar Ecol Prog Ser 391:107–115. https://doi.org/10.3354/meps08121

Sheppard C (1993) Physical environment of the Gulf relevant to marine pollution: an overview. Mar Pollut Bull 27:3–8. https://doi.org/10.1016/0025-326X(93)90003-3

Sheppard C, Price A, Roberts C (1992) Marine ecology of the Arabian region: patterns and processes in extreme tropical environments. Academic, London

Sheppard C, Al-Husiani M, Al-Jamali F, Al-Yamani F, Baldwin R, Bishop J, Benzoni F, Dutrieux E, Dulvy NK, Durvasula SV, Jones DA, Loughland R, Medio D, Nithyanandan M, Pilling GM, Polikarpov I, Price ARG, Purkis S, Riegl B, Saburova M, Namin KS, Taylor O, Wilson S, Zainal K (2010) The Gulf: a young sea in decline. Mar Pollut Bull 60(1):13–38. https://doi.org/10.1016/j.marpolbul.2009.10.017

Shraim R, Dieng MM, Vinu M, Vaughan G, McParland D, Idaghdour Y, Burt JA (2017) Environmental extremes are associated with dietary patterns in Arabian Gulf reef fishes. Front Mar Sci 4:285. https://doi.org/10.3389/fmars.2017.00285

Van Lavieren H, Burt J, Feary DA, Cavalcante G, Marquis E, Benedetti L, Trick CG, Kjerfve B, Sale PF (2011) Managing the growing impacts of development on fragile coastal and marine ecosystems: lessons from the Gulf. United Nations University Press, Hamilton, p 100

Vaughan GO, Al-Mansoori N, Burt JA (2019) The Arabian gulf. In: World seas: an environmental evaluation. Elsevier, New York, pp 1–23

Vaughan GO, Shiels HA, Burt JA (2021) Seasonal variation in reef fish assemblages in the environmentally extreme southern Persian/Arabian Gulf. Coral Reefs 40(2):405–416. https://doi.org/10.1007/s00338-020-02041-2

Wabnitz CCC, Lam VWY, Reygondeau G, Teh LCL, Al-Abdulrazzak D, Khalfallah M, Pauly D, Deng Palomares ML, Zeller D, Cheung WWL (2018) Climate change impacts on marine biodiversity, fisheries and Society in the Arabian Gulf. PLoS One 13(5):e0194537. https://doi.org/10.1371/journal.pone.0194537

Part IV
Human Interactions with the Environment

Chapter 22
Human–Environment Interactions in the United Arab Emirates: An Archaeological Perspective

Timothy Power

22.1 Introduction

The purpose of this chapter is to provide a summary of human-environment interactions within the borders of the present United Arab Emirates (UAE). A diachronic approach is important, since both human societies and the natural environment have developed constantly since their first interactions about 200,000 years ago. Each has developed separately according to its own internal dynamics but, at the same time, their interaction has provided a catalyst to development. We must therefore sketch out the development of human societies and the natural environment as discrete parallel processes, noting particular periods and places where their interaction was significant to the other.

It is further worth stressing that the territory of the present UAE includes a number of topographical and ecological zones, to which human societies adapted their subsistence strategies over time (see Chaps. 2 and 3). For instance, the gravel outwash plains of the Hajar Mountains have these past 8000 years played host to both nomadic pastoralists and sedentary agriculturalists. The development of subsistence strategies was not necessarily evolutionary—i.e. increasingly complex over time—since development could be reversed and was never complete, as witnessed in the persistence of nomadic pastoralism into the mid twentieth century. Indeed, a single topographic/ecological zone might support one or more subsistence strategies in symbiosis, with, for instance, herders and farmers exchanging animal products for agrarian produce. We should moreover be wary about retrospective projections or Orientalist tropes of the 'unchanging East'. The landscape of date-palm oases familiar today, for instance, may well be 3000 years old but its present reconfiguration is probably only about 300 years old.

T. Power (✉)
United Arab Emirates University, Al Ain, Abu Dhabi, United Arab Emirates
e-mail: timothy.power@uaeu.ac.ae

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_22

Human-environment interactions were historically driven largely by economic factors, namely the extraction of natural resources (Heard-Bey 2004: 164–197). Copper mined in the Hajar Mountains, pearls gathered from the Arabian Gulf, and access to aquifers of the Hajar Mountains enabling date cultivation on the outwash plains constitute the key natural resources. External demand for these commodities led to the development of large-scale industries. The first historical references to the Southeast Arabia, in the mercantile correspondence and state propaganda of Bronze Age Mesopotamia, associate it with the copper-producing land of Magan (Potts 1990: 133–149). During the Middle Age, the region attracted the attention of the Arabic geographers—written in distant Spain and Turkmenistan—largely as a consequence of its pearl exports (Carter 2012: 38–51). By the mid nineteenth century, following the opening of the Suez Canal in an age of galloping globalisation, Southeast Arabia was exporting dates to as far as America (Hopper 2013, 2015: 51–79). The oil of Abu Dhabi is but the latest natural resource around which a national industry has developed (Heard 2011).

22.2 Topographic/Ecological Zones and Adaptive Subsistence Strategies

The Emirates can be divided into six overlapping topographic or ecological zones. Each of these had a particular set of natural resources leading to a variety of adaptive subsistence strategies. We can image these zones as a transect, moving west to east as follows: (i) the sandy desert of the Rub al-Khali, of which the inhabited part is mostly situated in the Dhafra region of Abu Dhabi; (ii) the Abu Dhabi Islands and facing coastal salt pans or *sabkha;* (iii) the North Coast, running along the Arabian Gulf between Dubai and Ras al-Khaimah; (iv) the Dhahira gravel plain of the piedmont; (v) the Hajar Mountains and their wadi systems; (vi) the East Coast looking out to the Indian Ocean (see also Chap. 2). Alternative attempts to delineate geographic zones tend to group the entire coastal plain of the Arabian Gulf into a single zone, but this is problematic since the coast of the Abu Dhabi with its islands and *sabkha* is quite different to that of the northern Emirates with their lagoons and creeks (Potts 2001: 28. *Cf.* Wilkinson 1977: 63–66, Table 7; Cleuziou and Tosi 2007: 3–15, Fig. 5).

These topographic zones are borne out by traditional Arabic place names and have informed human geography. The principal geographical feature is the great arc of the Hajar Mountains that runs from Ras al-Had to Musandam to project "*like a spur into the vitals of Persia*" (Lees 1928: 444) as one geographer notably phrased it. Either side of this are the outwash plains. The western is known as the *Dhahira,* 'the outside,' and looks out across the Rub al-Khali to the Arabian Gulf; the eastern is called the *Batina,* 'the inside,' and faces the Indian Ocean. These plains have given their names and/or defined the territories of two of the autochothonic tribes of the Emirates, the *Dhawahir,* 'Plain Dwellers', of the Dhahira and the *Sharqieen,* 'Easterners', of the Batina (Wilkinson 1964: 341). Similarly, the original homeland of the Bani Yas tribe was coterminous with the Dhafra, and they expanded into the neighbouring regions of the Dhahira and the North Coast (*sahil 'Uman al-shimal*), where they established their authority in Dubai (Heard-Bey 1982: 27–57, 102–112). In a parallel process, the Qawasim took control of the North Coast and spread through the wadi networks of the Hajar Mountains to seize the Batina and northern approaches of the Dhahira (Heard-Bey 1982: 68–80, 82–100). Human history, in the Emirates as elsewhere, is shaped by natural geography.

22.2.1 Dhafra Desert and Liwa Oasis

The sand dunes of the *Rub al-Khali,* 'Empty Quarter,' sweep in from Saudi Arabia and cover the majority of the United Arab Emirates (Fig. 22.1). The bulk of their north-eastern extent is known as the Dhafra, taking up most of the emirate of Abu Dhabi, with the *Ramlat al-Hamra*, 'the Red Sands,' at its northern and eastern fringe neighbouring the Dhahira gravel plain. A scattered strip of interdunal palm groves known collectively as the Liwa Oasis lies at the heart of the Dhafra (Wilkinson 2009). This region is at once a place of transit and a place of settlement. It has

Fig. 22.1 A historic seasonal Bedouin camping ground in the Dhafra Desert. Credit: Timothy Power

repeatedly constituted the main land route into and out of southeast Arabia, an east-west axis linking the oases of al-Hasa in Saudi Arabia and al-Ain made possible by Liwa, fortuitously positioned between them. Its strategic importance meant that it could not be left unoccupied. The landscape was not entirely without resources, however. Winter rains provided enough pasturage to support seasonal grazing and the palm groves of Liwa provided a summer crop of dates (Wilkinson 1977: 54–56; Heard-Bey 1982: 180–81). This was supplemented by fishing and pearling in the Abu Dhabi Islands, and, like many places in the Emirates, survival was only possibly in so marginal an environment by an opportunistic diversification of subsistence strategies.

22.2.2 Abu Dhabi Islands and Sabkha

Much of the northern coast of Abu Dhabi emirate is taken up with barren coastal salt pans known as *sabkha*. The principal feature of the coastline is Jebel Dhanna, whose dark silhouette rises 114 m above sea level and forms a distinctive landmark. Most of the islands of archaeological interest—including Ghagha, Sir Bani Yas, Marawah and Abu Dhabi itself (King 1998)—are located at no great distance from the coast. A smaller number of salt-dome islands—most notably Dalma and Das—are located farther offshore. The seas here are notably shallow and covered intermittently with pearl oyster beds (see Chap. 12). The Abu Dhabi islands and *sabkha* together form a coherent topographic zone that served as a communications corridor and provided a rich maritime resource. In addition, the sulphur, used in the manufacture of gunpowder, was mined at Jebel Dhanna in the Late Islamic period (King 2003).

22.2.3 North Coast

The North Coast runs between Dubai and Ras al-Khaimah. It is distinct from the Abu Dhabi Islands and *sabkha* to the south as well as the mountainous 'fjords' of Musandam to the north, being characterised by its various creeks and lagoons affording safe anchorages around which settlements developed. Dubai, Sharjah, Ajman and al-Hamriya formed around creeks, and Umm al-Quwain (Fig. 22.2), Jazirat al-Hamra and Ras al-Khaimah developed around lagoons (see also Chaps. 4 and 8). It seems likely that the two largest lagoons—Umm al-Quwain and Ras al-Khaimah—were more or less continuously occupied from the Neolithic period, whilst the creeks, which afforded less maritime resources, only seem to have been inhabited during regional episodes of growth. However, since the archaeological record of the North Coast has been massively and deleteriously impacted by modern development, this hypothesis remains difficult to establish beyond doubt.

Fig. 22.2 The lagoon of Umm al-Quwain. Note the mangroves and beach rock. Credit: Timothy Power

22.2.4 Dhahira Plain

The Dhahira extends along the western flank of the Hajar Mountains from the Dhaid region to al-Ain, continuing south into central Oman (Fig. 22.3). It consists of a gravel plain up to 10 km wide, sloping gently down from the mountains to meet the Ramlat al-Hamra. The porous gravels soak up surface run-off from the mountains, which allows for the formation of aquifers over the igneous bedrock. The aquifers and wadi systems supported the development of a network of *aflaj*—underground aqueducts—that supported a series of historic oases, including Dhaid, Madam and al-Ain, situated at the edge of the plain to maximise water collection. The plain is covered with acacia and ghaf trees which the bedouin traditionally used for grazing and charcoal production. During heavy winter rains the plain is prone to flooding and, as the flood waters retreat, the suddenly blooming vegetation affords excellent grazing (see Chaps. 5 and 13). The Dhahira has, therefore, been one of the most intensively utilised topographic/ecological zones in southeast Arabia.

Fig. 22.3 The site of Hili on the Dhahira Plain viewed from Jebel Haqlah. Credit: Timothy Power

22.2.5 Hajar Mountains

The ‘Rocky Mountains,’ as they translate into English, are aptly named (Fig. 22.4). They extend about 700 km from the Emirates into Oman, reaching their full width (100 km) and height (3000 m) in central Oman (Chap. 6). The Emirates section is divided into three distinct areas. To the northwest lies Rus al-Jibal and the Wadi Bih, from which flows the alluvial fan supporting the Shimal Oases of Ras al-Khaimah (Velde 2012); to the northeast is the Wadi Ham/Wadi Abadilah system, at the confluence of which the Masafi Oasis developed (Benoist et al. 2012); the south-central region is dominated by the Wadi Hatta, a key route linking the Arabian Gulf and Indian Ocean. The mountain oases and communication routes were valuable economic and strategic resources, of which Masafi, as both a reasonably large oasis and the gate to the Dhahira and North Coast, was the most important. They were also a small but significant focus of population. The mountains are criss-crossed with myriad minor wadis with hamlets and homesteads supported by scattered palm-groves. During periods of economic boom, there was sufficient demand for agricultural produce from the coastal towns that the mountain slopes were terraced and farming villages developed, as was notably the case in Rus al-Jibal during the fourteenth and fifteenth centuries (Kennet 2002).

Fig. 22.4 The Hatta region of the Hajar Mountains. Note the deep wadis providing access through the mountains. Credit: Timothy Power

22.2.6 East Coast

Much of the eastern seaboard of Southeast Arabia is taken up with the Batina coastal plain. However, the mountains come closer to the sea and the coastal plain tappers off as we move north, so that the Batina plain ends before we enter the Emirates. At the southern end of the East Coast, the historic settlements of Fujairah and Kalba grew up at the broad mouth of the Wadi Ham, where sufficient silt was deposited to allow for agriculture (Ziolkowski and Sharqi 2008). The flat *sabkha* behind Khawr Kalba indicates that the creek was once part of an extensive lagoon, which would have offered rich marine resources attracting settlement (Eddisford and Philips 2009). At the northern end of the East Coast, the ancient town of Dibba was established at the head of the Wadi Abadilah, which grew to become an important trading station (Jasim 2006). Between them lies Khawr Fakkan. This offers a fine natural harbour but its utility as a port of trade is inhibited by the lack of a natural route to the interior. As a result, it developed into an important way station on the maritime route linking the Gulf to India (Sasaki and Sasaki 2019).

22.3 The Development of Human Societies and Their Economic Needs

Archaeology is the study of the material culture of past human societies. The archaeological record of the Emirates can be divided into five epochs (Table 22.1): (i) hunter gatherers using a Palaeolithic toolkit between 200,000 and 40,000 years ago; (ii) hunter gatherers and nomadic pastoralists using a Neolithic toolkit between 8000 and 3000 BCE; (iii) sedentary agriculturalists and mercantile elites using Bronze and Iron Age tool technology between 3000 and 300 BCE; (iv) large-scale settlements with long-distance trade links to the Classical Mediterranean and Islamic Indian Ocean between 300 BC and AD 1000; (v) urban settlements with long-distance trade links increasingly oriented towards Europe and America between AD 1000 and 1950. These periods can be defined by changes in their material culture and subsistence strategies. Very generally, we can observe an evolutionary trajectory from less to more complex systems with the pace of development accelerating over time.

22.3.1 Early Prehistoric, 200,000–40,000 BP

By far the longest epoch in the archaeological sequence is the Early Prehistoric, roughly equivalent to the Middle Palaeolithic (Cleuziou and Tosi 2007: 19–31). The evidence for human activity in the territories of the modern UAE is patchy and scattered, with long periods between clusters of absolute dates. For example, stone tools found at Jebel Baraka in Abu Dhabi may be dated to around 200,000 years ago, but there is a gap of tens of thousands of years before the next evidence for activity, at Jebel Faya in Sharjah around 125,000 years ago (Wahida et al. 2008; Armitage et al. 2011). There were three major occupations at Jebel Faya, again separated by tens of thousands of years, of which the last can be dated to around 40,000 years ago. This is followed by another occupational lacuna before we reach the Neolithic around 10,000 years ago. Although the limitations of the evidence need to be stressed, the general impression is that the region of the present Emirates was not intensively occupied in the Palaeolithic period. As a result, the impact of humans on the environment—so far as it is possible to tell—seems to have been limited.

22.3.2 Late Prehistoric, 8000–3000 BCE

It is not until the Neolithic period (c. 8000–3000 BCE) that evidence for human occupation becomes more consistent (Cleuziou and Tosi 2007: 35–60; Potts 2012: 17–33; Magee 2014: 46–86). Most archaeologists would therefore probably agree that the lands of the Emirates have been more or less continuously occupied for the

Table 22.1 Chronological outline of the socio-cultural phases of human society in the region of the present United Arab Emirates

Epoch	Regional	Local
Early prehistoric *200,000–40,000 BP*	Palaeolithic *200,000–40,000 BP*	Palaeolithic *200,000–40,000 BP*
Late prehistoric *8000–3000 BCE*	Neolithic *8000–3000 BCE*	Neolithic *8000–4000 BCE*
		'Dark millennium' 4000–3000 BCE
Protohistoric *3000–300 BCE*	Bronze age *3000–1300 BCE*	Hafit *3000–2500 BCE*
		Umm al-Nar *2500–2000 BCE*
		Wadi Suq *2000–1600 BCE*
		Late bronze age *1600–1300 BCE*
	Iron age *1300–300 BCE*	Iron age I *1300–1100 BCE*
		Iron age II *1100–600 BCE*
		Iron age III *600–300 BCE*
Early historic *300 BCE–1000 CE*	Classical antiquity *300 BCE–300 CE*	PIR.A *300–150 BCE*
		PIR.B *150–0 BCE*
		PIR.C *0–150 CE*
		PIR.D *150–300 CE*
	Late antiquity *300–650 CE*	Early Sasanian *300–500 CE*
		Late Sasanian *500–650 CE*
	Early Islamic *650–1000 CE*	Early Islamic I *650–800 CE*
		Early Islamic II *800–1000 CE*
Late historic *1000–1950 CE*	Middle Islamic *1000–1650 CE*	Middle Islamic I *1000–1250 CE*
		Middle Islamic II *1250–1500 CE*
		Middle Islamic III *1500–1650 CE*
	Late Islamic 1650–1950 CE	Late Islamic I *1650–1800 CE*
		Late Islamic II *1800–1950 CE*

past 10,000 years. The Palaeolithic and Neolithic are distinct from the ensuing periods in that the climate was still changing dramatically, subsequently stabilising into the present climatic regime in the fourth millennium BCE. We should further note that the ‘agricultural revolution’ does not reach the Emirates until the end of the Neolithic period, around 3000 BCE, and most of the local Neolithic societies instead practiced nomadic pastoralism, i.e. the herding of domesticated animal species. During this epoch, human-environmental interactions appear still to have favoured the natural world, with social change in many cases a consequence of adaptions to the changing climate.

22.3.3 Protohistoric, 3000–300 BCE

Writing was invented in Mesopotamia around 5000 years ago. From this moment on, we have sporadic historical references to *Magan,* as southeast Arabia was known to the Mesopotamians (Potts 1990: 133–49). However, it is not until the Graeco-Roman period that the quantity and quality of the historical sources becomes more consistent, for which reason we have adopted the term Protohistoric. The local Chalcolithic period is synonymous with the Hafit culture (3000–2500 BCE), named after the type site where it was first discovered, which witnessed the beginnings of metallurgy and agriculture (Cleuziou and Tosi 2007: 107–132; Potts 2012: 35–43; Magee 2014: 87–98). This is followed by the local Bronze Age societies again named after type sites, the Umm al-Nar (2500–2000 BCE) and Wadi Suq (2000–1600 BCE) cultures, with the Late Bronze Age (1600–1200 BCE) only defined relatively recently (Cleuziou and Tosi 2007: 139–278; Potts 2012: 45–87; Magee 2014: 98–125, 152–196). Thereafter comes the Iron Age (1200–300 BCE), which arguably constitutes the peak of prehistoric population associated with the development of extensive oasis agrosystems supported by *falaj* irrigation (Cleuziou and Tosi 2007: 281–303; Potts 2012: 89–105; Magee 2014: 214–258). These periods display a significant degree of cultural continuity, as evidenced by traditions of collective burial continuing from the Hafit period into the Iron Age, or locally produced coarse wares developing from the Wadi Suq through the Iron Age. Indeed, many sites of the Protohistoric epoch, including well-known sites like Tell Abraq, Hili and Saruq al-Hadid, were continuously or repeatedly occupied between the Umm al-Nar and Iron Age. This epoch is when humans began to have a more serious impact on the natural world, a process that has been dubbed ‘taming the desert’ (Cleuziou and Tosi 2007: 137–157).

22.3.4 Early Historic, 300 BCE–1000 CE

The *période préislamique récente* (300 BCE–300 CE), often abbreviated to PIR and rendered into English as the Late Pre-Islamic period, marks a major departure from the local prehistoric cultures of Southeast Arabia (Mouton 2008; Potts 2012: 107–133). From this period on, the material culture of the Emirates demonstrates strong links with western Indian Ocean networks, whilst the appearance of funerary and numismatic inscriptions represents the beginning of an indigenous historical record. Settlement and trade rather mysteriously fell into abeyance for much of Late Antiquity (300–650 CE), possibly because the region of the modern Emirates constituted a demilitarised frontier of the Sasanian Empire (Kennet 2007; Mouton and Cuny 2012; Potts 2012: 135–41). The Early Islamic period (650–1000 CE) witnessed a sustained episode of economic and demographic growth, since the region lay between the major ports of Siraf and Sohar through which much of the Indian Ocean trade of the Abbasid Caliphate was filtered (Wilkinson 1964; King 2001). These periods display a significant degree of cultural continuity, with, for example, many of the common wares that make up the ceramic assemblage develop over the course of the first millennium CE. The integration of Southeast Arabia into Indian Ocean networks led to growing external demand for local natural resources, and it is in this period that the first large scale/proto-industrial exploitation of the environment occurred.

22.3.5 Late Historic, AD 1000–1950

It is not until the arrival of the Turks in the eleventh century CE that the synthesis of Arab, Persian and Turkish culture that Western scholarship dubs ‘Islamic’ began to take root. Historical evidence becomes increasingly important for our understanding of the past societies of Southeast Arabia during the Islamic centuries. The Emirates was first conquered by the Saljuq Turks of Kirman and then ruled by the Persian Arabs of Hormuz during the Middle Islamic (1000–1600 CE) period (Fiorani Piacentini and Maestri 2009; Fiorani Piacentini 2013). The region was subsequently integrated into the Indian Ocean empire of the Portuguese between 1507 and 1622 CE, a traumatic first encounter with a globally ascendent Europe (Farinha 2009). The entirely of Southeast Arabia was united under the Yarubid Empire of Oman for the first century the Late Islamic period (1600–1950 CE), the fragmentation of which in the eighteenth century led to the emergence of a patchwork of local sheikhdoms and emirates (Bathurst 1967). These included the Bani Yas confederation of Abu Dhabi and Dubai which expanded into the al-Ain Oases, and the Qasimi confederation of Ras al-Khaimah and Sharjah which expanded across the Northern Emirates (Heard-Bey 1982). The region was subsequently dominated by the British between 1822 and 1971 CE, whose divide and rule policy ultimately bequeathed seven emirates to the present federation (Zahlan 1978). The Late Historic epoch is characterised by the emergence of an increasingly globalised world economy, with unprecedented international demand for natural resources giving rise of local industries.

22.4 Climate Change and Human Adaptions

The climate of the Emirates fluctuated considerably during the Mid to Late Pleistocene (Parker 2009: 42–43). Fluvial silts and lacustrine sediments from the Wadi Dhaid and Liwa Oasis indicate the presence of rivers and lakes between 350–130 ka. Anatomically modern humans emerged in Africa around 300 ka and began to move into Arabia by 200 ka, when hunter gatherer communities were active in the region of Jebel Baraka, a 63 m high hill rising above the Abu Dhabi coastline to the west of Jebel Dhanna (Richter et al. 2017; Wahida et al. 2008). A number of stone tools were found in the area, including hand-axes and scrappers used for butchering animals. These tools were made using the Levallois technique, indicative of a Middle Palaeolithic date around 200,000 years ago. At the time, the Arabian Gulf constituted a vast river-valley system and Jebel Baraka offered a vantage position to hunters preying on game moving along ancient river courses. The period 130–75 ka seems to have been particularly wet, indicated by the formation of alluvial fans along the western edge of the Hajar Mountains in Ras al-Khaimah. It is to this period that the oldest human settlement outside of Africa belongs, a rock shelter at Jebel Faya occupied around 125 ka (Fig. 22.5), a globally important site in the story of the human journey 'out of Africa' (Armitage et al. 2011; Zorich 2011).

Fig. 22.5 The Palaeolithic rock shelter at Jebel Faya. Credit: Timothy Power

Climatic conditions became increasingly arid between 20 and 10 ka, part of a global warming that brought the Ice Age to an end (Parker 2009: 43–46). During this period, the Rub al-Khali entered a major phase of aeolian accumulation and sand dunes formed at Awafi near al-Ain. Progressive aridisation was interrupted by a regional wet phase between 15–13 ka, which, as a 'climatic optimum,' may have kick-started the Neolithic revolution (Scarre 2018). At Awafi, for instance, the dune field was stabilised and vegetated with grasslands and scattered trees. These conditions may have prompted the migration of nomadic groups out of the Fertile Crescent across the Arabian Peninsula, with a second wave during the Holocene Climatic Optimum (c. 7500–4000 BC), a process known as the 'Holocene repopulation of Eastern Arabia' (Uerpmann et al. 2009).

For the much of the Late Pleistocene epoch, the area today occupied by the Arabian Gulf constituted a fertile river valley. This has been conceptualised as a 'Gulf Oasis,' where it has been argued the majority of the Palaeolithic population lived, which helps explain the general lack of sites of this period in eastern Arabia (Rose 2010). The Arabian Gulf formed between 12–6 ka as the ice sheets melted and global sea levels rose. Between 14–8.5 ka the shoreline of the emerging Gulf ran due west from Ras al-Khaimah to al-Qatif, so that the Abu Dhabi islands and Qatar Peninsula lay within a vast area of salt marsh much like the present Shatt al-Arab in Iraq (Lambeck 1996). Neolithic settlements on the Abu Dhabi Islands belong to a liminal landscape between land and sea.

The earliest evidence for the Holocene repopulation of Arabia comes from the Abu Dhabi Islands. This rich maritime environment—dubbed the 'fertile coast' (al-Hameli et al. 2023)—attracted migrants from the disappearing 'Gulf Oasis.' Late Prehistoric occupations are accordingly attested on the islands of Ghagha, Marawah and Dalma. Indeed, the oldest buildings yet found in the Arabian Gulf were recently discovered on Ghagha, consisting of multi-chambered curvilinear structures built of local beach rock, which can be radiocarbon dated to 8500 BCE (*Ibid.*). Similar structures were found on Marawah with radiocarbon dates ranging between 6000 and 4000 BCE (Beech et al. 2019). Settlement at Dalma was instead characterised by a circular post-hole structure dated between 5000 and 4500 BC (Beech et al. 2000). As such, we see both push and pull factors in play—the flooding of the 'Gulf Oasis' and the 'fertile coast' of the Emirates—driving population movement.

In a parallel process, the Dhafra desert played an important role in the Holocene repopulation of Arabia. The dunes formed in episodes over tens of thousands of years, beginning around 63–50,000 years ago and ending around 22–11,000 years ago as the climate heated up (Parker 2009: 43). Climatic conditions improved during the Holocene Climatic Optimum (7500–4000 BCE) that followed the end of the last Ice Age, enabling hunter gatherers and/or nomadic pastoralists to migrate from the Fertile Crescent. A cluster of sites was discovered at Umm al-Zamul in the Ramlat al-Hamra, located in an interdunal plain 7 km long by 1 km wide, which produced over 3000 pieces of worked stone (Kallweit et al. 2008). Another cluster of sites from this period is al-Ashoosh in Dubai, located in a broad desert pan c. 1 km^2, from which over 4000 pieces of worked stone were retrieved (Casana et al. 2009: 33–35).

Both sites include arrowheads in the 'Arabian Bifacial Tradition' dated between 8000 and 3500 BCE. These extensive stone scatters are evidence for a seasonal occupation by hunter gatherers and/or nomadic pastoralists preying on game drawn to interdunal lakes fed by winter rains. Here the pull factors appear to be stronger—a benign climate creating new opportunities—serving to populate previously uninhabited regions.

The shoreline of the Arabian Gulf stabilised around 6 ka and the present climate was established around 5 ka, i.e. between 4000 and 3000 BCE (Parker 2009: 46). The drop in the number of sites during the terminal Neolithic has been dubbed the 'dark millennium' (Uerpmann 2002), which, it has been claimed, was the result of a deterioration of the climate to something approaching present conditions. Although there have been attempts to identify wetter and drier episodes over the past 5000 years, not all of these have been convincing and it is perhaps safest to assume the climate has not changed significantly in that time.

22.5 Taming the Desert: Early Farming and Herding

One of the key human-environment interactions involved the domestication of plants and animals, as well as the harnessing of water resources needed for agriculture and animal husbandry. It took thousands of years for these early experiments to develop into the date-palm oases and camel caravan networks that have been so fundamentally important to the social and economic history of the Emirates. Probably the oases took their place in the landscape around the start of the Iron Age II period about 3000 years ago, following the development of the *falaj* irrigation system. Southeast Arabia was not integrated into the pan-Arabian camel caravan networks until the PIR.A period over 2000 years ago, a process which was to have long-term repercussions, for it was through these networks that the Arabs and eventually Islam arrived around fourteen centuries ago.

22.5.1 Early Agriculture

The earliest move towards sedentary agriculturalism in the UAE began in the Hafit period (3000–2500 BCE). Perhaps the most characteristic aspect of the Hafit culture are the circular stone cairns containing collective burials (Fig. 22.6), up to 12 m in diameter and 2 m high, usually located prominently on the crests of hills and therefore probably intended to delineate tribal territory and grazing grounds. It has nevertheless been demonstrated that the tombs generally overlook areas of agricultural potential, raising the possibility that they were once associated with ephemeral proto-agricultural communities (Giraud 2009). Indeed, an agropastorlist interpretation of Hafit society can be put forward on the basis of ethnographic analogies with Mahra and Dhofar, wherein a largely pastoralist subsistence strategy is

Fig. 22.6 Reconstructed beehive tombs at Jebel Hafit near al-Ain. Credit: Timothy Power

complemented by opportunistic agriculture following heavy winter rains and the intensive utilisation of wild cereals, legumes and fruits (Magee 2014: 97–98).

Only a handful of settlement sites are known from the Hafit period. The first to have been discovered and still one of the most impressive is that of Hili 8 in al-ʿAin (Cleuziou 1982). The beginning of occupation is dated by a C14 sample to approximately 3000 BCE, whilst the Mesopotamian-influenced ceramics may be placed in the first half of the third millennium. Links with the Hafit culture are underscored by the cairn burials on the crest of nearby Jabal Haqlah, just over the border in Oman, so that the settlement flourished in 'the shadow of the ancestors.' Hili 8 produced the first clear evidence for agriculture in the Emirates and southeast Arabia more broadly. Palaeobotanical finds include charred grains of wheat, barley and possibly sorghum, peas, jujube and melon seeds, and over a hundred carbonised date stones; the imprints of many of these species were moreover found on the mud bricks (Cleuziou and Costantini 1980).

22.5.2 Falaj Irrigation

One of the key developments of this period was the introduction of the *falaj* (pl. *aflaj*), a kind of underground aqueduct cut through the bedrock delivering a

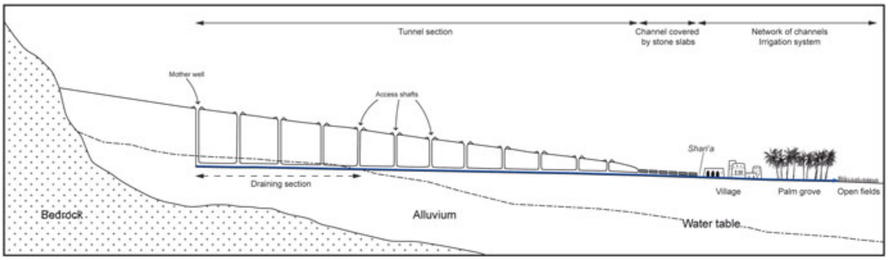


Fig. 22.7 Schematic cross-section through an archetypal falaj. Credit: Julien Charbonnier

continuous supply of water (Fig. 22.7). Many *aflaj* were still in use as late as the 1970s and the previous generation of archaeologists, ethnographers and historians had ample opportunity to study them (Wilkinson 1977; al-Tikriti 2011; Heard-Bey 2004: 176–181). Two types of *falaj* were observed operating in ‘traditional’—i.e. Late Islamic—oases. The *ghayl falaj* is fed by shallow surface and sub-surface water flowing through wadi gravels and alluvial fans; and the *dawudi falaj* taps into deep underground aquifers formed at the base of mountains (Charbonnier 2014).

The structure of the *falaj* consists of five key elements: the mother well, the tunnel, the cut-and-cover section, the *shari‘a* and the surface channels. Only the *dawudi falaj* is fed by one or more mother wells (lit. *umm ma’*, ‘mother of water’) located at the foot of the mountains, whilst rudimentary dams or diversion channels push water from the wadi into the *ghayl falaj*. The tunnel runs at an incline of between 1/500 and 1/2500 to enable the water to flow perpetually by force of gravity alone; it is built by excavating a series of vertical shafts (*thuqba*, pl. *thiqab*) which are subsequently linked by the sloping tunnel. As the tunnel passes through unconsolidated ground to approach the surface it is lined and covered with cemented (*tasrij*, noun *saruj*) stone blocks to create the cut-and-cover section; uniquely in the early Islamic period baked bricks were also used, for which Sohar was a famous production centre. The *falaj* finally comes to the surface at the *shari‘a*, an open section often expanded into a pool, where people could collect drinking water and wash; domestic settlement therefore usually formed around the *shari‘a* and, as a strategic resource, it was often guarded by defensive structures. Grey water was then carried through a dendritic network of surface channels, which, by the Late Islamic period at least, were formed by parallel rows of cemented stones and framing a smooth *saruj* base.

When exactly the *falaj* first appeared in Southeast Arabia has long been a subject of the debate (Magee 2014: 217). The best dated *falaj*, known as AM-2, was found at al-Madam in Sharjah (Córdoba 2013: 148). The tunnel is 1.6 m high × 50 cm wide and runs for 800 m before coming to the surface. From there an arterial surface channel 1 m wide × 50 cm deep extends a further 52 m, feeding flanking rows of perpendicular subsidiary channels each linked to a linear series of tree pits. This irrigated area may plausibly be identified as a palm grove. The case for an Iron Age II date rests on an uncontaminated ceramic assemblage and a 1160–808 BCE radiocarbon date from a shell found in the irrigation channels. Perhaps the most securely dated *falaj* was found at Salut in central Oman. Uranium-Thorium dating of stalagtites formed in the underground tunnels of the Falaj Shaww suggests that it was used between 450 BCE and 1150 CE (Cremaschi et al. 2018: Table 1, p. 137). This places its excavation in the Iron Age III period (600–300 BCE). Although the number of *aflaj* for which absolute dating is available is extremely limited, the evidence is sufficient to determine that *falaj* use spread through Southeast Arabia in the first half of the first millennium BC.

22.5.3 Oasis Agrosystem

The oasis landscape of Southeast Arabia emerged in fits and starts over a very long period of time. It was perhaps not until the eighteenth century CE, however, that the present reconfiguration of the oases was finalised (Fig. 22.8). The historic oases of southeast Arabia are in fact comprised of three discrete zones: an inner oasis made up of sunken irrigation basins planted with date palms and sub-canopy fruits and vegetables; an outer oasis consisting of open fields given over to the cultivation of

Fig. 22.8 The palm groves at the heart of the oasis agrosystem. Note the bananas growing in the shade of the canopy. Qattara Oasis, al-Ain. Credit: Timothy Power

cereals and animal fodder; and an oasis hinterland constituting a managed savannah landscape providing grazing (Wilkinson 1977: 69, Fig. 12). The surviving palm groves the visitor sees today belong to the inner oasis zone, with much of the outer oasis and oasis hinterland lost to modern development, leaving only isolated areas of the historic landscape intact.

An excellent case study in the origin and development of oasis agrosystems is presented by archaeological work in al-Ain and Buraimi. Seven historic oasis agrosystems survive amidst the suburban sprawl of the late twentieth century towns (Power and Sheehan 2012). Excavations appear to capture the moment of transition from open field systems of arable crops to intensive cultivation of date-palms in sunken basins (*bustan,* pl. *basateen*) fed by *aflaj* in the early Iron Age (Power and Sheehan 2011: 273). Episodes of expansion and contraction can be detected by archaeological survey (Power et al. 2015, 2016, 2017; Sheehan et al. 2018). When placed in their proper historical context, it is possible to put forward theories as to the developmental dynamics that transformed the historic environment (Power 2018). We shall shortly return to this issue, but for now it is sufficient to note that the oasis agrosystem formed the basis for settled life in the interior, while the agricultural surplus enabled an expansion of settlement on the coast.

22.5.4 Animal Husbandry

Herding reached the Emirates earlier than farming. Arrowheads employing Neolithic technology—known as Fasad points from the type-site in Oman where they were first discovered (Charpentier 1996)—appear at a number of sites. Those at Jabal Faya in Sharjah Emirate, for example, were found together with a marine shell which produced a radiocarbon date between the mid ninth and early eighth millennium BCE (Uerpmann et al. 2009: 209–10). It is unclear whether the spread of Neolithic stone technology into southeast Arabia was part of a package further including nomadic pastoralism. However, unambiguous evidence for nomadic pastoralism has been found at the later site of Buhais 18, not far from Jabal Faya, which was occupied in the fifth millennium BCE. A large number of animal bones were recovered and studied from butchery sites (Uerpmann and Uerpmann 2008). Over 90 per cent of the bones are from domesticated sheep, goat and cattle, with the remainder from wild animals like gazelle and camels, indicating the declining importance of hunting. Most of the sheep and goat were elderly females, indicating that they had been kept for their milk. Indeed, this nomadic herding community very likely moved to Buhais 18 during the lambing season in the spring, and spent the summers fishing on coastal and island settlements like ʿAqab and Marawah. Already in the Neolithic, life in the Emirates was characterised by the seasonal migration between the coast and interior (Uerpmann and Uerpmann 2000: 232–33).

22.5.5 Camel Domestication

The domestication of the Arabian camel—more properly, the dromedary—probably occurred at the end of the Bronze Age and beginning of the Iron Age, in the later centuries of the second millennium BCE (Magee 2014: 197–213). A general characteristic of domesticated compared to wild species is an overall reduction in body size, so that archaeozoologists are able to distinguish between wild and domesticated camel bones. Bones from Buhais 18 indicate that wild camels were being hunted in the Neolithic period and provided a significant amount of the meat diet. The faunal assemblage at the butchery sites of al-Safouh in Dubai city and Baynunah in Abu Dhabi emirate is almost entirely dominated by wild camel bones, testifying to the existence of specialised hunting zones in the Bronze Age (Von der Driesch et al. 2008). Indeed, the proportion of camel bones in the faunal assemblage of Tell Abraq in Umm al-Qaiwain fell from 50% to 5% over the course of the Bronze Age, suggesting that the overhunting led to a crash in the local wild camel population. Yet by the Iron Age II period (1100–600 BCE) the proportion of camel bones at Tell Abraq had recovered even as the bone size has decreased, immediately implying that we are now dealing with a managed herd of domesticated camels. This is confirmed by an Iron Age II faunal assemblage from Muweilah, which was sufficiently large enough to ascertain that most of the bones belonged to juveniles slaughtered for their meat (Uerpmann and Uerpmann 2002). No zooarchaeological data from the late Bronze and early Iron Age has yet been found, but the comparison of the two periods suggests the camel was domesticated in this transitional period.

The use of camels for transport seems to have been a secondary development. Archaeozoology has not yet been able to identify when camels were used for carrying riders and bearing loads, and we must instead rely on historical sources and material culture. The earliest regional depictions of camels being ridden are found on carved reliefs from a palaces at Tell Halaf and Carchemish in Syria, dated loosely from the late tenth to ninth century. At much the same time in the Emirates, camel figurines with saddles and/or loads strapped to their backs begin to appear at Muweilah in Sharjah (Fig. 22.9), which flourished between the tenth and eighth centuries BCE (Magee 2015). The domestication of the camel therefore led to the emergence of new forms of nomadic pastoralism in the tenth and ninth centuries BCE. An Assyrian victory stela records the defeat in 853 BC of Arab bedouin in the Badiyat al-Sham, the semi-desert region between Syria and Iraq, resulting in the capture of a thousand camels (Hoyland 2001: 59). However, there is as yet no evidence that camels were used for long-distance trade. One might argue that a network of pan-Arabian caravan networks could only emerge after the hitherto impenetrable deserts had been populated by camel herding nomads.

Fig. 22.9 Camel figurine from Muweilah. Source: Figura de camello (50390168996).jpg by Ángel M. Felicísimo, licensed under Creative Commons (CC BY-SA 4.0)

22.5.6 Caravan Networks

It is not until the eighth century BC that we have firm evidence for long-distance camel-borne trade, beginning with the frankincense trade between Yemen and the Levant (Crone 1987: 12–29). Arguably, it was not until the third century BCE that Southeast Arabia became integrated into the pan-Arabian caravan networks (Potts 1988). The excavators of Mleiha in Sharjah believed that the site was first settled by nomads arriving from northern Arabia, who established a sprawling settlement of semi-permanent palm-frond houses that, over time, developed into permanent town of mudbrick houses (Mouton and Schiettecatte 2014). Almost a third of the ceramic assemblage of the earliest occupational levels is made up of 'Thaj Ware' imported from Northeast Arabia, and its locally produced coinage—the earliest minted in the Emirates—imitated that of Thaj, the largest city in eastern Arabia (Mouton 2008: 47; Macdonald 2010). The caravan network reached as far as southwest Arabia, as evidenced by Yemeni alabaster beehive vessels likely imported via Thaj (Hassell 1997). The integration of southeast Arabia into the pan-Arabian caravan networks, which so influenced the social and economic history of the Emirates, was only made possible by the domestication of the camel and camel-herding nomadic pastoralism.

22.6 From Subsistence Strategies to Local Industries

By taming the landscape, the past societies of the Emirates developed adaptive subsistence strategies suited to a range of topographic/ecological zones. Certainly, during the Protohistoric epoch these societies were producing a regular agricultural surplus that could be taxed, stored, redistributed and traded. From this moment on we are dealing with economics and politics. By the Iron Age, local polities with walled cities and columned halls—'chiefdoms' rather than 'states' owing to the lack of writing and record keeping—based on the successful management of the oasis agrosystem had emerged. The Protohistoric economy thus developed far beyond the subsistence level. At certain moments external demand for the natural resources of southeast Arabia caused traditional subsistence strategies to develop into regional industries. This seems already to have been the case with copper mining in the Umm al-Nar period. But it was not until the Early Historic period that pearling and date production reached something approaching an industrial scale. The evidence is much better for the Late Historic period, when globalisation unlocked new markets and external demand spiked, leading to a rapid acceleration of the human impact on the natural environment (Heard-Bey 2004: 164–97).

22.6.1 Pearling

It is not until the PIR.C period, from the late first century BCE to the early second century CE, that the exploitation of the pearl beds reached semi-industrial proportions. The expansion of Indian Ocean trade opened up large new international markets, not least with the Roman Empire: pearl earrings appear frequently in the Fayyum portraits. The Early Historic site of ed-Dur, located on the southern shore of the lagoon of Umm al-Quwain, flourished during this period. Coins, ceramics and glass from ed-Dur attest to trade with Greece, Rome, Persia and India (Haerinck 1998). On this basis, ed-Dur has been identified as the port of *Omana,* mentioned as a source of pearls in the *Periplus Maris Erythraei,* a Graeco-Roman mercantile treatise of the first century AD (Potts 1990: 306–310). Evidence for pearling included a lead weight with an iron ring used by pearl divers to descend rapidly to the pearl beds, virtually identical to those used up to the twentieth century, and forty-one pearls have been found scattered among the excavated graves (Carter 2012: 18–19). Most impressive of all are the vast oyster shell middens covering nearby Akab Island, a clear indication of the scale of activity.

During the Middle Islamic period, between the twelfth and sixteenth centuries CE, the site of Julfar in Ras al-Khaimah became the leading pearling centre of the lower Gulf (Power 2017: 228–237). It is first mentioned as a place where pearls are to be found by the twelfth-century geographer al-Idrisi (Carter 2012: 45–48). The industry was well-established by the time the Portuguese arrived in the early sixteenth century:

> Passing above this place Profam [Khor Fakkan], we come to another called Julfar, where dwell persons of worth, great navigators and wholesale dealers. Here is a very great fishery as well of seed-pearls as of large pearls, and the Moors of Ormus [Hormuz] come hither to buy them and carry them to India and many other lands. The trade of this place brings in a great revenue to the King of Ormus. (Barbosa 1918–1921: 73–74).

Julfar is associated with the sites of al-Mataf (Fig. 22.10) and al-Nudud, located either side of the entrance to the lagoon of Ras al-Khaimah (Velde 2012). They

Fig. 22.10 The site of al-Mataf in Ras al-Khaimah, part of the ancient pearling city of Julfar. Credit: Derek Kennet

developed a truly urban character between the fourteenth and sixteenth century, with tightly packed stone houses along narrow lanes within city walls (Kennet 2003; Carter et al. 2020). A considerable extramural settlement of post-hole structures grew up in this period, and the whole coastline from Rams to Ras al-Khaimah appears to have been intensely occupied. Historical sources demonstrate that virtually all of the present coastal settlements existed by the sixteenth century (King 2006), and recent survey work in Umm al-Quwain has revealed the undisturbed remains of a stone-town of this period (Power et al. 2022), so we might place the first urbanisation of the coast in the Middle Islamic period.

Whether or not the growing scale and intensity of human settlement placed a strain on the natural environment is unclear. It has been suggested that one of the two major pearl beds collapsed in the early sixteenth century as a result of overfishing (Floor 2014: 1), leading to conflict over the remaining pearl fisheries. Certainly Julfar itself declined in the course of the sixteenth century, and though this was clearly a complex multicausal phenomenon that included silting of the lagoon (Velde 2012: 219), it is possible that environmental degradation was a contributing factor.

A second urbanisation of the coast occurred between the eighteenth and early twentieth centuries in response to a regional pearling boom (Carter 2009). Unfortunately, the archaeology of most of these towns has largely been obscured by modern development, with the notable exception of the forts, which have been preserved as heritage monuments. Abu Dhabi is a case in point. It was established in the late eighteenth century, but all that remains of premodern settlement is the core of Qasr al-Hosn, the dynastic seat of the Al Nahayyan (Maitra and Hajji 2001). The only well-preserved historic town of the north coast is Jazirat al-Hamra, the ruins of which—abandoned in the mid twentieth century—largely date to the eighteenth and nineteenth centuries (Priestman 2020).

The pearl boom peaked in the late nineteenth and early twentieth centuries. By this time the British had ended the mass transport of enslaved Africans, forcing reduced slave trade underground, and the labour needs of the industry were met by the mass mobilisation of the population. A pattern of seasonal migration (*tahwil*) from the interior to the coast emerged, with up to 78% of the male population involved in the 'great dive' (*ghaws al-kabir*) each summer (Heard-Bey 1982: 199; Carter 2009: 276).

22.6.2 Dates

It is probably not until the Early Historic epoch that dates began to be grown as a cash crop for export. The Batina port of Sohar emerged in the ninth and tenth centuries as a major Indian Ocean entrepôt, connecting East Africa with the Persia, India and China (Averbuch 2017). East African ivory, slaves and gold were exchanged for Iraqi date-wine and southeast Arabian dates, the importance of which one contemporary account makes clear:

> The Zanj feel great awe in their hearts for the Arabs. If they catch sight of an Arab, they prostrate themselves before him and say, 'This man is from a kingdom where the date tree grows!' This is because of the prestige that dates enjoy, both in their land and in their hearts. (Abu Zayd al-Sirafi trans. Macintosh-Smith 2014: 121)

To produce dates in large enough quantities to maintain a balance of trade, the historic oases were expanded by the digging of new *aflaj* and excavation of new sunken palm groves, the labour for which was provided by enslaved East Africans. The Omani sources refer to the slaves of the Batina. In one account, they speak of the justice of a local ruler who forbade slaves being worked day *and* night (al-Rawas 1990: 234–236). Archaeological surveys of the hinterland of Sohar demonstrates that 6200 hectares were brought under intensive cultivation during the peak of settlement in the ninth and tenth centuries (Costa and Wilkinson 1987: 225–226). In a subsidiary development, the oases of al-Ain and Buraimi—connected to Sohar by the Wadi al-Jizzi—appear to have expanded significantly at this time (Power and Sheehan 2012; Power et al. 2015, 2016, 2017; Sheehan et al. 2018).

The Late Historic period witnessed a major increase in date exports and the expansion of the oasis landscape. The stimulus again came from the Indian Ocean when, in the course of the seventeenth century, the Yarubids of Oman united Southeast Arabia and conquered East Africa. The oases grew in the eighteenth century as the Yarubids secured access to new markets in India and ensured a supply of cheap labour from Africa. The Imam Sayf b. Sultan al-Ya'rubi is reported to have "improved a large portion of Oman by making water-courses and planting date and other trees... [At the time of his death in 1711] he had acquired one-third of all the date-trees in Oman" (Ibn Raziq trans. Badger 1871: 93. *Cf.* Mershen 2001: 158–159). In al-Ain and Buraimi, the archaeological evidence suggests a massive building boom and significant expansion of the oases, and once again access to the Indian Ocean via nearby Sohar was likely a key factor in this growth (Power and Sheehan 2012: 297–303; Power 2018).

Another phase of expansion occurred in the late nineteenth and early twentieth centuries. This time the investment capital came from the Arabian Gulf, which, as we have seen, was being transformed by the pearling boom. Shaikh Zayed I b. Khalifa invested the bumper profits of the pealing industry in the oases of al-Ain, either buying derelict palm groves and repairing choked *aflaj,* or establishing new agricultural estates (Lorimer 1915: 264; Heard-Bey 1982: 225). Slaves were readily available and widely used across the Arabian Gulf and Southeast Arabia. A letter to the Sultan of Zanzibar observed that "with ten baskets' worth of dates that a man now gets on credit he can get 20 slaves at Zanzibar worth $1000" (cited by Hazell 2011: 124). In 1902, a visitor to the Buraimi Oasis noted that "the gardens are well kept, and all the labour is done by slaves, who form, I think, at least one-half of the population" (Zwemer 1902: 62). An argument can be made that the traditional oasis agrosytems of southeast Arabia were transformed into a plantation style economy, using slaves to produce a cash crop for export, a trajectory that peaked in response to the massive new markets opening up in Europe and America (Hopper 2013, 2015: 51–79).

22.7 Conclusion

Human-environmental interactions in the pre-modern Emirates were, like most places and periods in world history, primarily driven by economic exigencies. Subsistence strategies adapted to changing climatic conditions across a diverse range of topographic/ecological zones allowed early human societies to thrive. As southeast Arabia was brought into a series of ever larger exchange networks, first in the Arabian Gulf and then across the Arabian Peninsula and Indian Ocean, external demand for its natural resources grew. This led to craft diversification and social stratification: certain sections of society specialised in resource procurement and elites manipulated resource redistribution to maintain their position. By the Early Bronze Age, the economy was perhaps already orientated to the supply of raw materials to early states in Mesopotamia and the Indus Valley. We might even identify world-system patterns of unequal exchange (Algaze 1993). For example, copper was certainly being used by the sixth millennium in the Fertile Crescent but did not start to be used in southeast Arabia until the third millennium BCE. One might simply assume that it took centuries for the pioneering technology of the core to permeate the periphery, but we might alternatively suggest that technological progress was inhibited by the ready supply of manufactured commodities exchanged for raw materials.

This reliance on the export of raw materials to foreign markets helps explain the settlement patterns noted by archaeologists over the longue durée. The Abu Dhabi Islands and North Coast were, once the current climate regime stabilised around 5000 years ago, incredibly inhospitable and difficult places to live. The only reason to intensively inhabit such as barren landscape was the extraction and exchange of raw materials, notably the native pearls so highly prized by foreign merchants. The people of the Gulf were themselves aware of this. As one local ruler explained to a nineteenth century British traveller, "we are all from the highest to the lowest slaves to one master, the Pearl" (quoted in Hopper 2015: 8). This is why the Abu Dhabi Islands and North Coast were only intensively occupied during periods of high foreign demand for pearls. Something similar may be said for the rocky slopes of the Hajar Mountains in Ras al-Khaimah, which were only worth cultivating when there was strong foreign demand to make the meagre returns worthwhile. In periods of low foreign demand, the local people sought their fortunes on the facing shore of the Gulf or retreated to the most fertile regions of southeast Arabia. It is further possible to posit the oases and lagoons—where food and shelter was most readily available—as *refugia* where pockets of the indigenous population waited out the economic depressions and political disturbances that periodically gripped the region.

Human societies therefore survived in a marginal environment by remaining highly mobile and diversifying their subsistence strategies. The exploitation of natural resources, indeed, the very inhabitation of areas outside the *refugia*, may be understood as an opportunistic adaptation responding to external demand. This could at times result in overexploitation, as when the pearl beds were overfished in the early sixteenth century, leading to political fallout. Or else the overdependence on a single industry could lead to catastrophic social trauma, as when the pearling industry collapsed in the 1930s. Generally, however, the small pre-modern population size and limited technological capabilities meant that the human-environmental interactions were relatively well-balanced.

22.8 Recommended Readings

This paper provides an overview of archaeological perspectives on human-environmental interactions in the Emirates, highlighting some of the key topics of research and providing major bibliographic references for the general reader, and as such functioning in some sense as a bibliographic essay. For readers wishing to develop their interest in the history and archaeology of the Emirates, I would recommend the following introductory and/or reference works given in suggested order of reading: Potts (2012), Cleuziou and Tosi (2007), Magee (2014), Heard-Bey (2004), Wilkinson (1977).

References

Algaze G (1993) The Uruk world system: the dynamics of expansion of early mesopotamian civilisation. University of Chicago Press, Chicago

al-Hameli NH et al (2023) New light on the Neolithic fertile coast: recent excavations on Ghagha Island (Abu Dhabi emirate, UAE) and the emergence of domestic architecture in ancient Arabia. In: Proceedings of the Seminar for Arabian Studies

al-Rawas IAA (1990) Early Islamic Oman (ca - 622/280–893): a political history. Durham University, Durham

al-Sīrāfī AZ (2014) Accounts of China and India (trans: Mackintosh-Smith T). New York University Press, New York

al-Tikriti WY (2011) Archaeology of the Falaj: a field study of the ancient irrigation Systems of the United Arab Emirates. Abu Dhabi Cult Heritage, Abu Dhabi

Armitage SJ, Jasim SA, Marks AE, Parker AG, Usik VI, Uerpmann HP (2011) The southern route 'out of Africa:' evidence for an early expansion of modern humans into Arabia. Science 331: 453–456

Averbuch B (2017) Sohar: forelands, Umland, and hinterland in the history of an Omani Entrepôt. In: Al Salimi A, Staples E (eds) The ports of Oman. Georg Olms Verlag, Hildesheim, pp 179–211

Barbosa E (1918–1921) The book of Duarte Barbosa: an account of the countries bordering on the Indian Ocean and of their inhabitants. (trans: Dames ML). The Hakluyt Society, London

Bathurst RD (1967) The Ya'rubi dynasty of Oman. DPhil Thesis, University of Oxford

Beech M, Elders J, Shepherd E (2000) Reconsidering the 'Ubaid of the southern gulf: new results from excavations on Dalma Island, UAE. Proc Semin Arab Stud 30:41–47

Beech MJ, Cuttler RTH, Al Kaabi AK, El Faki AA, Martin J, Al Hameli NH, Roberts HM, Spencer P, Tomasi D, Brunet O (2019) Excavations at MR11 on Marawah Island (Abu Dhabi, UAE): new insight into the architecture and planning of Arabian Neolithic settlements and early evidence for pearling. Arab Archaeol Epigr 31:19–31

Benoist A, Bernard V, Brunet O, Hamel A (2012) Iron age occupation in Masafi: report on two seasons of excavation. In: Potts DT, Hellyer P (eds) Fifty years of emirates archaeology. Motivate Publishing, Dubai, pp 149–161

Carter RA (2009) How pearls made the modern emirates. In: Proceedings of the international history conference on new perspectives on recording UAE history. National Center for Documentation & Research, Abu Dhabi, pp 265–281

Carter RA (2012) Sea of pearls: Arabia, Persia and the industry that shaped the Gulf. Arabian Publishing, London

Carter RA, Zhao B, Lane K, Velde C (2020) The rise and ruin of a medieval port town: a reconsideration of the development of Julfar. Arabian Archaeol Epigr 31:501–523

Casana J, Herrmann JT, Qandil HS (2009) Settlement history in the eastern Rub al-Khali: preliminary report of the Dubai Desert survey (2006-2007). Arab Archaeol Epigr 20:30–45

Charbonnier J (2014) Groundwater management in Southeast Arabia from the bronze age to the iron age: a critical reassessment. Water Hist 7:39–71

Charpentier V (1996) Entre sables du Rub' al Khali et mer d'Arabie, Préhistoire récente du Dhofar et d'Oman: les industries à pointes de 'Fasad'. Proc Semin Arab Stud 26:1–12

Cleuziou S (1982) Hili and the beginning of oasis life in eastern Arabia. Proc Semin Arab Stud 12: 15–22

Cleuziou S, Costantini L (1980) Premiers Éléments Sur L'Agriculture Protohistorique De L'Arabie Orientale. Paléorient 6:245–251

Cleuziou S, Tosi M (2007) In the shadow of the ancestors: the prehistoric foundations of the early Arabian civilization in Oman. Ministry of Heritage & Culture, Muscat

Córdoba JM (2013) New perspectives about iron age and the oasis culture in the Oman peninsula: two conclusive seasons at al Madam (Sharjah, UAE). Isimu 16:139–151

Costa PM, Wilkinson TJ (1987) The hinterland of Sohar: archaeological surveys and excavations within the region of an Oman Seafaring City. J Oman Stud 9:13–238
Cremaschi M, Degli Esposti M, Fleitmann D, Perego A, Sibilia E, Zerboni A (2018) Late Holocene onset of intensive cultivation and introduction of the falaj irrigation system in the Salut oasis (Sultanate of Oman). Quat Sci Rev 200:123–140
Crone P (1987) Meccan trade and the rise of Islam. Princeton University Press, Princeton
Eddisford D, Phillips C (2009) Kalbā in the third millennium (emirate of Sharjah, UAE). Proc Semin Arab Stud 39:99–112
Farinha AD (2009) Arabs and Portuguese in the area of the emirates and the Arabian Gulf (XVI-XVIII centuries). In: Proceedings of the international history conference on new perspectives on recording UAE history. National Center for Documentation & Research, Abu Dhabi, pp 185–197
Fiorani Piacentini V (2013) The eleventh - twelfth centuries: an ʿUmān-Kīy-Kirmān/Harmuz Axis. Proc Semin Arab Stud 43:261–276
Fiorani Piacentini V, Maestri E (2009) Rise and splendour of the Sāhil ʻUmān al-Shamāl within a new order (13th – 16th centuries AD). In: Proceedings of the international history conference on new perspectives on recording UAE history. National Center for Documentation & Research, Abu Dhabi, pp 155–182
Floor WM (2014) The Hula Arabs of the Shibkuh coast of Iran. Mage Publishers, Washington, DC
Giraud J (2009) The evolution of settlement patterns in the eastern Oman from the Neolithic to the early Bronze age (6000-2000 BC). C R Geosci 341:739–749
Haerinck E (1998) International contacts in the southern Persian Gulf in the late 1st century BC/1st century AD: numismatic evidence from Ed-Dur (Emirate of Umm Al-Qaiwain, UAE). Iran Antiq 33:273–302
Hassell J (1997) Alabaster beehive-shaped vessels from the Arabian peninsula: interpretations from a comparative study of characteristics, contexts and associated finds. Arab Archaeol Epigr 8: 245–281
Hazell A (2011) The last slave market: Dr John Kirk and the struggle to end the east African slave trade. Constable, London
Heard-Bey F (1982) From trucial states to United Arab Emirates. Longman, London
Heard-Bey F (2004) From Trucial States to United Arab Emirates. Motivate Publishing, Dubai
Heard D (2011) From pearls to oil: how the oil industry came to the United Arab Emirates. Motivate Publishing, Dubai
Hopper MS (2013) The globalization of dried fruit: transformations in the eastern Arabian economy, 1860s-1920s. In: Gelvin JL, Green N (eds) Global Muslims in the age of steam and print. University of California Press, Berkeley, CA
Hopper MS (2015) Slaves of one master: globalization and slavery in Arabia in the age of empire. Yale University Press, New Haven, CT
Hoyland RG (2001) Arabia and the Arabs from the bronze age to the coming of Islam. Routledge, London
Ibn Razīq, S (1871) History of the Imams and Seyyids of Oman. (trans and ed: Badger GP). London
Jasim SA (2006) Trade centres and commercial routes in the Arabian Gulf: post-Hellenistic discoveries at Dibba, Sharjah, United Arab Emirates. Arab Archaeol Epigr 17:214–237
Kallweit H, Beech M, Al-Tikriti WY (2008) New neolithic sites in the Rub al-Khali: survey and excavations at Umm az-Zumul - the 2004 season. In: Hellyer P, Ziolkowski MC (eds) Emirates heritage. Proceedings of the 2nd Annual Symposium on recent archaeological discoveries in the emirates and of the symposium on the history of the emirates, vol 2. Zayed Center for Heritage and History, Al Ain, pp 6–24
Kennet D (2002) The development of northern Ra's Al-Khaimah and the 14th-century Hormuzi economic boom in the lower gulf. Proc Semin Arab Stud 32:151–164
Kennet D (2003) Julfar and the urbanisation of Southeast Arabia. Arab Archaeol Epigr 14:103–125
Kennet D (2007) The decline of eastern Arabia in the Sasanian period. Arab Archaeol Epigr 18:86–122

King GRD (1998) The Abu Dhabi Islands archaeological survey season 1. Trident Press, London
King GRD (2001) The coming of Islam and the Islamic period in the UAE. In: Al Abed I, Hellyer P (eds) The United Arab Emirates: a new perspective. Trident Press, London, pp 70–97
King GRD (2003) Sulphur, camels and gunpowder: the Sulphur mines at Jebel Dhanna Abu Dhabi. Zodiac Publishing, Dubai
King GRD (2006) Delmephialmas and Sircorcor: Gasparo Balbi, Dalma, Julfar and a problem of transliteration. Arab Archaeol Epigr 17:248–252
Lambeck K (1996) Shoreline reconstructions for the Persian Gulf since the last glacial maximum. Earth Planet Sci Lett 142:43–57
Lees GM (1928) The physical geography of south-eastern Arabia. Geogr J 71:441–470
Lorimer JG (1915) Gazetteer of the Persian Gulf, Oman and Central Asia. Superintendent Government Printing, Calcutta
Macdonald MCA (2010) The 'Abiel' coins of eastern Arabia: a study of the Aramaic legends. In: Huth M, Van Alfen P (eds) Coinage of the caravan kingdoms: studies in ancient Arabian monetization, numismatic studies. American Numismatic Society, New York, pp 403–548
Magee P (2014) The archaeology of prehistoric Arabia: adaptation and social formation from the Neolithic to the iron age. Cambridge University Press, Cambridge
Magee P (2015) When was the dromedary domesticated in the ancient near east. Zeitschrift für Orient-Archäologie 8:253–278
Maitra J, Hajji A (2001) Qasr Al Hosn: the history of the rulers of Abu Dhabi, 1793–1966. Centre for Documentation and Research, Abu Dhabi
Mershen B (2001) Observations on the archaeology and ethnohistory of rural estates of the 17th through early 20th centuries in Oman. Proc Semin Arab Stud 31:145–160
Mouton M (2008) La Péninsule d'Oman de la fin de l'Âge du Fer au début de la période Sassanide (250 av.-350 ap. JC). Archaeopress, Oxford
Mouton M, Cuny J (2012) The Oman Peninsula at the beginning of the Sasanian period. In: Potts DT, Hellyer P (eds) Fifty years of emirates archaeology. Motivate Publishing, Dubai, pp 174–187
Mouton M, Schiettecatte J (2014) In the desert margins: the settlement process in ancient south and East Arabia. L'Erma di Bretschneider, Rome
Parker AG (2009) Pleistocene climate change in Arabia: developing a framework for hominin dispersal over the last 350 ka. In: Petraglia MD, Rose JI (eds) The evolution of human populations in Arabia: Paleoenvironments, prehistory and genetics. Springer, Dordrecht, pp 39–49
Potts DT (1988) Trans-Arabian routes of the Pre-Islamic period. In: Salles J-F (ed) L'Arabie et ses mers bordières: Itinéraires et voisinages Séminaire de recherche 1985-1986. Presses Universitaires de Lyon, Lyon, pp 126–162
Potts DT (1990) The Arabian gulf in antiquity. Clarendon Press, Oxford
Potts DT (2001) Before the emirates: an archaeological and historical account of developments in the region ca 5000 BC to 676 Abu Dhabi. In: Al Abed I, Hellyer P (eds) The United Arab Emirates: a new perspective. Trident Press, London, pp 28–69
Potts DT (2012) In the land of the emirates: the archaeology and history of the UAE. Trident Press, London
Power TC (2017) Julfar and the ports of northern Oman. In: Al Salimi A, Staples E (eds) The ports of Oman. Georg Olms Verlag, Hildesheim, pp 215–240
Power TC (2018) The role of Indian Ocean trade inland: the Buraimi oasis. In: Fromherz AJ (ed) The Gulf in world history: Arabian, Persian and global connections. Edinburgh University Press, Edinburgh, pp 219–235
Power TC, Sheehan PD (2011) Bayt bin ʿĀtī in the Qaṭṭārah oasis: a prehistoric industrial site and the formation of the oasis landscape of al-ʿAin, UAE. Proc Sem Arab Stud 41:267–282
Power TC, Sheehan PD (2012) The origin and development of the oasis landscape of al-ʿAin (UAE). Proc Semin Arab Stud 42:291–307

Power TC, Al Jahwari NS, Sheehan PD, Strutt KD (2015) First preliminary report on the Buraimi oasis landscape archaeology project. Proc Semin Arab Stud 45:233–252
Power TC, Sheehan PD, al Dhaheri S, Al Hammadi M, al Hammadi K, Al Noaimi A (2016) Al Ain oases mapping project: Qaṭṭārah oasis, past and present. Proc Semin Arab Stud 46:227–236
Power TC, Sheehan PD, Al Mansoori FN, Al Mansoori MS, Al Mansoori MH, Mohammed MN (2017) al-ʿAyn oases mapping project: Jīmī oasis. Proc Semin Arab Stud 47:209–214
Power TC, Borgi F, Degli Esposti M, Hoyland R, Kannouma RH (2022) Archaeological survey of Sīnīya Island. Études et Travaux, Umm al-Quwain
Priestman S (2020) Late Islamic ceramic distribution networks in the Gulf: new evidence from Jazirat al-Hamra in Ras al-Khaimah. Proc Semin Arab Stud 50:293–306
Richter D, Grün E, Joannes-Boyau R, Steele TE, Amani F, Rué M, Fernandes P, Raynal JP, Geraads D, Ben-Ncer A (2017) The age of the hominin fossils from Jebel Irhoud, Morocco, and the origins of the middle stone age. Nature 546:293–296
Rose J (2010) New light on human prehistory in the Arabo-Persian gulf oasis. Curr Anthropol 51: 849–883
Sasaki T, Sasaki H (2019) Ceramics from Khor Fakkan west fort, Oman Gulf Coast in the UAE. Archaeological Bulletin Kanazawa University 40:77–103
Scarre C (2018) The world transformed: from foragers and farmers to states and empires. In: Scarre C (ed) The human past: world prehistory and the development of human societies. Thames & Hudson, London, pp 174–197
Sheehan PD, Power TC, al-Kaabi OS, Khalifa M, al-Dhaheri M, Al-Mansoori B, al-Zaabi L, al-Dhaheri M, al-Mansoori R (2018) al-ʿAyn oases mapping project: Al-Hīlī oasis 2017. Proc Semin Arab Stud 48:327–338
Uerpmann M (2002) The dark millennium – remarks on the final stone age in the emirates and Oman. In: Potts DT, al-Naboodah H, Hellyer P (eds) Archaeology of the United Arab Emirates. Proceedings of the First International Conference on the Archaeology of the UAE. Trident Press, London, pp 74–81
Uerpmann M, Uerpmann HP (2000) Faunal remains of al-Buhais 18, an aceramic neolithic site in the Emirate of Sharjah (SE Arabia) excavations 1995-1998. In: Mashkour M, Choyke AM, Buitenhuis H, Poplin F (eds) Archaeozoology of the near east IVB. Proceedings of the fourth international symposium on the archaeozoology of southwestern Asia and adjacent areas. ARC Publicatie 32, Groningen, pp 40–49
Uerpmann HP, Uerpmann M (2002) The appearance of the domestic camel in south-East Arabia. J Oman Stud 12:235–260
Uerpmann M, Uerpmann HP (2008) Neolithic faunal remains from al-Buhais 18 (Sharjah, UAE). In: Uerpmann M, Uerpmann HP, Jasim SA (eds) The archaeology of Jebel al-Buhais, Sharjah, United Arab Emirates. The natural environment of Jebel Al-Buhais: past and present, vol 2. Kerns, Tübingen, pp 97–132
Uerpmann HP, Potts DT, Uerpmann M (2009) Holocene (re-)occupation of eastern Arabia. In: Petraglia MD, Rose JI (eds) The evolution of human populations in Arabia: paleoenvironments, prehistory and genetics. Springer, Dordrecht, pp 205–214
Velde C (2012) The geographical history of Julfar. In: Potts DT, Hellyer P (eds) Fifty years of emirates archaeology. Motivate Publishing, Dubai, pp 214–221
Von der Driesch A, Brückner H, Obermaier H, Zander A (2008) The hunt for wild dromedaries at the United Arab Emirates coast during the 3rd and 2nd millennia BC camel bones from the excavations at Al Sufouh 2, Dubai, UAE. MOM Éditions 49:487–497
Wahida G, al-Tikriti WY, Beech M, al-Meqbali A (2008) Barakah: a middle Palaeolithic site in Abu Dhabi Emirate. Proc Semin Arab Stud 38:55–64
Wilkinson JC (1964) A sketch of the historical geography of the Trucial Oman down to the beginning of the sixteenth century. Geogr J 130:337–349
Wilkinson JC (1977) Water and tribal settlement in south-East Arabia. Clarendon Press, Oxford
Wilkinson JC (2009) From Liwa to Abu Dhabi. Liwa J Natl Center Doc Res 1:4–11

Zahlan RS (1978) The origins of the United Arab Emirates: a political and social history of the Trucial states. Macmillan, London
Ziolkowski MC, Al Sharqi AS (2008) Fujairah fort and its associated settlement: a study based on historical, archaeological and ethnographic information. In: Hellyer P, Ziolkowski MC (eds) Emirates heritage. Proceedings of the 2nd Annual Symposium on recent archaeological discoveries in the Emirates and of the Symposium on the history of the Emirates Al Ain 2004, vol 2. Zayed Center for Heritage and History, Al Ain, pp 112–132
Zorich Z (2011) New evidence for mankind's earliest migrations. Archaeology 64(9–10):66
Zwemer SM (1902) Three journeys in northern Oman. Geogr J 19:54–64

Chapter 23
Cities as Ecosystems in the Emirates

John A. Burt, Oscar Campbell, and Jacky Judas

23.1 Recent Urban Growth in the Emirates

The total population of the United Arab Emirates (UAE) has grown from less than a 100,000 people in 1960 to just under 10 million by 2021 (Fig. 23.1). The most dramatic growth has occurred quite recently, with the population more than doubling since 2005. Today's population is highly urban, with 88% of residents living in a city. As a result, there has been a dramatic expansion of urbanization across the nation to accommodate growing populations, with the built environment, green spaces, water amenities and other features of our cities serving as habitat for a wide variety of commensal species that benefit from the artificial environments and microclimates that our cities provide.

As populations have expanded, so too has urban sprawl across the Emirates. Most of our urban spaces occur along the coastal fringe (Fig. 23.2), with the cities of Abu Dhabi, Dubai, Sharjah, Umm Al Quwain, Ras Al Khaimah and Fujairah, among others, growing from the much smaller early trading villages that developed in these areas due to their proximity to coastal resources such as fuel (mangroves) and fisheries. The only major exception is Al Ain, which grew from the oases and falaj-associated town that occurred at the base of Jebel Hafit. The dramatic

J. A. Burt (✉)
Center for Interacting Urban Networks (CITIES) and Arabian Center for Climate and Environmental Sciences (ACCESS), New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
e-mail: John.Burt@nyu.edu

O. Campbell
Nautica Environmental Associates LLC, Abu Dhabi, United Arab Emirates

British School Al-Kubairat, Abu Dhabi, United Arab Emirates

J. Judas
Soudah Development, Abha, Kingdom of Saudi Arabia

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_23

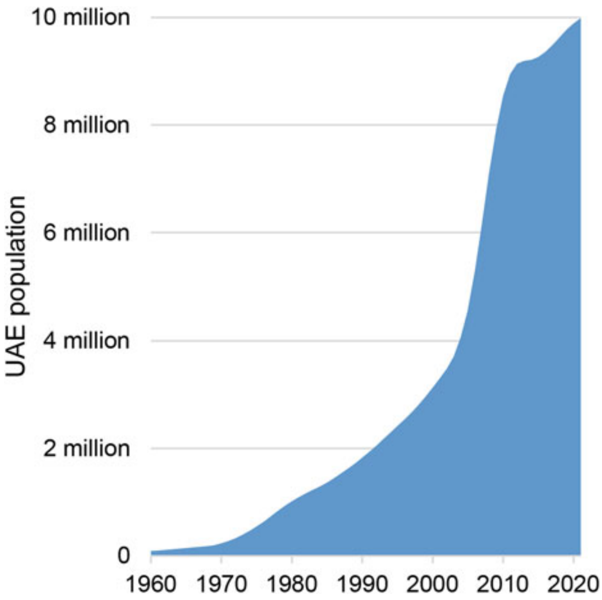


Fig. 23.1 Total population of the United Arab Emirates from 1960 to 2021. Graph data source: Population total, United Arab Emirates by the World Bank (CC BY-4.0)

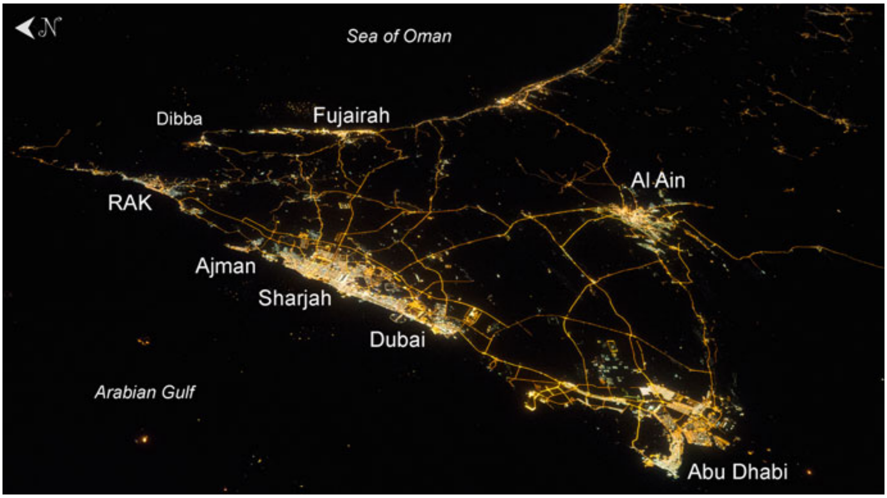


Fig. 23.2 Population growth has resulted in concomitant expansion of urban areas across the UAE, particularly along coastal margins. This image, taken by an astronaut in the International Space Station on 11 Dec. 2013, illustrates the significance of urbanization across the Emirates. Image credit: NASA Photo ID ISS038-E-16335 courtesy of the Earth Science and Remote Sensing Unit, NASA Johnson Space Center, under their conditions of use

expansion of the UAE's cities, often merging laterally into one another along the Arabian Gulf coastline east of Abu Dhabi, and the country's entire Gulf of Oman coastline, has led to urban habitats being the predominant ecosystem along much of

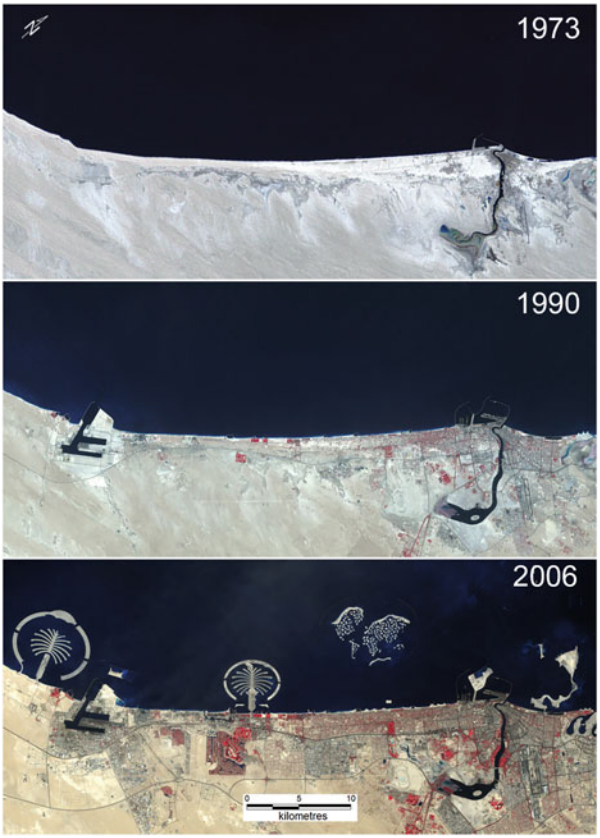


Fig. 23.3 The dramatic development of Dubai since the 1970s exemplifies the urban expansion across coastal fringes and into the sea occurring across the entire United Arab Emirates over the past half-century. Source: Fig. 2 in Burt (2014), reused with permission

the coastal fringe. Inland areas are bisected by vegetation-lined roadways, which in many cases follow traditional seasonal human migration routes, and consequently expand green habitat and act as corridors for the animals, plants and other organisms that have benefited from our presence.

In addition to expansion across terrestrial ecosystems, our cities have also expanded into the sea. Human-built infrastructure now dominates the seascapes of coastal cities, including structures such as seawalls, breakwaters, and piers, along with submarine pipelines and cables. Added to this are the semi-natural channels, beaches and intertidal areas created by coastal reclamation for real estate development (e.g. the 'fronds' of the Palm Jumeirah, among many others). While generally unrecognized by the public, such marine urban habitat occurs in incredible abundance. In the city of Dubai alone, over 200 km of artificial coastline has been created by dredging, with over 65 km of rocky breakwaters added for its protection, more than doubling the 90 km of natural coastline that had occurred here in the late 1990s (Fig. 23.3) (Burt et al. 2009b, 2012). While Dubai may be an extreme case, it is not an outlier; extensive addition of coastal infrastructure has occurred across much of the Emirates' coastline. Offshore, the Arabian Gulf hosts over 2000 oil wellhead platforms that are connected by a network of thousands of kilometers of subsea pipelines (Stachowitsch et al. 2002). All of this infrastructure is rapidly colonized by marine organisms shortly after construction, and can develop highly diverse and abundant marine communities in just a few years as marine organisms co-opt our urban infrastructure into becoming large-scale artificial reefs (Burt et al. 2011, 2012; but see Sect. 23.2 below).

Thus, UAE cities provide novel, varied and very recent ecosystems for organisms to exploit. While many species occurring in cities have reached them naturally, deliberate introductions and accidental escapes of non-native species—a phenomenon relatively frequent in urban areas globally but particularly marked in the cities of the Arabian Peninsula—have created unique assemblages of species in our urban areas. In addition to resident species, urban ecosystems also support transient species, particularly migratory birds and even marine animals such as the Whale Shark (*Rhincodon typus*), that stop off to feed and rest in urban marine habitats while *en route* to other parts of the world. Population densities of particularly successful urban species may be many times greater than those found naturally in the surrounding desert, despite many difficulties inherent in adapting to city life. These include direct dangers posed by traffic and predators such as feral cats, excessive noise and light pollution, and temperatures and humidity that often surpass those of adjacent natural habitats. Cities as ecosystems are also important as the only places where a large proportion of the human population regularly comes into contact with the natural world, where bold and conspicuous organisms may regularly come to one's attention in a manner that is exceptional in natural habitats of the UAE. These may be anything from the Purple Sunbird (*Cinnyris asiaticus*) that squabble over flowering tobacco (*Nicotiana* sp.) plants on a balcony or weave an intricate hanging nest under roof eaves, to the Red Fox (*Vulpes vulpes*) or the Gazelle (*Gazella arabica*; Fig. 23.4) that are surprisingly tame on local golf courses. This chapter will showcase the cities of the UAE as ecosystems and discuss the challenges posed, opportunities provided, and the organisms that have taken advantage and thrived.

23.2 Cities Are Not Surrogates for Natural Ecosystems

Urban expansion, of course, has not occurred without environmental challenges. Much of the fragile and unique coastal dune habitat of the UAE's Arabian Gulf coast has now disappeared under our cities, threatening unique vegetation assemblages that occur only in these specific soil types (e.g. Panic Grass, *Panicum turgidum*), as well as associated habitat-specific biota (e.g. the critically endangered Wonder Gecko, *Teratoscincus keyserlingii*, Fig. 23.5) (see Chap. 5). Similarly, the east coast is now almost wholly dominated by urban sprawl, with natural habitat such as the now protected mangroves of Khor Kalba very much an exception. Specialist mammals reliant on particularly patchy resources, such as dugongs (*Dugong dugong*) and green turtles (*Chelonia mydas*) living in seagrass meadows, and large populations of breeding seabirds such as terns that are reliant on a small number of

Fig. 23.4 Arabian Mountain Gazelle (*Gazella arabica*), part of herd that are well-established at a large golf course complex on the outskirts of Abu Dhabi. Photo credit: Oscar Campbell

Fig. 23.5 While urbanization can have ecological benefits, it also has costs. Urban expansion across the coastal dune systems of eastern Abu Dhabi and western Dubai have heavily impacted highly localized Panic Grass (*Panicum turgidum*) habitats, which are home to the critically endangered Wonder Gecko (*Teratoscincus keyserlingii*). Image credit: Andrew Gardner

relatively undisturbed islands for nesting areas, are also negatively impacted by such development. Impacts can be direct or secondary, for example by increases in leisure activities such as boating, fishing and even by increased disturbance by beach visits from nearby urban populations, which represent a continuing and growing threat to turtle nests on UAE beaches (Whelan et al. 2019; Adhavan 2020). Our cities have also introduced light, noise and chemical pollution, disrupted hydrological cycles, favored the spread of non-native species, including feral predators such as cats and rats, and fragmented natural breeding populations, among other pressures. Our impacts in the sea have been equally destructive, if less visible. Coastal dredging and reclamation have resulted in incredible loss and degradation of some of the most biodiverse and productive ecosystems in the Emirates and the generation of new habitat by such processes in no way compensates for this. Further, sewage treatment, desalination and other industrial facilities continuously discharge into the shallow nearshore environments (Burt 2014; Le Quesne et al. 2021). As a whole, cities support a subset of 'urban adaptable' species, while suburban areas tend to favor species with life traits such as successional pioneer species or 'edge' specialists (McKinney 2006), all of which differ markedly from natural communities. Thankfully, in many cases some of the more destructive invasive species that have spread through UAE cities occur as urban specialists that seem unable to survive the extreme climate conditions prevailing in natural environments of the UAE. One example is the House Crow (*Corvus splendens*), a native of south Asia, which has remained a strictly coastal species in the UAE and is almost unknown both inland and from areas west of the Abu Dhabi capital. It does, however, readily travel to barren inshore islands that it would otherwise avoid to predate the eggs of nesting terns, and appears annually in spring in urban parks to seek out left-over food and the eggs and young of smaller birds such as doves, bulbuls and mynas.

While these issues should not be discounted in their importance, at the same time our growing cities have developed unique ecologies of their own, much of which remains underappreciated and understudied in the Emirates. In a climate as harsh as the UAE's, for many species our urban habitats provide a refuge in which access to water, shade, unique microhabitats, and food resources allows populations to persist at far higher abundance than they could occur in natural habitats. Urban habitats have also resulted in the rapid development of interesting and indeed unique assemblages of species.

23.3 Cities as Amenable Environments for Organisms

Elsewhere in the world, cities are typically considered 'urban heat islands' as a result of the preponderance of radiative heating from glass, concrete, steel and related materials, waste heat from air conditioners and vehicle engines, and low evaporative cooling potential due to the dominance by impervious surfaces (Heisler and Brazel 2010). However, in arid areas the built environment can create a setting that favors far more benign conditions than in the surrounding desert.

The tall, vertical shapes of buildings, particularly around downtown cores and high-density areas, create conditions that favor wind funneling and shading that may be of benefit for urban-dwelling organisms (so called 'street-canyons'; Pearlmutter et al. 1999), particularly during summer, and related design features are being

Fig. 23.6 Undeveloped land plots in desert cities can develop high-density plant assemblages. Here, *Calotropis procera*, *Heliotropium kotschyi* and *Zygophyllum qatarense* near the Sheikh Zayed road in Dubai. Such plants, being native to the UAE, likely also support diverse assemblages of invertebrates. Image credit: Gary Brown

actively incorporated into urban planning in the UAE for enhanced human comfort (Al-Sallal et al. 2001). Even in the absence of shading effects, buildings can reduce wind shear stress in their lee, and studies on desert plants have shown enhanced growth (in terms of height and biomass) compared with plants growing in exposed natural desert habitats (Bang et al. 2010). The stronger winds produced between buildings and the impervious surfaces of surrounding roadways can also act to enhance long-distance dispersal of seeds (Kowarik and von der Lippe 2011). In contrast, in areas that are dominated by impervious surfaces where bare soil is rare, adaptations can develop to enhance non-dispersal so that seeds remain on or near the soil patches where they originate, ensuring continuation of these urban populations and maintaining their diversity on vacant lots through time (Cheptou et al. 2008; Johnson et al. 2018). Thus, undeveloped plots in cities can represent important hotspots for vegetation growth (Fig. 23.6). The dynamic wind environment around buildings is also advantageously used by birds, who use building-induced updrafts and wind gradients to reduce energy expenditure during flight in urban settings (Shepard et al. 2016).

Planted vegetation is an important feature of desert cities, which has been repeatedly shown to reduce urban temperatures relative to the surrounding arid environment because the evaporative cooling from plant transpiration causes temperatures within cities to be substantially lower than in surrounding landscapes (Lazzarini et al. 2014, 2015; Hall et al. 2016; Al-Ruzouq et al. 2022), including in

Fig. 23.7 Tree plantations around urban areas can reduce understory temperatures through shading. Here, Socotra Cormorants preferentially nest in the shade of planted *Acacia* trees in Umm Al Quwain, where hatching success is substantially higher than in the open. Image credit: Sabir Muzaffar

the UAE (Frey et al. 2007; Issa and Saleous 2014; Mirou et al. 2022). At smaller scales, the presence of xerophilic (desert-adapted) trees can reduce temperatures at micro- to local-scales through shading (Wolf et al. 1996; Chow and Brazel 2012), allowing for distinctly cooler microenvironments for more mobile species to utilize. In the UAE such shading has been shown to provide a distinct advantage, where the Socotra Cormorant (*Phalacrocorax nigrogularis*) preferentially nest in the shade of planted trees (Fig. 23.7), and their offspring have significantly higher hatching success than those in unshaded areas (Muzaffar et al. 2012). Such shade-seeking is a common behavioral strategy used by a wide variety of arid-adapted animals to reduce thermal stress (Hetem et al. 2012; Newbold and MacMahon 2014; Roberts et al. 2016).

Urban water sources are also a critical feature that allows persistence of animals in desert cities. Access to urban water sources not only permits survival in an environment where freshwater is scarce to nonexistent, but also supports the greatly magnified water demand needed for evaporative cooling during the peak summer months (Riddell et al. 2019), and can reduce the metabolic costs of digestion compared to desert populations that do not have supplemental water available (Shochat et al. 2004).

Similar to terrestrial systems, the urbanization of marine systems can also provide opportunities for aquatic species. Coastal cities around the UAE are surrounded by relatively featureless bottoms comprised of sand and mud. By constructing submerged habitats made of rock, concrete and related materials, humans have dramatically increased the amount of hard-bottom habitat around coastal cities. This can have important implications for biodiversity, as many marine organisms are incapable of colonizing and growing on soft or mobile substrates. In Dubai, for example,

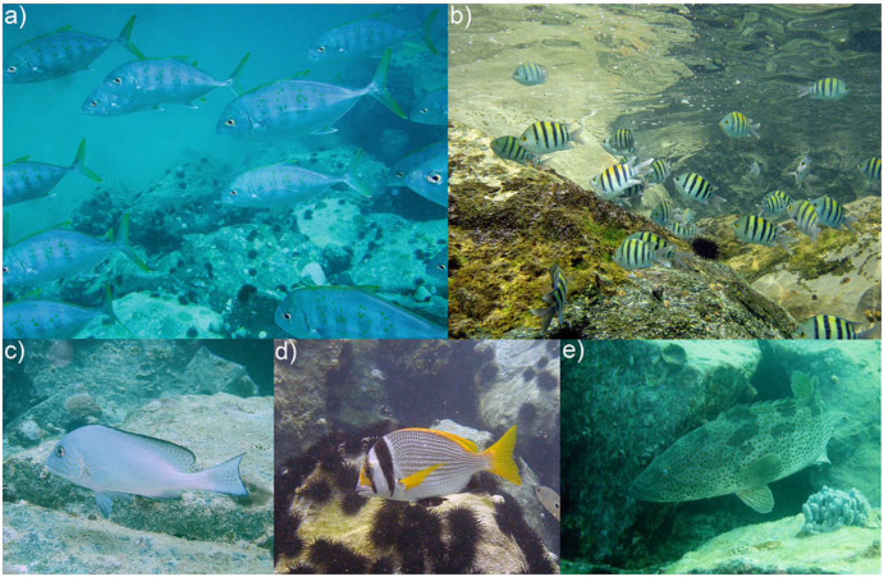


Fig. 23.8 Rocky breakwaters surrounding UAE coastal cities serve as an important habitat for fishes, many of which are attracted to the complex, three-dimensional structures, including (**a**) jacks (*Carangoides bajad*), (**b**) sergeant majors (*Abudefduf vaigiensis*), (**c**) painted sweetlips (*Diagramma pictum*), (**d**) two-bar seabream (*Acanthopagrus bifasciatus*), and (**e**) hammour (*Epinephelus coioides*). Photo credits: John Burt

where less than 10 km^2 of natural hard-bottom reef habitat occurred historically, over 65 linear kilometers of rocky substrates have been added in the form of defensive breakwaters (Burt et al. 2012), dramatically increasing the total available area that could be colonized by organisms such as corals, sponges, oysters and other fauna that are reliant on access to hard-bottom to growth. In addition, these structures provide a complex, three-dimensional habitat that is highly attractive to fishes (Fig. 23.8), providing shelter, foraging areas and spawning grounds in an environment that is largely flat, two-dimensional sand bottom (Burt et al. 2013). Such structures can also strongly affect the currents travelling along the coast, resulting in entrainment (i.e. pooling) and enhanced colonization by marine larvae that would most likely have been lost to offshore currents and predation had these structures not been in place (Burt et al. 2009a). Thus, marine infrastructure can play an important, although largely underappreciated, role in supporting biodiversity in the UAE (but see Burt (2014) for a discussion of the environmental costs of coastal development).

23.3.1 Urban Green Spaces

Urban green spaces such as parks, private gardens, sports facilities and urban woodlands provide access to water, shade, complex three-dimensional microhabitats and food resources in desert cities, housing highly concentrated areas of biodiversity and interactive food webs in an arid environment typically supporting far fewer species. These green spaces are dense and highly productive due to water and nutrient enrichment, allowing the plants in these habitats to support far more extensive food webs than would be possible in less productive vegetation communities outside of cities. In addition to the introduced amenity plants that are typically included in these areas, urban green spaces can also act as refugia for native species. For example, Dubai's Mushrif Park and the Mushrif Palace Gardens of Abu Dhabi act as *de facto* protected areas for woodlands of native ghaf (*Prosopis cinerea*) trees which can grow to their natural stature in the absence of the intense camel grazing that heavily impacts populations located outside of cities. Constructed ex-urban green spaces such as forestry and, particularly, agricultural areas, may be particularly significant for biodiversity in arid landscapes but are beyond the scope of this chapter (but see Chap. 15 for discussion of their importance more broadly).

In general, the floral composition of UAE cities is largely composed of non-native introduced species that create a completely new ecosystem, which is then colonized by a mix of native and non-native animal species. The proportion of non-native species is relatively high and the end-result is the formation of a completely distinct community. For example, of the 18 species of butterflies that occur in UAE urban areas, five (28%) are non-native (Feulner et al. 2021), while out of 36 regularly breeding bird species typical of urban areas, 14 (39%) are non-native (Pedersen et al. 2021). The prevalence of non-native organisms in urban areas in the UAE is in part due to supply, as humans have continuously introduced plants and animals to cities purposely (e.g. ornamental plants) and accidentally (e.g. domesticated cats that have gone feral), but also because of the environmental suitability of cities. The vast majority of non-native species are simply unable to survive in the arid, thermally hostile natural environment of the UAE (a factor labeled 'environmental resistance' in invasion ecology; Lovell et al. 2021), and therefore non-native species tend to concentrate in and expand throughout the more benign urban habitats that can support them. The reason many UAE native species have not proliferated to the same extent is likely down to their biology and interactions with other species. Most invasive non-native species are typically characterized by rapidly-reproducing, highly dispersive, generalist lifestyles that are highly amenable to urban settings (Kolar and Lodge 2001), while many native species may have far more restrictive habitat needs, lifestyles that limit their success in urban settings, and/or slower reproduction rates. In addition, species interactions likely also play a role. Invasive common mynas (*Acridotheres tristis*), house crows, rats and other commensal animals occur in urban environments in exceptional densities. Such species are generally highly aggressive and may out-compete and, in some cases, directly predate the eggs and young of other species; such characteristics are unusual in

Fig. 23.9 The Verdant Ghaf (*Prosopis cinerea;* foreground) and the Toothbrush Tree, *Salvadora persica*; background) with lush growth in the absence of grazing in Abu Dhabi. Photo credit: Oscar Campbell

most native fauna, which ordinarily occur at much lower population densities in any case. Similarly, non-native plants likely 'crowd out' native species that may disperse seeds into urban green spaces, and the liberal use of herbicides and 'weeding' in managed greenspaces likely exacerbates issues for native plants establishing in these areas.

In urban parks native trees such as the delicately leaved, sweeping Ghaf are increasingly regarded as both culturally and environmentally significant and are widely planted. The Sidr Tree (*Ziziphus spina-christii*) is another native species that supports high biodiversity. For example, four species of native butterflies use one or the other as food-plants (Feulner et al. 2021). Such trees, although often planted at densities far beyond what is normal in natural environments in the UAE and causing a shaded and often very dry ground layer beneath, may often reach an older age, greater stature and much more luxuriant growth form than they are able to in wider countryside (Fig. 23.9). Again, this is attributable to the absence of severe grazing pressure that blights much of the UAE desert, although the inevitable over-zealous weeding, pruning and 'tidying' by the local municipalities generally has essentially the same effect. Another issue is over-watering, discouraging the formation of deep tap-roots; this may account for the overly severe damage suffered by many urban trees during the high winds encountered during occasional storms.

Thanks to the deliberate intervention of humans, soils are much richer and better developed in urban areas than virtually anywhere else in the UAE, and parameters such as humus (the organic component of soil) and nutrient content are much higher (Abdelfattah 2009; Abdelfattah et al. 2009). Such soils, and the non-native plants that are then grown in them, are responsible for the accidental introduction and subsequent establishment of many alien species and microbial pathogens into the UAE (Elsheikh et al. 2021). For example, the Soldier Orchid (*Zeuxine strateumatica*), a species native to south and east Asia, is believed to have reached the UAE (and many other parts of the world) thanks to importation of grass seed (Aspinall 2006). Populations of the Cycad Cupid (*Chilades pandava*), a small blue butterfly discovered in the UAE for the first time in Dubai in 2014, are completely restricted to association with the ornamental cycad *Cycas revolute* (Feulner et al. 2014). This invasive butterfly, native to south and southeast Asia has now reached Korea, Japan, Egypt and various islands in the Pacific and Indian Oceans, and is a severe pest of native cycads in many regions, although—as there are no such native cycads in Arabia—the butterfly's persistence in the UAE is certainly reliant on horticulture. Similarly, widespread plantings of Mexican Petunia (*Ruellia simplex*), now a very common flowerbed shrub, have led to the establishment over a wide area of another butterfly, the Tiny Grass Blue (*Zizula hylax*; Feulner et al. 2021). Since its discovery in Dubai in 2016, it had broadened its distribution to Abu Dhabi, Al Ain and even Jebel Dhanna in the far west of the Emirates by 2021.

23.3.2 Urban Water Sources

As described earlier, water features are an important aspect of urban environments that help support biodiversity in desert cities. Fountains and related amenities are the most common freshwater sources in downtown cores, while swimming pools pepper the suburban landscape in areas where villas dominate, and these are widely used as drinking water sources by birds, feral mammals such as cats, and lizards. Often urban and suburban settings will also have small standing-water pools around leaking irrigation pipes, and these soon attract patrolling Slender Skimmers (*Orthetrum sabina* Fig. 23.10), one of the UAE's commonest dragonflies and particularly tolerant of ephemeral and poor quality water. Birds often appreciate even the smallest drip in areas where water sources are uncommon, with Common Chiffchaffs (*Phylloscopus collybita* Fig. 23.11), a small over-wintering warbler particularly partial to such areas. Other standing water areas are 'lake' amenities in planned communities, which are most typically comprised of treated water from community sewage treatment plants and are typically brackish and nutrient-rich, supporting little other than algae. Aside from these planned and managed water features, unplanned ponds often develop where over-irrigation occurs in areas with shallow water tables. These often develop dense reed beds (mainly *Phragmites*) that can provide habitat for associated avifauna, although the water is typically brackish to saline and low in aquatic faunal diversity.

Fig. 23.10 Slender Skimmer (*Orthetrum sabina*), a common UAE dragonfly that is quick to appear at even ephemeral puddles. Photo credit: Oscar Campbell

Fig. 23.11 Common Chiffchaff (*Phylloscopus collybita*) attending a puddle created by a leaking irrigation pipe. Photo credit: Oscar Campbell

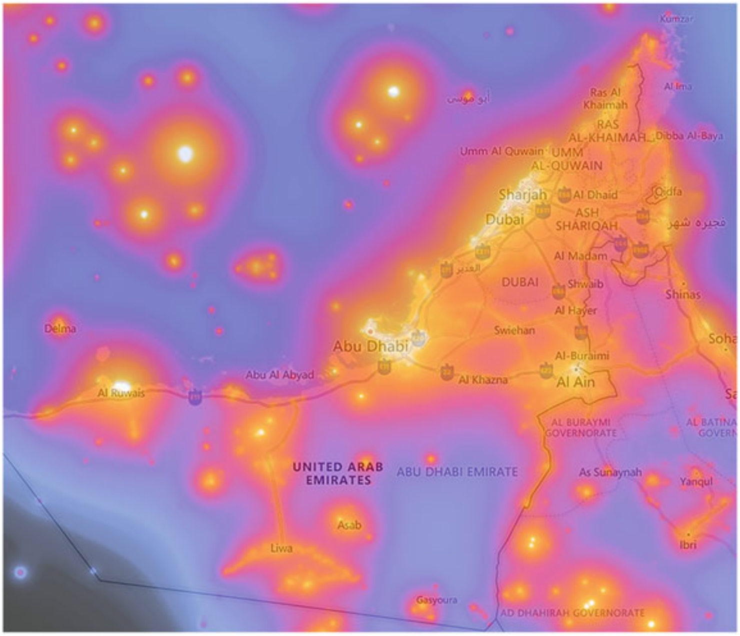


Fig. 23.12 Artificial light brightness in the UAE in 2015. Source: Data derived from Supplementary Data in Falchi et al. (2016) and shared under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC).

Box 23.1 The City That Never Sleeps: Urban Animals at Night

Artificial illumination is a defining phenomenon of urban development. In developed countries only the most remote areas are genuinely free of light pollution and the UAE is amongst the top twenty countries globally for artificial illumination, the extent of which is still increasing (Figs. 23.2 and 23.12) (Falchi et al. 2016). Such artificial light has profound implications for many organisms, particularly those that are nocturnally active.

Various species of marine turtles occur in the UAE, several of which utilize beaches to nest. Turtles hatchlings will typically use the ocean horizon, the brightest portion of the night sky in areas without light pollution, to orient after hatching so that they can reach the sea. As such, artificial lights adjacent to beaches have been implicated in disorienting hatchling migrations for nesting Olive Ridley turtles (*Lepidochelys olivacea*) on the UAE's east coast (Yaghmour and Rodríguez-Zárate 2021), and light pollution management is being promoted for Hawksbill turtle (*Eretmochelys imbricata*) nesting sites on Arabian Gulf beaches (Grichting 2020).

(continued)

Box 23.1 (continued)

Bats in urban environment are also particularly impacted by the development of artificial lights at night. Illumination changes their flight pattern and reduces their foraging activity, which suggests that lighting strongly reduces habitat availability and likely connectivity (Barré et al. 2021). Not all bat species are impacted in the same way, and some species show light tolerance, potentially shifting community composition (Seewagen and Adams 2021). Moreover, light can affect caterpillars' development, reducing their abundance (Boyes et al. 2021), and as such prey availability for bats.

Light does not always have negative impacts, and can be used by visual species to expand their foraging opportunities. The effects of artificial illumination on birds has been relatively well-studied compared to many taxa, although work has concentrated on behavioral rather than physiological effects (Dominoni 2015). In the UAE, several shorebirds, including the locally common, breeding Black-winged Stilt (*Himantopus himantopus*) and Kentish Plover (*Charadrius alexandrinus*) regularly feed nocturnally on illuminated grasslands such as golf courses and even central reservations along busy city roads. Shorebirds, whose foraging cycles are generally tidal-dependent frequently feed nocturnally in natural intertidal habitats, but these species rarely use such urban grasslands diurnally. It is not clear if such habitats are favored at night due to reduced disturbance from people (or aggressive diurnal species such as House Crows) or if prey is more readily found at night. These two species are resident in the UAE but artificial light is known to have a direct and highly adverse impact on migratory birds (see Sect. 23.4).

23.4 An Overview of the Avifauna of Urban Areas

Green areas in cities, mainly parks, roadside verges and small plantations (sometimes comprising indigenous trees such as Ghaf but also gardens and golf courses hold very high densities of commensal bird species such as doves, bulbuls and House Sparrows (*Passer domesticus*). Non-natives such as bulbuls and parakeets are disproportionally well-represented in the avifauna urban areas throughout Arabia, with particular concentrations in the Abu Dhabi and Dubai (Jennings 2010) and both those and species with capacity to arrive independently (e.g. doves) have spread greatly with the general greening of the urban environment. Such areas provide oases of moisture and shade, often with abundant food. A number of species formerly restricted to montane areas or their environs, having reached urban areas under their own steam, have now adapted to city ecosystems and are as easy to find there as in their original natural habitats. These include Green Bee-eater (*Merops orientalis*) which relies on shallow banks of sand piles, readily found on construction sites, to excavate nesting holes and Indian Silverbill (*Lonchura malabarica*), a granivorous small finch that has adapted to forage on ornamental grasses such as *Pennisetum*.

Fig. 23.13 Recently fledged juvenile Pale Crag Martins (*Ptyonoprogne obsoleta*). This species readily uses urban ledges as a substitute for traditional cliff nesting sites. Photo credit: Oscar Campbell

Pale Crag Martin (*Ptyonoprogne obsoleta*; Fig. 23.13), the UAE's only regular breeding swallow, is now as at home nesting on buildings and under bridges as on rocky cliffs whilst Common Kestrels (*Falco tinnuculus*) and Pallid Swifts (*Apus pallidus*) have equally accepted large buildings as a suitable substitute for sea cliffs. The latter is a highly aerial species that lands only to nest, otherwise spending all its' life on the wing. With a winter breeding season, they are present in the UAE from mid-autumn to late spring and the screaming hordes formed as they gather shortly before dusk make a wonderfully evocative spectacle over favored sites such as Dubai Museum. Their whereabouts from May to September remain a mystery. Figure 23.14 depicts four species that have benefit from new food sources and/or in urban ecosytems of the UAE. Several species (e.g. Eurasian Hoopoe *Upupa epops* and Indian Roller *Coracias benghalensis*) are common and conspicuous breeders in urban parks of the northern Emirates but extremely uncommon breeders on Abu Dhabi island and absent further west. Being mainly resident, the roller may still be in the process of very slowly spreading southwards but this is not true in the case of Eurasian Hoopoe, large numbers of which migrate through the entire country in spring and autumn. Instead, its general absence from seemingly suitable habitats in the western UAE may reflect subtle climatic variation. Increases in range and population are still on-going and may occur surprisingly suddenly. The most outstanding recent example is Northern Shikra (*Accipiter badius*), a small woodland-dwelling hawk first discovered in Dubai in 1996 and which soon became well-established there (Campbell 2018). However, it remained unknown away from the Greater Dubai area until 2013, since when it has spread spectacularly, with 498 records from 31 sites in 2019 alone (Campbell et al. 2022). Most of these sites are urban and include records from the entire span of the Arabian Gulf coastline from Sila'a on the Saudi border to the east coast and Al-Ain areas. The ultimate origins of the original Northern Shikra found in the UAE are subject to speculation (Campbell 2018), although no such doubt is associated with the Crested Honey-Buzzard (*Pernis ptilorhynchus*), a much larger raptorial species that breeds in south and east Asia and has steadily increased its numbers as a migrant and winter visitor to Arabia as a whole and the UAE in particular since the first record in 1992

Fig. 23.14 Four species that have adapted well to urban environments in the UAE. Clockwise from top left, Pallid Swift (*Apus pallidus*), Crested Honey-Buzzard (*Pernis ptilorhynchus*), Northern Shikra (*Accipiter badius*), at nest in a Eucalyptus tree in urban Abu Dhabi and Indian Silverbill (*Lonchura malabarica*). Photo credits: Oscar Campbell

(Babbington and Campbell 2016). A similar change of this species' status in southern Israel has been linked to the spread of the introduced Dwarf Honey Bee (*Apis florea*) (Olsson et al. 2022), although the bee is native to the UAE, while the European Honey Bee (*Apis mellifera*) has flourished in urban areas in the UAE after its introduction for honey production. However not all species who rely on urban green areas in the UAE show a positive population trend. Eastern Olivaceous Warbler (*Iduna pallida*) is small, dull plumaged but vocal songbird that breeds in mature, shady plantations dominated by Ghaf trees on Abu Dhabi island only, where there is a small, dwindling resident population. It is otherwise very rare as an Arabian breeder (Jennings 2010) but occurs commonly as a migrant, as it breeds in central Asia and winters in tropical East Africa. Other species use urban areas to spend the winter, with, for example, dapper White Wagtails (*Motacilla alba*) arriving from early October onwards to any areas of grassland, especially if damp. Some winter visitors are even more conspicuous; Cattle Egrets (*Bubulcus ibis*) frequent central reservations and roundabouts and are regularly seen, and commented on, by the members of the general public as they wait at traffic lights. What is less appreciated is that these birds make daily flights to and from areas of mangroves where they roost in flocks of 50 or more (often using the same tree for many years) but additionally, in April, withdraw northwards to breed, presumably in Iran and southern Asia, before returning in September.

Finally, green areas in cities regularly provide life support, in the form of shade, water and food for many species of small migrant songbirds that battle through Arabia twice a year on migratory journeys spanning thousands of kilometers (see Chap. 15). Although representing a very small proportion of an urban site's avian diversity or biomass at given time, these migrants greatly increase species diversity for a site as a whole; of the ten sites with the most diverse species lists in the UAE, three are wholly urban (eBird 2022). Migrations of the species involved are conducted mainly at night and it is likely that the now widespread and intense illumination of the UAE frequently causes disorientation and death of many migrants. This issue has come under increasing scrutiny elsewhere in the world (e.g. Loss et al. 2014) but is barely acknowledged as an issue, let alone studied, in Arabia. This is despite the region's pre-eminence as a global stepping-stone for migratory birds.

23.5 Mammals in our Cities

Relatively few native mammal species have adapted to live in the urban environments of UAE. Most of these species are human-shy, highly adapted to live in arid habitats, and do not find favorable environmental conditions in our towns and cities. There are, however, a few exceptions, where species have found their way into the cities and—in some cases—even greatly benefited from urban habitats.

The Red Fox (*Vulpes vulpes*), a medium-size predator, is one of these native species that has adapted well to urban environments due to its dietary and behavioral plasticity. Worldwide, this widespread commensal species has colonized cities, finding food and shelter in parks and gardens, and reaching higher population densities than in its natural habitat. Mainly active at night, it is not rare to see them at dusk or dawn in the suburbs of all main UAE cities (Fig. 23.15), where they catch small animals or feed on food waste. The Ethiopian Hedgehog (*Paraechinus aethiopicus*), an insectivorous species that is widespread on the Arabian Peninsula and north of the Sahara in Africa, also frequents the parks and gardens of our cities. This species appears tolerant of habitat modification to a certain degree, and even in its natural habitat, generally prefers areas where food is more easily available, such as oasis and well-vegetated wadis. Green urban areas with enriched soils and an abundance of insects offer a good substitute to the often degraded natural habitats of the UAE. Al Ain, which has been occupied by human populations for several millennia and has extended its oases thanks to an ingenious underground irrigation system (*falaj*), has kept agricultural activities embedded in its urban development. This provides suitable conditions for Hedgehogs and other mammals, like bats.

Fig. 23.15 The Red Fox (*Vulpes vulpes*) is commonly observed in UAE cities. Image credit: Fouad Itani

The underground falaj system of Al Ain—Buraimi was known in the 1950s to shelter large populations of Trident Leaf-nosed Bat (*Asellia tridens*) and Persian Trident Bat (*Triaenops persicus*) (Harrison and Bates 1991), and these species may have occurred there for centuries. Although their populations have substantially decreased in recent years, both species are still present in the remains of falaj system, which were abandoned after they became dry in the past two decades due to the declining underground water table. Bats can often travel dozens of kilometers in one night between their roosting sites and foraging areas. Cities located in the vicinity of mountainous habitats, like Fujairah—half-surrounded by the Hajar Mountains—or Al Ain—at the foot of Jebel Hafit—attract more species of bats than the towns of the Arabian Gulf coast. The Muscat Mouse-tailed Bat (*Rhinopoma muscatellum*) often roosts in small caves or old buildings, and forage at night in the orchards and above the open green fields of Al Ain, Dibba and Fujairah (Judas et al. 2018). This is also the case of the Egyptian Fruit Bat (*Rousettus aegyptiacus*), that spends the day either in montane caves or in trees, and emerges to forage at night over city orchards or gardens. They also regularly drink water from urban artificial ponds and private swimming pools. The most common bat species in UAE cities is the ubiquitous Kuhl's Pipistrelle (*Pipistrellus kuhlii*). This small bat, widespread around the Mediterranean basin in Arabia and West Asia, is encountered in all major towns where it roosts in colonies, sometimes of few hundred individuals. Tiny holes under the roof of buildings in well-vegetated compounds provide access to their roosts in the vicinity of foraging areas. Urban residents who may come across a colony in their home are often scared by their presence, more from lack of knowledge than any genuine threats. These animals are completely inoffensive, and are actually helping by predating on moths, mosquitoes or other pest insects. The Naked-rumped Tomb

Fig. 23.16 Common Kestrel (*Falco tinnuculus*) with recently caught Brown Rat (*Rattus norvegicus*). Photo credit: Oscar Campbell

Bat (*Taphozous nudiventris*), who lives in rocky areas of the Emirates, is sometimes observed in old or under-construction buildings, but these are probably only temporary visitors from nearby natural habitats, than real urban inhabitants.

Native rodents, like the Arabian Spiny-mouse (*Acomys dimidiatus*), gerbils (*Gerbillus spp.*) and jirds (*Meriones spp.*) also prefer natural habitats to urban environments, and only venture to the edges of towns. During the strict quarantine period enforced at the beginning of the Covid-19 pandemic, cities became exceptionally quiet with virtually no traffic. Testimonies of wildlife entering cities came from all over the world. This also occurred in Dubai, where Sand Gazelles (*Gazella marica*) were seen walking peacefully on the highways in urbanized areas, showing that wildlife is never far and ready to quickly reconquer its lost habitats.

Beside the few native mammals that frequent UAE cities, four introduced non-native rodents are also ubiquitous in UAE urban environments. Mice (*Mus musculus*), the Brown Rat (*Rattus norvegicus*) and the Black Rat (*Rattus rattus*) are widespread species that often become pests, entering buildings and causing damage to food stores. These very adaptable species have followed human expansion for millennia and now provide food for predators that can also adapt to cities (Fig. 23.16). Urban domestic cats, feral cats and dogs are also very common in all UAE cities, and can have a high cost for urban wildlife, as documented in South Africa (Seymour et al. 2020). Feral dogs (*Canis familiaris*) live, forage and occasionally hunt in packs in parks, suburbs and landfills, often subsisting on food offerings from residents. Feral or domestic cats (*Felis catus*) are solitary animals that have retained the predatory hunting instinct of their ancestors, causing negative impacts on small urban fauna like reptiles, rodents, bats and birds. Feral Donkeys

(*Equus asinus*), which lives mainly in the Hajar mountains, regularly venture in the suburbs of the east coast cities of Fujairah, Khor Fakkan, Kalba or Dibba. The Northern Palm Squirrel (*Funambulus pennantii*) has been introduced in UAE, first being noticed in agricultural areas of Ras-Al-Khaimah and Fujairah town in 2011 (Judas and Hellyer 2016). Since then, this very adaptable generalist species has invaded many urban parks across all UAE cities as well as agricultural areas. They do not appear to venture into natural habitats, suggesting that they will remain urban specialists in the UAE.

Cities comprise a complex assortment of habitat types, and we still know relatively little about the effects of their composition and spatial configuration on species distribution, and how these species respond to urbanization. Even species considered relatively common and well adapted to the urban landscape like *Pipistrellus* spp. may respond negatively to the built environment (Lintott et al. 2016). Mammals are exposed to multiple threats, noise, lights, sound and air pollution, as well as habitat changes (Finch et al. 2020), that may impact their feeding success. Effects of anthropogenic noise has deleterious effects on the foraging ecology of many animals, including bats (Song et al. 2020), although their effects can vary between species and situations. Noise can mask echolocation calls—due to frequency overlap—or create noise avoidance. In some cases, traffic noise has been shown to increase food intake of roosting bats, presumably as a response to stress and can induce metabolic dysregulation, immune disorders and disease. On the other hand, another study showed that noise affected bat activity and feeding behavior with a decrease of food intake in the proximity of the noise sources (Finch et al. 2020). Light at night can also affect foraging activities of nocturnal species. Since some species are more light tolerant than others, this can lead to shifts in community composition (Seewagen and Adams 2021). Road traffic also has an important toll on mammals, increasing road-kills in urban areas.

23.6 Cities Underwater: Importance of Submerged Infrastructure

Although knowledge of urban marine ecology in the Emirates remains underdeveloped, a series of research studies performed in the late 2000s, focused mainly on the coastal infrastructure of Dubai, has shed light on some general patterns. A study of large-scale rocky breakwaters across the emirate showed that they were rapidly colonized by corals (within two years) and that the coverage of the submerged rocks by coral grew relatively consistently over time (Fig. 23.17), such that by the time a breakwater was 20 years old it would typically have higher coverage by coral than is seen on natural coral reefs (Fig. 23.18), largely because these rocky breakwaters were elevated above the mobile sands that surround the low-lying reefs of Dubai (Burt et al. 2011). Fishes, because they are mobile, colonize these structures even more quickly from the surrounding environment. Surveys on the-then five year

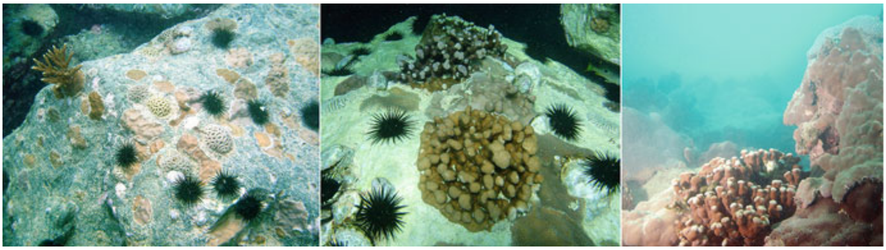


Fig. 23.17 Rocky breakwaters are constructed to provide coastal defense for ports and marinas, but they also act as unintended artificial reefs. Juvenile corals colonize these structures within 1–2 years of construction (left) and grow laterally, developing three-dimensional complexity within 5 years (middle); they can eventually encrust most of the rocky substrate on decade or older breakwaters (right) if water quality conditions are favorable. Photo credits: John Burt

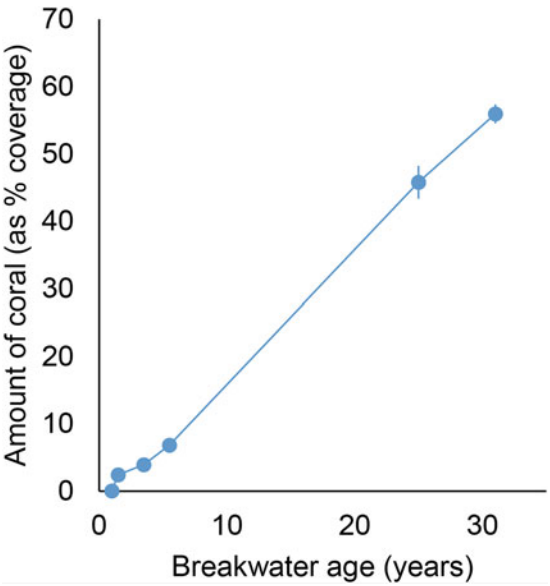


Fig. 23.18 Coral growth on UAE breakwaters over time. Corals typically colonize new breakwaters within a year or two after construction, with the total amount of coral increasing over decades. On mature breakwaters (more than 25 years) corals can cover nearly half of the available space on rocky breakwaters. Data from Fig 3e in Burt et al. (2011), reprinted with permission

old Palm Jumeirah breakwater showed it to hold fish communities with diversity that was comparable to the natural coral reefs, and abundance that was significantly higher, presumably due to the complex three-dimensional structure provided by the breakwater (Burt et al. 2013).

Grizzle et al. (2016) conducted a nation-wide study to compare the abundance and diversity of coral communities on natural coral reefs and breakwaters. They showed that the highest species diversity observed at any location in the UAE was on the Saqr Port breakwater in Ras Al Khaimah, and that all other surveyed breakwaters had diversity comparable to or greater than on all coral reefs (Fig. 23.19, orange dots); they also showed that coral abundance was comparable to that seen on coral reefs (Fig. 23.19, green bars).

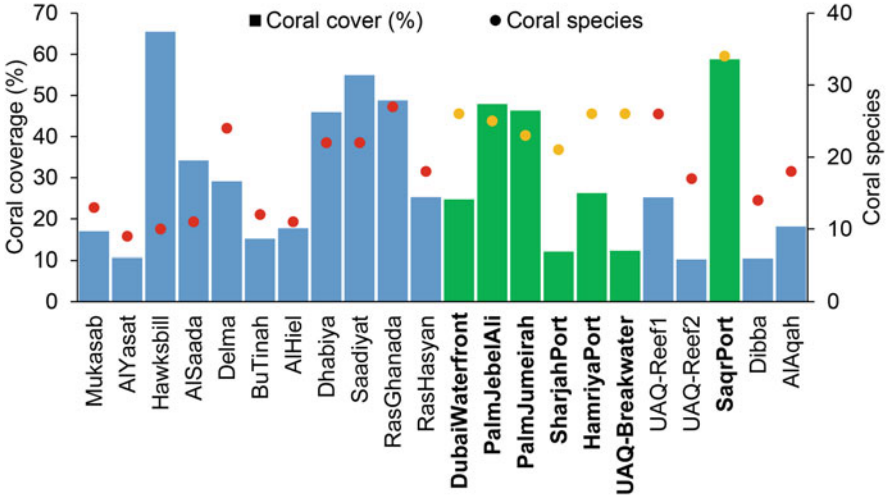


Fig. 23.19 The amount of coral (as percent coverage of the sea bottom, bars) and the total number of coral species observed (circles) on coral reefs (blue/red) and breakwaters (green/orange) across the UAE. The amount and number of species of coral on breakwaters are generally comparable, if not higher, than is observed on coral reefs, likely because they act as 'walls' for drifting coral larvae and because they are elevated above the mobile sands that typically surround natural reefs. Modified from Fig. 2 in Grizzle et al. (2016), reused with permission

While these observations are encouraging, it should be noted that such marine infrastructure cannot serve as surrogates for natural ecosystems. While species diversity and abundance may be high, the species composition of these communities, both in terms of the corals and the fishes, is highly distinct between breakwaters and coral reefs (Burt et al. 2009b, 2013), with many functional roles also operating differently between these systems (for example, higher abundance of predatory fishes on breakwaters) (Burt et al. 2013). As such, there has been a push against using ecological benefits of infrastructure for 'greenwashing' purposes to promote further development (Burt 2014), but rather to recognize infrastructure as important but unique systems. Further, 'ecological engineering' approaches—where knowledge of biology is factored into the design of marine infrastructure—are being promoted to further enhance the ecological value of any new developments that occur along our coastline (Burt and Bartholomew 2019).

23.7 Conclusion

There exists a great potential for the use of urban green spaces, either constructed (e.g. city parks) or natural (e.g. mangroves forests) for environmental education (Burt et al. 2019, 2021). This has the potential to both raise awareness of the importance and vulnerability of local ecosystems and habitats amongst the local populations, but

Fig. 23.20 Mangrove forests represent an ecosystem where people can experience nature in cities, allowing opportunity for enhanced environmental awareness and education. Image credit: Jay Alonzo

also greatly enhance the quality of life of many city-dwelling residents. Many large urban centers of the UAE, including Abu Dhabi, Al Ain, Dubai and the city of Fujairah, are blessed with wonderful natural landscapes, and much more could be done to promote both the surrounding nature and the biodiversity of even the most mundane of urban green spaces.

Al-Wasit Reserve in Sharjah exemplifies bringing people and nature together in an urban setting; opportunities such as those presented by Ras al-Khor (Dubai) or Eastern Mangrove National Park (Abu Dhabi; Fig. 23.20) are still far from being fully realized. Simple signage, attractively designed and including informative highlights on a few common organisms and key ecological processes, could be provided for a very modest cost, yet are rare in the UAE, although such efforts are increasing. A deliberate policy of leaving even small areas of urban green space, including parks, relatively unmanaged (with information provided on why this is being done) could be enacted as a small but valuable gesture to increase awareness of 'reclaiming nature' by allowing natural successional processes to occur. A recent policy evident in the Western Region to plant selected roundabouts and verges with native herbs that are then allowed to flower and set seed, produces hotspots rich in biodiversity with greatly reduced water and maintenance demands than species that are more typically planted. Developments such as this, while small, are welcome and guide the way towards a more sustainable and publicly-engaged future for the Emirates.

23.8 Recommended Readings

Readers interested in learning more about the birds and mammals of UAE urban areas are recommended to seek out Aspinall (2005) and Hellyer and Aspinall (2005), respectively, with bats specifically described in Judas et al. (2018). For those interested in the marine ecology of urban infrastructure in the Emirates, Burt et al. (2012) provides a summary written towards the public, but the benefits of such 'artificial reefs' should be considered against the environmental costs that also come with undermanaged coastal development, which is discussed in detail in Burt (2014).

References

Abdelfattah MA (2009) Land degradation indicators and management options in the desert environment of Abu Dhabi, United Arab Emirates. Soil Surv Horizons 50:3–10. https://doi.org/10.2136/sh2009.1.0003

Abdelfattah MA, Dawoud MAH, Shahid SA (2009) Soil and water management for combating desertification-towards implementation of the United Nations convention to combat desertification from the UAE perspectives. In: Proceedings of the international conference on soil degradation, Riga, Latvia, 17–19 February 2009

Adhavan D (2020) Loss of critically endangered hawksbill turtle nesting beach at EGA facility, Abu Dhabi, UAE. J Threat Taxa 12:15668–15670

Al-Ruzouq R, Shanableh A, Khalil MA, Zeiada W, Hamad K, Abu Dabous S, Gibril MBA, Al-Khayyat G, Kaloush KE, Al-Mansoori S, Jena R (2022) Spatial and temporal inversion of land surface temperature along coastal cities in arid regions. Remote Sens 14:1893

Al-Sallal KA, AboulNaga MM, Alteraifi AM (2001) Impact of urban spaces and building height on airflow distribution: wind tunnel testing of an urban setting prototype in Abu-Dhabi City. Archit Sci Rev 44:227–232. https://doi.org/10.1080/00038628.2001.9697477

Aspinall S (2005) Town, park and garden. In: Hellyer P, Aspinall S (eds) The emirates—a natural history. Trident Press, Abu Dhabi, pp 288–289

Aspinall S (2006) Soldier's orchid Zeuxine strateumatica marches on. Tribulus 16:19

Babbington J, Campbell O (2016) Recent status and occurrence of crested honey buzzards Pernis ptilorhynchus in the Arabian peninsula, with emphasis on Saudi Arabia and The United Arab Emirates. Sandgrouse 38:12–22

Bang C, Sabo JL, Faeth SH (2010) Reduced wind speed improves plant growth in a Desert City. PLoS One 5:e11061. https://doi.org/10.1371/journal.pone.0011061

Barré K, Spoelstra K, Bas Y, Challéat S, Kiri Ing R, Azam C, Zissis G, Lapostolle D, Kerbiriou C, Le Viol I (2021) Artificial light may change flight patterns of bats near bridges along urban waterways. Anim Conserv 24:259–267. https://doi.org/10.1111/acv.12635

Boyes DH, Evans DM, Fox R, Parsons MS, Pocock MJO (2021) Street lighting has detrimental impacts on local insect populations. Sci Adv 7:eabi8322. https://doi.org/10.1126/sciadv.abi8322
Burt J (2014) The environmental costs of coastal urbanization in the Arabian Gulf. City 18:760–770. https://doi.org/10.1080/13604813.2014.962889
Burt J, Bartholomew A (2019) Towards more sustainable coastal development in the Arabian Gulf: opportunities for ecological engineering in an urbanized seascape. Mar Pollut Bull 142:93–102. https://doi.org/10.1016/j.marpolbul.2019.03.024
Burt J, Bartholomew A, Bauman A, Saif A, Sale PF (2009a) Coral recruitment and early benthic community development on several materials used in the construction of artificial reefs and breakwaters. J Exp Mar Biol Ecol 373:72–78
Burt J, Bartholomew A, Usseglio P, Bauman A, Sale PF (2009b) Are artificial reefs surrogates of natural habitats for corals and fish in Dubai, United Arab Emirates? Coral Reefs 28:663–675
Burt J, Bartholomew A, Sale P (2011) Benthic development on large-scale artificial reefs: a comparison of communities among breakwaters of different age and natural reefs. Ecol Eng 37:191–198. https://doi.org/10.1016/j.ecoleng.2010.09.004
Burt J, Bartholomew A, Feary D (2012) Man-made structures as artificial reefs in the Gulf. In: Riegl B, Purkis S (eds) Coral reefs of the Gulf: adaptation to climatic extremes. Springer, New York, pp 171–186. https://doi.org/10.1007/978-94-007-3008-3_10
Burt JA, Killilea ME, Ciprut S (2019) Coastal urbanization and environmental change: Opportunities for collaborative education across a global network university. Reg Stud Mar Sci 26:1–10. https://doi.org/10.1016/j.rsma.2019.100501
Burt J, Killilea M, Rademacher A (2021) Unexpected Nature? Proliferating Mangroves on the Coast of Abu Dhabi. In: Durr E, Keller R (eds) Urban Environments as Spaces of Living in Transformation: Position Papers Collection. Urban Environments Initiative, Rachel Carson Center, Munich, Germany, pp44-47. https://urbanenv.org/burt-killilea-rademacher_uei_2021/
Burt J, Feary D, Cavalcante G, Bauman A, Usseglio P (2013) Urban breakwaters as reef fish habitat in the Persian Gulf. Mar Pollut Bull 72:342–350
Campbell O (2018) Recent sudden expansion in the breeding range of *Shikra accipterbadius* in the UAE. Tribulus 26:65–70
Campbell O, Al-Ali A, AlMazrouie M (2022) Significant breeding bird records from the United Arab Emirates from 2020 and 2021, including the first confirmed breeding record of barn swallow *Hirundo rustica*. Sandgrouse 44:175–185
Cheptou P-O, Carrue O, Rouifed S, Cantarel A (2008) Rapid evolution of seed dispersal in an urban environment in the weed *Crepis sancta*. PNAS 105:3796–3799. https://doi.org/10.1073/pnas.0708446105
Chow WTL, Brazel AJ (2012) Assessing xeriscaping as a sustainable heat Island mitigation approach for a desert city. Build Environ 47:170–181. https://doi.org/10.1016/j.buildenv.2011.07.027
Dominoni DM (2015) The effects of light pollution on biological rhythms of birds: an integrated, mechanistic perspective. J Ornithol 156:409–418. https://doi.org/10.1007/s10336-015-1196-3
eBird (2022) United Arab Emirates. The Cornell Lab of Ornithology, New York
Elsheikh EAE, El-Keblawy A, Mosa KA, Okoh AI, Saadoun I (2021) Role of endophytes and rhizosphere microbes in promoting the invasion of exotic plants in arid and semi-arid areas: a review. Sustainability 13:13081
Falchi F, Cinzano P, Duriscoe D, Kyba CCM, Elvidge CD, Baugh K, Portnov BA, Rybnikova NA, Furgoni R (2016) The new world atlas of artificial night sky brightness. Sci Adv 2:e1600377. https://doi.org/10.1126/sciadv.1600377
Feulner GR, Roobas B, Carlisle T, Meyer H (2014) First UAE and Arabian records of *Chilades pandava*, the cycad cupid butterfly, an introduced oriental species (Lepidoptera: Lycaenidae) hosted by the ornamental sago plant *Cycas revoluta*. Tribulus 22:48–57
Feulner G, Roobas B, Hutchings V, Otto H, Campbell O, Roberts H, Hornby R, Howarth B (2021) Butterflies of the United Arab Emirates and northern Oman. Motivate Publishing, Dubai

Finch D, Schofield H, Mathews F (2020) Traffic noise playback reduces the activity and feeding behaviour of free-living bats. Environ Pollut 263:114405. https://doi.org/10.1016/j.envpol.2020.114405

Frey CM, Rigo G, Parlow E (2007) Urban radiation balance of two coastal cities in a hot and dry environment. Int J Remote Sens 28:2695–2712. https://doi.org/10.1080/01431160600993389

Grichting A (2020) Blue design for urban resilience in drylands: the case of Qatar. In: Roggema R (ed) Nature driven urbanism. Springer, Cham, pp 175–208. https://doi.org/10.1007/978-3-030-26717-9_9

Grizzle RE, Ward KM, AlShihi RMS, Burt JA (2016) Current status of coral reefs in the United Arab Emirates: distribution, extent, and community structure with implications for management. Mar Pollut Bull 105:515–523. https://doi.org/10.1016/j.marpolbul.2015.10.005

Hall SJ, Learned J, Ruddell B, Larson KL, Cavender-Bares J, Bettez N, Groffman PM, Grove JM, Heffernan JB, Hobbie SE, Morse JL, Neill C, Nelson KC, O'Neil-Dunne JPM, Ogden L, Pataki DE, Pearse WD, Polsky C, Chowdhury RR, Steele MK, Trammell TLE (2016) Convergence of microclimate in residential landscapes across diverse cities in the United States. Landsc Ecol 31:101–117. https://doi.org/10.1007/s10980-015-0297-y

Harrison D, Bates P (1991) The mammals of Arabia, 2nd edn. Harrison Zoological Museum, Kent, UK

Heisler GM, Brazel AJ (2010) The urban physical environment: temperature and urban Heat Islands. Urban Ecosyst Ecol 2010:29–56. https://doi.org/10.2134/agronmonogr55.c2

Hellyer P, Aspinall S (2005) The emirates: a natural history. Trident Press, London

Hetem RS, Strauss WM, Fick LG, Maloney SK, Meyer LCR, Shobrak M, Fuller A, Mitchell D (2012) Activity re-assignment and microclimate selection of free-living Arabian oryx: responses that could minimise the effects of climate change on homeostasis? Zoology 115:411–416. https://doi.org/10.1016/j.zool.2012.04.005

Issa S, Saleous N (2014) Satellite image-based analysis of the greening impact on the formation of an urban Heat Island (UHI) in Abu Dhabi City. Arab World Geographer 17:91–101. https://doi.org/10.5555/arwg.17.1.q540p55865h1jr04

Jennings M (2010) Atlas of the breeding birds of Arabia. Fauna of Arabia Saudi Wildlife Commission & Senckenberg Forschungsinstitut und Naturmuseum, Jeddah, Saudi Arabia, pp 37–44

Johnson AL, Borowy D, Swan CM (2018) Land use history and seed dispersal drive divergent plant community assembly patterns in urban vacant lots. J Appl Ecol 55:451–460. https://doi.org/10.1111/1365-2664.12958

Judas J, Hellyer P (2016) Five-striped Palm Squirrel, *Funambulus pennantii* (Wroughton, 1905): a new addition to the UAE's exotic fauna. Tribulus 24:126–130

Judas J, Csorba G, Benda P (2018) The bat fauna (Mammalia: Chiroptera) of the United Arab Emirates: a review of published records and museum specimens with conservation notes. J Threat Taxa 10:11379–11390. https://doi.org/10.11609/jott.3096.10.3.11379-11390

Kolar CS, Lodge DM (2001) Progress in invasion biology: predicting invaders. Trends Ecol Evol 16:199–204. https://doi.org/10.1016/S0169-5347(01)02101-2

Kowarik I, von der Lippe M (2011) Secondary wind dispersal enhances long-distance dispersal of an invasive species in urban road corridors. NeoBiota 9:49–70. https://doi.org/10.3897/neobiota.9.1469

Lazzarini M, Marpu PR, Molini A, Ouarda TBMJ, Ghedira H (2014) Urban heat Island and land cover-temperature interactions in desert cities. In: EGU general assembly conference abstracts 13696

Lazzarini M, Molini A, Marpu PR, Ouarda TBMJ, Ghedira H (2015) Urban climate modifications in hot desert cities: the role of land cover, local climate, and seasonality. Geophys Res Lett 42:9980–9989. https://doi.org/10.1002/2015GL066534

Le Quesne WJF, Fernand L, Ali TS, Andres O, Antonpoulou M, Burt JA, Dougherty WW, Edson PJ, El Kharraz J, Glavan J, Mamiit RJ, Reid KD, Sajwani A, Sheahan D (2021) Is the development of desalination compatible with sustainable development of the Arabian Gulf? Mar Pollut Bull 173:112940. https://doi.org/10.1016/j.marpolbul.2021.112940

Lintott PR, Barlow K, Bunnefeld N, Briggs P, Gajas Roig C, Park KJ (2016) Differential responses of cryptic bat species to the urban landscape. Ecol Evol 6:2044–2052. https://doi.org/10.1002/ece3.1996

Loss SR, Will T, Loss SS, Marra PP (2014) Bird–building collisions in the United States: estimates of annual mortality and species vulnerability. Condor 116:8–23. https://doi.org/10.1650/condor-13-090.1

Lovell RSL, Blackburn TM, Dyer EE, Pigot AL (2021) Environmental resistance predicts the spread of alien species. Nat Ecol Evol 5:322–329. https://doi.org/10.1038/s41559-020-01376-x

McKinney ML (2006) Urbanization as a major cause of biotic homogenization. Biol Conserv 127: 247–260. https://doi.org/10.1016/j.biocon.2005.09.005

Mirou SM, Zeiada W, Al-Ruzouq RI, Hassan RN (2022) Investigation of diurnal and seasonal land surface temperature. In: 2022 advances in science and engineering technology international conferences (ASET), pp 1–6

Muzaffar SB, Gubiani R, Benjamin S (2012) Reproductive performance of the Socotra cormorant *Phalacrocorax nigrogularis* on Siniya Island, United Arab Emirates: planted trees increase hatching success. Waterbirds 35:626–630

Newbold TAS, MacMahon JA (2014) Determinants of habitat selection by desert horned lizards (Phrynosoma platyrhinos): the importance of abiotic factors associated with vegetation structure. J Herpetol 48:306–316. https://doi.org/10.1670/10-141

Olsson KH, Weiss N, Shalev S, Schäckermann J (2022) Spread of the invasive dwarf honey bee *Apis florea* facilitates winter presence of oriental honey buzzard *Pernis ptilorhynchus* in Eilat, Israel. Acta Ornithol 56:189–198

Pearlmutter D, Bitan A, Berliner P (1999) Microclimatic analysis of “compact” urban canyons in an arid zone. Atmos Environ 33:4143–4150. https://doi.org/10.1016/S1352-2310(99)00156-9

Pedersen T, Aspinall S, Campbell O, Smiles M (2021) EBRC annotated checklist of the birds of the United Arab Emirates

Riddell EA, Iknayan KJ, Wolf BO, Sinervo B, Beissinger SR (2019) Cooling requirements fueled the collapse of a desert bird community from climate change. PNAS 116:21609–21615. https://doi.org/10.1073/pnas.1908791116

Roberts JA, Coulson G, Munn AJ, Kearney MR (2016) A continent-wide analysis of the shade requirements of red and western grey kangaroos. Temperature 3:340–353. https://doi.org/10.1080/23328940.2016.1163452

Seewagen CL, Adams AM (2021) Turning to the dark side: LED light at night alters the activity and species composition of a foraging bat assemblage in the northeastern United States. Ecol Evol 11:5635–5645. https://doi.org/10.1002/ece3.7466

Seymour CL, Simmons RE, Morling F, George ST, Peters K, O’Riain MJ (2020) Caught on camera: the impacts of urban domestic cats on wild prey in an African city and neighbouring protected areas. Global Ecol Conserv 23:e01198. https://doi.org/10.1016/j.gecco.2020.e01198

Shepard ELC, Williamson C, Windsor SP (2016) Fine-scale flight strategies of gulls in urban airflows indicate risk and reward in city living. Philos Trans R Soc B Biol Sci 371:20150394. https://doi.org/10.1098/rstb.2015.0394

Shochat E, Lerman S, Katti M, Lewis D (2004) Linking optimal foraging behavior to bird community structure in an urban-desert landscape: field experiments with artificial food patches. Am Nat 164:232–243. https://doi.org/10.1086/422222

Song S, Chang Y, Wang D, Jiang T, Feng J, Lin A (2020) Chronic traffic noise increases food intake and alters gene expression associated with metabolism and disease in bats. J Appl Ecol 57:1915–1925. https://doi.org/10.1111/1365-2664.13710

Stachowitsch M, Kikinger R, Herler J, Zolda P, Geutebruck E (2002) Offshore oil platforms and fouling communities in the southern Arabian Gulf (Abu Dhabi). Mar Pollut Bull 44:853–860

Whelan R, Clarke C, Gubiani R, Muzaffar SB (2019) Sea turtle observations on and around Siniya Island, umm Al Quwain, United Arab Emirates. Mar Turt Newsl 2019:10–12

Wolf BO, Wooden KM, Walsberg GE (1996) The use of thermal Refugia by two small desert birds. Condor 98:424–428. https://doi.org/10.2307/1369162

Yaghmour FA, Rodríguez-Zárate CJ (2021) First record of olive Ridley Sea turtle *Lepidochelys olivacea* (Eschscholtz, 1829) nesting in the United Arab Emirates. Herpetol Notes 14:353–356

Part V
The Future Emirates

Chapter 24
The Emirates at 2050: Balancing Development and Environmental Stewardship

John A. Burt, Noura Al-Mansoori, Ivonne Bejarano, Gary Brown, Oscar Campbell, Johannes Els, Gary R. Feulner, Guillermo Friis-Montoya, Aaron Henderson, Brigitte Howarth, David M. John, Jacky Judas, Daniel Mateos-Molina, Matthew Mitchell, Ada Natoli, Francesco Paparella, and Fadi Yaghmour

24.1 Introduction

The natural history of a region is shaped by the interplay between the forces of nature and the actions of humankind. Currently, the world finds itself in the Anthropocene, an era characterized by unprecedented human impacts on the environment (Steffen et al. 2011; Crutzen 2016). It is against this background that the United Arab

J. A. Burt (✉)
Arabian Center for Climate and Environmental Sciences (ACCESS) and Water Research Center (WRC) , New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
e-mail: John.Burt@nyu.edu

N. Al-Mansoori
Marine Biology Lab, New York University, Abu Dhabi, United Arab Emirates

Marine Biodiversity Division, Environment Agency Abu Dhabi, Abu Dhabi, United Arab Emirates

I. Bejarano
Department of Biology, Chemistry and Environmental Sciences, American University of Sharjah, Sharjah, United Arab Emirates

G. Brown
Leibniz Institute for the Analysis of Biodiversity Change, Centre for Biodiversity Monitoring and Conservation Science, Bonn, Germany

O. Campbell
Nautica Environmental Associates LLC, Abu Dhabi, United Arab Emirates

British School Al Khubairat, Abu Dhabi, United Arab Emirates

J. Els
Environment and Protected Areas Authority, Breeding Centre for Endangered Arabian Wildlife, Sharjah, United Arab Emirates

J. A. Burt (ed.), *A Natural History of the Emirates*,
https://doi.org/10.1007/978-3-031-37397-8_24

Emirates (UAE) faces the challenge of balancing its rapid economic development with environmental preservation and conservation of its natural assets (Sale et al. 2011; Jayaraman et al. 2015; Mateos-Molina et al. 2021).

Throughout its history, the people of the area now called the UAE have had an outward-looking perspective, engaging in trade from Mesopotamia to the Indus and East Africa, serving as a nexus for the exchange of goods, ideas and cultures across the region and beyond (Boivin and Fuller 2009; Morton 2016; Ryan et al. 2021). In the modern era, the UAE has embraced globalism, becoming a respected voice and valued player in the international order, seeking peace and prosperity through its domestic policies and international engagements (Korany et al. 2010; Maitner and Stewart-Ingersoll 2016; Ulrichsen 2016). In considering the future of the Emirates at 2050, it is presumed that those internationally focused efforts will continue to succeed. On the local stage, however, balancing economic development with environmental conservation will be an important challenge for the UAE as it navigates the complexities of the Anthropocene era.

G. R. Feulner
Dubai Natural History Group, Dubai, United Arab Emirates

G. Friis-Montoya
Center for Genomics and Systems Biology (CGSB), New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

Plant Health and Adaptation, Royal Botanic Gardens, Kew, Richmond, Surrey, UK

A. Henderson
Biology Department, College of Science, UAE University, Al Ain, United Arab Emirates

B. Howarth
Department of Culture and Tourism, Natural History Museum Abu Dhabi (NHMAD), Abu Dhabi, United Arab Emirates

D. M. John
Life Sciences Department, Natural History Museum, London, UK

J. Judas
Soudah Development, Abha, Saudi Arabia

D. Mateos-Molina
Emirates Nature-WWF, Bay Square Building 4, Level 2, Business Bay, Dubai, United Arab Emirates

M. Mitchell
Marine Biology Lab, New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

A. Natoli
College of Natural and Health Science, Zayed University, Dubai, United Arab Emirates

F. Paparella
Arabian Center for Climate and Environmental Sciences (ACCESS), New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

F. Yaghmour
Hefaiyah Mountain Conservation Centre (Scientific Research Department), Environment and Protected Areas Authority, Kalba, Sharjah, United Arab Emirates

24.2 Our Natural Emirates: Valuable but Vulnerable

The UAE is characterized by a diverse range of geographical features and ecosystems, both terrestrial and marine. The country is home to vast expanses of arid desert, austere mountain terrain and a coastline that supports valuable lagoon and marine ecosystems, including mangrove forests, seagrass meadows, algal beds and coral reefs that support a rich and distinctive community of marine life (Hellyer and Aspinall 2005; Lamine et al. 2020; Mateos-Molina et al. 2021). In the terrestrial realm, the UAE's arid sand dunes, rugged mountains, fertile wadis, sabkhas and coastal sands are home to plant and animal species specially adapted to the harsh environmental conditions of the Emirates (Vine and Al-Abed 1996; Hellyer and Aspinall 2005). These habitats and their interrelated ecosystems are the cradle for the region's unique biodiversity, and they combine to offer a variety of ecosystem goods services that contribute to human well-being, as they have done for many millennia.

The unique ecosystems in the UAE are particularly vulnerable to disturbance because they exist in an environment that is already at the limits of physiological tolerance for most organisms. Extreme conditions, such as high temperatures, low rainfall and high evaporation rates, make the native flora and fauna susceptible to even slight alterations to their environment (Scherf et al. 2007; Soorae et al. 2013; El-Keblawy et al. 2015; Sakkir et al. 2015; Paparella et al. 2019; Friis and Burt 2020; Bouwmeester et al. 2021). Human-induced transformations, such as rapid urbanization, the degradation and fragmentation of habitats, groundwater extraction and modification of the coastline and coastal marine environments, pose significant threats to the delicate balance of the UAE's ecosystems (Tourenq and Launay 2008; Gardner and Howarth 2009; Tourenq et al. 2011; Burt 2014; Burt and Bartholomew 2019). Additionally, global climate change has the potential to exacerbate many of these issues (Shahin and Salem 2015; Lincoln et al. 2021; Melville-Rea et al. 2021). As the nation continues to grow and develop, it is essential to carefully consider and address the potential consequences of human activities on the natural environment of the Emirates in order to ensure the long-term health and welfare of its ecosystems and the diverse organisms they contain.

24.3 Challenges to the Natural Emirates

The United Arab Emirates has successfully promoted rapid economic development in recent decades, transforming itself into a prosperous modern nation (Nyarko 2010). However, rapid growth has brought with it a number of challenges, placing increasing pressure on its vulnerable ecosystems and its unique plant and animal life.

Population growth and extensive urbanization, both on land and into the seas, have led to extensive habitat loss and degradation. The expansion of cities and development of infrastructure, such as roads, power lines, pipelines and fences on land and dredged channels and industrial structures in the sea, has resulted in habitat fragmentation and degradation, often creating barriers that disrupt the movement of species (Tourenq and Launay 2008; Gardner and Howarth 2009; Burt 2014). Overgrazing by camels and goats, and also by wild but management-supported animals within protected areas, has further contributed to widespread habitat degradation, leading to the decline of native plant species, the onset of desertification and the spread of invasive species (Böer 1998; Gallacher and Hill 2006a, b; Shahid 2017; Howari et al. 2022). One has only to look at the all too rare examples of genuinely protected desert to see the difference (e.g. El-Keblawy and Alsharhan 2003).

Water resources are another concern. The UAE is one of the most water-scarce countries in the world, and the extraction of groundwater, mainly for agricultural purposes, has led to the depletion and salinization of aquifers and the decline and sometimes the disappearance of unique freshwater ecosystems in mountain wadis (Freyhof et al. 2015, 2020; Shahin and Salem 2015; Liaqat et al. 2021; Sherif et al. 2021). Desalination, while providing a critical source of freshwater, creates its own set of environmental challenges, including the discharge of hypersaline brines back into the sea and large emissions of greenhouse gases to the air (Le Quesne et al. 2021; Paparella et al. 2022).

Global climate change poses a growing challenge to the UAE's environment. Rising temperatures, and the increasing frequency and severity of extreme weather events threaten to exacerbate existing environmental issues and overwhelm the ability of the country's ecosystems and natural resources to respond. We are already witnessing more frequent and severe regional marine heat waves than in the recorded history (Riegl et al. 2018; Beyraghdar Kashkooli et al. 2022), affecting more vulnerable ecosystems such as coral reefs across the Emirates (Burt et al. 2019) and accelerating the growth of a low-oxygen zone that threatens fisheries on the UAE's Gulf coast (Lachkar et al. 2022). Additionally, climate-driven sea level rise is likely to substantially impact the ecology of widespread low-lying coastal areas that harbor many of the UAE's most unique habitats (e.g. lagoons, sabkhas and mangrove forests) (Brown 2006; Elkabbany 2019; Melville-Rea et al. 2021). The precise impacts of climate change on the UAE's ecosystems and organisms are difficult to predict in detail (Paparella et al. 2019), as are its consequences for the human population, but are likely to include a decrease in water resources, fisheries resources and agricultural potential (due to a decrease in arable land and pollinating organisms), as well as risks for coastal real estate and infrastructure (e.g. power and desalination plants and ports) (Ajaj et al. 2019; Dougherty et al. 2019; Bolleter et al. 2021; Melville-Rea et al. 2021).

The combined effects of all of the foregoing challenges have already led to a decline in the biodiversity of the UAE, with many species categorized as critically endangered, endangered or vulnerable to extinction at the national scale (together representing 28% of assessed species; Allen et al. 2021). The loss of biodiversity has implications not only for the health and resilience of natural ecosystems in the coming decades, but also for the cultural heritage and identity of the nation, and the well-being of people who rely on these ecosystems for their livelihoods and quality of life (Tourenq et al. 2009; Mateos-Molina et al. 2020; Luomi 2022; Pittman et al. 2022).

24.4 Envisioning a Future in Greater Harmony with Nature

In order to address these challenges and chart a more environmentally aware course for the Emirates at 2050, a comprehensive approach is needed that integrates environmental considerations into all aspects of planning and decision-making. The following policy recommendations are proposed to help guide the UAE towards a future in greater harmony with the natural environment (Fig. 24.1):

Fig. 24.1 Environmental policy recommendations for a more sustainable future for the Emirates (Image credit: Oliver Farrel)

- Adopt a national strategy for sustainable development that aligns with international goals and commitments, such as the United Nations' Sustainable Development Goals (SDGs) and the Paris Agreement on climate change. This strategy should prioritize the conservation of ecosystems and nature in the Emirates, while also promoting sustainable economic growth, social equity and sound decision-making and implementation (Umar et al. 2020; Meyer and Warren 2021; Umar and Umeokafor 2022).
- Strengthen environmental policies and regulations to ensure the protection and preservation of the UAE's ecosystems and biodiversity. Potential measures could include the expansion of protected areas, establishing habitat restoration initiatives, bolstering monitoring and assessment of environmental initiatives, and intensifying the enforcement of environmental impact assessments (EIAs) for new infrastructure and development projects, which should be strengthened to incorporate social impacts and cumulative pressures (i.e. rather than single-project based) (O'Brien et al. 2007; Heaton and Burns 2014; Howarth et al. 2019).
- Invest in urban planning and design that minimizes resource use, habitat loss and fragmentation, and promotes arid-adapted green spaces, biodiversity and connectivity between ecosystems. This could include the creation of urban wildlife corridors, use of native plants in landscaping, and promotion of green infrastructure such as green roofs and walls where desert-adapted local vegetation could be integrated into built infrastructure to support a variety of socio-environmental benefits (ADUPC 2014; D'Souza 2014; Haggag et al. 2014; Alam et al. 2017; Mateos-Molina et al. 2020).
- Promote sustainable water management practices to address water scarcity and protect freshwater ecosystems. This could involve further enhancement of water-efficient technologies and practices, promotion of water recycling and reuse, and exploration of alternative, less environmentally impactful sources of freshwater, such as fog harvesting and atmospheric water generation (Murad 2010; Aleisa and Al-Zubari 2017; Cattani et al. 2023; Hassan et al. 2023).
- Encourage use of Nature Based Solutions (NBS) to effectively tackle societal problems while also providing benefits for both human well-being and biodiversity. NBS are actions that include protection, sustainable management, restoration, habitat creation, and nature-based enterprises such as ecotourism and agroecology. The objective is to offer numerous socio-economic and environmental benefits in an efficient and adaptable way, with the benefits serving as a pathway to a sustainable economy (Maes and Jacobs 2017; Cohen-Shacham et al., 2019; Seddon et al. 2021; Pittman et al. 2022).
- Address climate change through the development and implementation of a national climate change adaptation and mitigation plan. This plan should prioritize the protection of vulnerable ecosystems and species, as well as the reduction of greenhouse gas emissions through the promotion of renewable energy and energy efficiency measures (Sgouridis et al. 2016; Krarti and Dubey 2018; Al-Sarihi and Mason 2020).

- Foster environmental education and awareness to promote an appreciation for the natural world, and an understanding of humanity's role in it, to support a culture of conservation and stewardship among the UAE's citizens and residents. This could include the further integration of environmental topics into the national curriculum, the establishment of environmental outreach programs, and the encouragement of citizen science initiatives to engage the public in monitoring and conserving nature in the Emirates (Howari et al. 2019; Natoli et al. 2022).
- Support research and development in environmental sciences, with a focus on understanding and addressing the unique environmental and anthropogenic challenges faced by the UAE's ecosystems and biodiversity. This could include the establishment of rigorous research institutes supported by graduate training programs, and the provision of sustained, competitive funding for environmental research focused on national priorities (Sale et al. 2011; van Lavieren et al. 2011; Al Marzouqi et al. 2019).
- Foster inter-Emirate and regional cooperation on environmental issues, by sharing best practices, participating in joint conservation initiatives, and collaborating on trans-boundary environmental challenges such as climate change, marine pollution and migratory species (Aspinall 1996, 2001; Knight et al. 2011; Sale et al. 2011; Al-Saidi 2021).
- Encourage the private sector to adopt environmentally responsible business practices and invest in green technologies. This could involve the development of incentives, such as corporate tax breaks and grants, for companies that demonstrate a commitment to environmental conservation, as well as the establishment of corporate reporting requirements and standards related to their environmental initiatives (Al Naqbi et al. 2019; Al Yammahi et al. 2019; Samour et al. 2022a, b).
- Monitor and evaluate the progress of environmental policies and initiatives to assess their effectiveness and inform future decision-making. This could include the development of a comprehensive set of environmental indicators and the regular publication of an environmental performance report (Van Lavieren and Klaus 2013; Gulseven 2020; Gulseven and Ahmed 2022).

Many of these policy recommendations are already being implemented in the UAE to some degree, demonstrating the nation's commitment to sustainable development and environmental conservation. For example, the UAE Net Zero 2050 initiative focuses on transitioning to a knowledge-based, sustainable and innovative economy while preserving the environment (MOCCAE 2021; Al Fahaam and Saleh 2023). It has also invested heavily in renewable energy projects, such as the Mohammed bin Rashid Al Maktoum Solar Park in Dubai and the Barakah Nuclear Energy Plant in Abu Dhabi, which aim to reduce greenhouse gas emissions and diversify the UAE's energy sources (Obaideen et al. 2021; Davidson 2022; Marketos et al. 2022). Such initiatives align with international commitments such as the United Nations' Sustainable Development Goals (SDGs) and the Paris Agreement on climate change, while also moving towards a more sustainable future for the Emirates. Mitigation of global climate change and a transition to renewables are necessary and laudable strategies as the UAE matures towards the middle of the century, but many of the pressures and challenges facing terrestrial and marine ecosystems within the Emirates are occurring on rapid time scales, requiring a more urgent commitment towards nationally focused initiatives.

24.5 Conclusion

As the UAE looks ahead to 2050, it is important that the nation strikes a balance between its ambitious development goals and the need to preserve and protect its unique natural heritage by acting as stewards of the environment for subsequent generations. By adopting an approach to development that incorporates environmental conservation, the UAE can hope to ensure that its rapid growth and modernization do not come at the expense of its invaluable natural assets.

The policy recommendations outlined here provide a roadmap for the UAE to navigate the challenges of the Anthropocene era and build a more prosperous future for its people, enhancing both its environment and its place in the world. Successfully implementing these recommendations would bring numerous benefits, including improved quality of life for the UAE's citizens and residents. Moreover, preserving the nation's distinctive nature would help to attract the growing number of environmentally minded tourists, bringing additional economic benefits while fostering an appreciation for the UAE's dedication to environmental stewardship.

By embracing a vision of development that respects the natural environment and safeguards its plant and animal life, the UAE can demonstrate its commitment and set an example for other nations to follow, earning international recognition for its responsible approach to development. Achieving this vision will require the concerted efforts of policymakers, businesses, researchers and the public, all working together to ensure that the UAE's unique natural heritage is preserved for generations to come.

At 2050, the Emirates could be a shining example of responsible development, whereby the country's rich natural heritage is protected and celebrated, and where economic growth, environmental stewardship and social well-being are all equally valued and pursued. The successful implementation of the proposed policy recommendations will lay the foundation for a future in which the UAE's natural environment flourishes alongside its thriving economy, setting a standard for environmentally-conscious development that inspires the world.

References

ADUPC (2014) Plan maritime 2030–Abu Dhabi coastal and marine framework plan–charette 1 proceedings book–existing conditions, constraints and opportunities. Abu Dhabi Urban Planning Council, Abu Dhabi

Ajaj RM, Shahin SM, Salem MA (2019) The challenges of climate change and food security in the United Arab Emirates (UAE): from deep understanding to quick actions. Curr Nutr Food Sci 15: 422–429. https://doi.org/10.2174/1573401314666180326163009
Al Fahaam T, Saleh A (2023) Mohammed bin Rashid witnesses signing of UAE governments net zero 2050 charter. WAM, Abu Dhabi, UAE. https://wam.ae/en/details/1395303136015. Accessed 25 March 2023
Al Marzouqi AH, Alameddine M, Sharif A, Alsheikh-Ali AA (2019) Research productivity in the United Arab Emirates: a 20-year bibliometric analysis. Heliyon 5:e02819. https://doi.org/10.1016/j.heliyon.2019.e02819
Al Naqbi S, Tsai I, Mezher T (2019) Market design for successful implementation of UAE 2050 energy strategy. Renew Sust Energ Rev 116:109429. https://doi.org/10.1016/j.rser.2019.109429
Al Yammahi K, Pereira V, Temouri Y (2019) Supporting national responsibilities in the quest to achieve an international agenda: an exploratory case study from the UAE. In: Rettab B, Mellahi K (eds) Practising CSR in the Middle East. Springer, Cham, pp 119–160. https://doi.org/10.1007/978-3-030-02044-6_7
Alam H, Khattak JZK, Ppoyil SBT, Kurup SS, Ksiksi TS (2017) Landscaping with native plants in the UAE: a review. Emir J Food Agric 2017:729–741
Aleisa E, Al-Zubari W (2017) Wastewater reuse in the countries of the Gulf Cooperation Council (GCC): the lost opportunity. Environ Monit Assess 189:553. https://doi.org/10.1007/s10661-017-6269-8
Allen DJ, Westrip J, Ralph GM, Burfield IJ, Harding KA, Hilton-Taylor C, Ali H, Al-Mheiri R, Alshamsi O (2021) UAE national red list: synthesis report. IUCN, Gland, Switzerland. https://www.moccae.gov.ae/assets/download/7f302c54/UAE%20National%20Red%20List%20Synthesis%20Report.pdf.aspx. Accessed 28 March 2023
Al-Saidi M (2021) Cooperation or competition? State environmental relations and the SDGs agenda in the Gulf Cooperation Council (GCC) region. Environ Dev 37:100581. https://doi.org/10.1016/j.envdev.2020.100581
Al-Sarihi A, Mason M (2020) Challenges and opportunities for climate policy integration in oil-producing countries: the case of the UAE and Oman. Clim Pol 20:1226–1241. https://doi.org/10.1080/14693062.2020.1781036
Aspinall S (1996) Time for a protected area network in the UAE. Tribulus 6:5–9
Aspinall S (2001) Environmental development and protection in the UAE. In: Vine P, Al-Abed I (eds) United Arab Emirates: a new perspective. Trident Press, London, pp 277–304
Beyraghdar Kashkooli O, Karimian S, Modarres R (2022) Spatiotemporal variability of the Persian Gulf and Oman Sea marine heatwaves during 1982–2020. Mar Pollut Bull 184:114174. https://doi.org/10.1016/j.marpolbul.2022.114174
Böer B (1998) Anthropogenic factors and their potential impacts on the sustainable development of Abu Dhabi's terrestrial biological resources. Int J Sustain Dev World Ecology 5:125–135. https://doi.org/10.1080/13504509809469976
Boivin N, Fuller DQ (2009) Shell middens, ships and seeds: exploring coastal subsistence, maritime trade and the dispersal of domesticates in and around the ancient Arabian peninsula. J World Prehist 22:113–180. https://doi.org/10.1007/s10963-009-9018-2
Bolleter J, Grace B, Hooper P, Foster S (2021) Wet-bulb temperature and sea-level rise in the United Arab Emirates – planning responses. Plan Pract Res 36:408–429. https://doi.org/10.1080/02697459.2020.1859199
Bouwmeester J, Riera R, Range P, Ben-Hamadou R, Samimi-Namin K, Burt JA (2021) Coral and reef fish communities in the thermally extreme Persian/Arabian Gulf: insights into potential climate change effects. In: Rossi S, Bramanti L (eds) Perspectives on the marine animal forests of the world. Springer, Cham, pp 63–86. https://doi.org/10.1007/978-3-030-57054-5_3
Brown G (2006) The sabkha vegetation of the United Arab Emirates. In: Khan MA, Boer B, Kust GS, Barth H-J (eds) Sabkha ecosystems. Springer, Dordrecht, pp 37–51

Burt J (2014) The environmental costs of coastal urbanization in the Arabian Gulf. City 18:760–770. https://doi.org/10.1080/13604813.2014.962889
Burt JA, Bartholomew A (2019) Towards more sustainable coastal development in the Arabian Gulf: opportunities for ecological engineering in an urbanized seascape. Mar Pollut Bull 142:93–102. https://doi.org/10.1016/j.marpolbul.2019.03.024
Burt J, Paparella F, Al-Mansoori N, Al-Mansoori A, Al-Jailani H (2019) Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. Coral Reefs 38:567–589. https://doi.org/10.1007/s00338-019-01767-y
Cattani L, Cattani P, Magrini A (2023) Air to water generator integrated system real application: a study case in a worker village in United Arab Emirates. Appl Sci 13:3094
Cohen-Shacham E, Andrade A, Dalton J, Dudley N, Jones M, Kumar C, Maginnis S, Maynard S, Nelson CR, Renaud FG, Welling R, Walters G (2019) Core principles for successfully implementing and upscaling nature-based solutions. Environ Sci Pol 98:20–29. https://doi.org/10.1016/j.envsci.2019.04.014
Crutzen PJ (2016) Geology of mankind. In: Crutzen PJ, Brauch HG (eds) Paul J. Crutzen: a pioneer on atmospheric chemistry and climate change in the Anthropocene. Springer, Cham, pp 211–215. https://doi.org/10.1007/978-3-319-27460-7_10
D'Souza U (2014) Measuring green roof performance, a solution to sustainable urban development in the UAE. Int J Sustain Dev Plan 9:376–388
Davidson A (2022) The role of nuclear energy in the global energy transition. Oxford Institute for Energy Studies, Oxford, UK
Dougherty WW, Yates DN, Pereira JE, Monaghan A, Steinhoff D, Ferrero B, Wainer I, Flores-Lopez F, Galaitsi S, Kucera P, Glavan J (2019) The energy-water-health nexus under climate change in the United Arab Emirates: impacts and implications. In: Qudrat-Ullah H, Kayal AA (eds) Climate change and energy dynamics in the Middle East: modeling and simulation-based solutions. Springer, Cham, pp 131–180. https://doi.org/10.1007/978-3-030-11202-8_6
Elkabbany MF (2019) Sea level rise vulnerability assessment for Abu Dhabi, United Arab Emirates. University of Lund, Lund, Sweden, p 119
El-Keblawy A, Alsharhan A (2003) Effects of protection from grazing on species diversity, abundance and productivity in two regions of Abu Dhabi, United Arab Emirates. In: Alsharhan AW, Wood W, Goudie A, Fowler A, Abdellatif E (eds) Desertification in the third millennium. Swets & Zeitlinger Publishers, Rotterdam, The Netherlands, pp 217–226
El-Keblawy A, Abdelfattah MA, Khedr A-HA (2015) Relationships between landforms, soil characteristics and dominant xerophytes in the hyper-arid northern United Arab Emirates. J Arid Environ 117:28–36. https://doi.org/10.1016/j.jaridenv.2015.02.008
Freyhof J, Hamidan N, Feulner G, Harrison I (2015) The status and distribution of freshwater fishes of the Arabian peninsula. In: García N, Harrison I, Cox N, Tognelli M (eds) The status and distribution of freshwater biodiversity in the Arabian peninsula. IUCN, Gland, Switzerland, pp 16–30
Freyhof J, Els J, Feulner GR, Hamidan NA, Krupp F (2020) Freshwater fishes of the Arabian peninsula. Motivate Media Group, Dubai, United Arab Emirates
Friis G, Burt JA (2020) Evolution of mangrove research in an extreme environment: historical trends and future opportunities in Arabia. Ocean Coast Manag 195:105288. https://doi.org/10.1016/j.ocecoaman.2020.105288
Gallacher D, Hill J (2006a) Effects of camel versus oryx and gazelle grazing on the plant ecology of the Dubai desert conservation reserve. In: Reclaiming the desert - towards a sustainable environment in arid lands: Proceedings of the Third Joint UAE-Japan Symposium on Sustainable GCC Environment and Water Resources, vol 3, pp 85–95
Gallacher DJ, Hill JP (2006b) Effects of camel grazing on the ecology of small perennial plants in the Dubai (UAE) inland desert. J Arid Environ 66:738–750
Gardner A, Howarth B (2009) Urbanisation in the United Arab Emirates: the challenges for ecological mitigation in a rapidly developing country. BioRisk 3:27–38. https://doi.org/10.3897/biorisk.3.18

Gulseven O (2020) Measuring achievements towards SDG 14, life below water, in the United Arab Emirates. Mar Policy 117:103972. https://doi.org/10.1016/j.marpol.2020.103972

Gulseven O, Ahmed G (2022) The state of life on land (SDG 15) in the United Arab Emirates. Int J Soc Ecol Sustain Dev 13:1–15. https://doi.org/10.4018/IJSESD.306264

Haggag M, Hassan A, Elmasry S (2014) Experimental study on reduced heat gain through green façades in a high heat load climate. Energ Buildings 82:668–674. https://doi.org/10.1016/j.enbuild.2014.07.087

Hassan AA, Ezzeddine M, Kordy MGM, Awad MM (2023) Techno-economic assessment of atmospheric water harvesting (AWH) technologies. In: Fosso-Kankeu E, Al Alili A, Mittal H, Mamba B (eds) Atmospheric water harvesting development and challenges. Springer, Cham, pp 153–183. https://doi.org/10.1007/978-3-031-21746-3_8

Heaton C, Burns S (2014) An evaluation of environmental impact assessment in Abu Dhabi, United Arab Emirates. In: Impact assessment and project appraisal. Taylor & Francis, pp 1–6. https://doi.org/10.1080/14615517.2014.908004

Hellyer P, Aspinall S (2005) The emirates: a natural history. Trident Press, London

Howari F, Qafisheh N, Nazzal Y (2019) Environmental service-learning in the United Arab Emirates: is it mediated by the effects of biographical and demographical variables? Appl Environ Educ Commun 18:300–312. https://doi.org/10.1080/1533015X.2018.1473820

Howari FM, Sharma M, Nazzal Y, El-Keblawy A, Mir S, Xavier CM, Salem IB, Al-Taani AA, Alaydaroos F (2022) Changes in the invasion rate of *Prosopis juliflora* and its impact on depletion of groundwater in the northern part of the United Arab Emirates. Plan Theory 11:682

Howarth B, Khafaga T, Simkins G, Joseph S (2019) Ecosystems as commodity frontiers—challenges faced by land set aside as protected areas (PAs) in the Dubai Emirate, United Arab Emirates (UAE). In: Joseph S (ed) Commodity frontiers and global capitalist expansion: social, ecological and political implications from the nineteenth century to the present day. Springer, Cham, pp 111–136. https://doi.org/10.1007/978-3-030-15322-9_5

Jayaraman R, Colapinto C, Torre DL, Malik T (2015) Multi-criteria model for sustainable development using goal programming applied to the United Arab Emirates. Energy Policy 87:447–454. https://doi.org/10.1016/j.enpol.2015.09.027

Knight MH, Seddon PJ, Midfa AA (2011) Transboundary conservation initiatives and opportunities in the Arabian peninsula. Zool Middle East 54:183–195. https://doi.org/10.1080/09397140.2011.10648909

Korany B, Dessouki AEH, Korany B, Dessouki AEH (2010) Politics of constructive engagement: the foreign policy of the United Arab Emirates the foreign policies of Arab states: the challenge of globalization. American University in Cairo Press. https://doi.org/10.5743/cairo/9789774163609.003.0014

Krarti M, Dubey K (2018) Review analysis of economic and environmental benefits of improving energy efficiency for UAE building stock. Renew Sust Energ Rev 82:14–24. https://doi.org/10.1016/j.rser.2017.09.013

Lachkar Z, Mehari M, Lévy M, Paparella F, Burt JA (2022) Recent expansion and intensification of hypoxia in the Arabian Gulf and its drivers. Front Mar Sci 9. https://doi.org/10.3389/fmars.2022.891378

Lamine EB, Mateos-Molina D, Antonopoulou M, Burt JA, Das HS, Javed S, Muzaffar S, Giakoumi S (2020) Identifying coastal and marine priority areas for conservation in the United Arab Emirates. Biodivers Conserv 29:2967–2983. https://doi.org/10.1007/s10531-020-02007-4

Le Quesne WJF, Fernand L, Ali TS, Andres O, Antonpoulou M, Burt JA, Dougherty WW, Edson PJ, El Kharraz J, Glavan J, Mamiit RJ, Reid KD, Sajwani A, Sheahan D (2021) Is the development of desalination compatible with sustainable development of the Arabian Gulf? Mar Pollut Bull 173:112940. https://doi.org/10.1016/j.marpolbul.2021.112940

Liaqat MU, Mohamed MM, Chowdhury R, Elmahdy SI, Khan Q, Ansari R (2021) Impact of land use/land cover changes on groundwater resources in Al Ain region of the United Arab Emirates using remote sensing and GIS techniques. Groundw Sustain Dev 14:100587. https://doi.org/10.1016/j.gsd.2021.100587

Lincoln S, Buckley P, Howes EL, Maltby KM, Pinnegar JK, Ali TS, Alosairi Y, Al-Ragum A, Baglee A, Balmes CO, Hamadou RB, Burt JA, Claereboudt M, Glavan J, Mamiit RJ, Naser HAA, Sedighi O, Shokri MR, Shuhaibar B, Wabnitz CCC, Le Quesne WJF (2021) A regional review of marine and coastal impacts of climate change on the ROPME sea area. Sustainability 13:13810. https://doi.org/10.3390/su132413810

Luomi M (2022) Environmental change and security. In: Gueraiche WA, K (ed) Facets of security in the United Arab Emirates. Routledge, Milton Park, Oxfordshire, pp 36–49 https://doi.org/10.4324/9781003025566-6

Maes J, Jacobs S (2017) Nature-based solutions for Europe's sustainable development. Conserv Lett 10:121–124. https://doi.org/10.1111/conl.12216

Maitner AT, Stewart-Ingersoll R (2016) Social identity and peace in the modern Middle East: insights from the United Arab Emirates. In: McKeown S, Haji R, Ferguson N (eds) Understanding peace and conflict through social identity theory: contemporary global perspectives. Springer, Cham, pp 317–331. https://doi.org/10.1007/978-3-319-29869-6_20

Marketos T, Mazzucchi N, Alexopoulos TA (2022) Energy transitions in EM and MENA regions, towards new alliances? Geostrategic alliances in the eastern Mediterranean and MENA: a universal paradigm shift. Springer, Cham, pp 69–84. https://doi.org/10.1007/978-3-030-97593-7_8

Mateos-Molina D, Antonopoulou M, Baldwin R, Bejarano I, Burt JA, Garcia-Charton JA, Al-Ghais SM, Walgamage J, Taylor OJS (2020) Applying an integrated approach to coastal marine habitat mapping in the North-Western United Arab Emirates. Mar Environ Res 161:105095. https://doi.org/10.1016/j.marenvres.2020.105095

Mateos-Molina D, Ben Lamine E, Antonopoulou M, Burt JA, Das HS, Javed S, Judas J, Khan SB, Muzaffar SB, Pilcher N, Rodriguez-Zarate CJ, Taylor OJS, Giakoumi S (2021) Synthesis and evaluation of coastal and marine biodiversity spatial information in the United Arab Emirates for ecosystem-based management. Mar Pollut Bull 167:112319. https://doi.org/10.1016/j.marpolbul.2021.112319

Melville-Rea H, Eayrs C, Anwahi N, Burt JA, Holland D, Samara F, Paparella F, Al Murshidi AH, Al-Shehhi MR, Holland DM (2021) A roadmap for policy-relevant sea-level rise research in the United Arab Emirates. Front Mar Sci 8. https://doi.org/10.3389/fmars.2021.670089

Meyer S, Warren MA (2021) Exploring the role of character strengths in the endorsement of gender equality and pro-environmental action in the UAE. Middle East J Posit Psychol 7:65–80

MOCCAE (2021) UAE Net Zero 2050. UAE Ministry of Climate Change and the Environment, Dubai. https://u.ae/en/information-and-services/environment-and-energy/climate-change/theuaesresponsetoclimatechange/uae-net-zero-2050. Accessed 24 March 2023

Morton MQ (2016) Keepers of the golden shore: a history of the United Arab Emirates. Reaktion Books, London, UK

Murad AA (2010) An overview of conventional and non-conventional water resources in arid region: assessment and constrains of the United Arab Emirates (UAE). Journal of Water Resource and Protection 02(02):181. https://doi.org/10.4236/jwarp.2010.22020

Natoli A, Moura AE, Sillero N (2022) Citizen science data of cetaceans in the Arabian/Persian Gulf: occurrence and habitat preferences of the three most reported species. Mar Mamm Sci 38:235–255. https://doi.org/10.1111/mms.12865

Nyarko Y (2010) The United Arab Emirates: some lessons in economic development (Working Paper No. 2010/11). United Nations University - World Institute for Development Economics Research, Helsinki, Finland

O'Brien J, Keivani R, Glasson J (2007) Towards a new paradigm in environmental policy development in high-income developing countries: the case of Abu Dhabi, United Arab Emirates. Prog Plan 68:201–256. https://doi.org/10.1016/j.progress.2007.09.001

Obaideen K, Nooman AlMallahi M, Alami AH, Ramadan M, Abdelkareem MA, Shehata N, Olabi AG (2021) On the contribution of solar energy to sustainable developments goals: case study on Mohammed bin Rashid Al Maktoum Solar Park. Int J Thermofluids 12:100123. https://doi.org/10.1016/j.ijft.2021.100123

Paparella F, Xu C, Vaughan GO, Burt JA (2019) Coral bleaching in the Persian/Arabian Gulf is modulated by summer winds. Front Mar Sci 6:1–15. https://doi.org/10.3389/fmars.2019.00205

Paparella F, D'Agostino DA, Burt J (2022) Long-term, basin-scale salinity impacts from desalination in the Arabian/Persian Gulf. Sci Rep 12:20549. https://doi.org/10.1038/s41598-022-25167-5

Pittman SJ, Stamoulis KA, Antonopoulou M, Das HS, Shahid M, Delevaux JMS, Wedding LM, Mateos-Molina D (2022) Rapid site selection to prioritize coastal seascapes for nature-based solutions with multiple benefits. Front Mar Sci 9. https://doi.org/10.3389/fmars.2022.832480

Riegl B, Johnston M, Purkis S, Howells E, Burt J, Steiner S, Sheppard C, Bauman A (2018) Population collapse dynamics in *Acropora downingi*, an Arabian/Persian Gulf ecosystem-engineering coral, linked to rising temperature. Glob Chang Biol 24:2447–2462. https://doi.org/10.1111/gcb.14114

Ryan SE, Dabrowski V, Dapoigny A, Gauthier C, Douville E, Tengberg M, Kerfant C, Mouton M, Desormeau X, Zazzo A, Bouchaud C (2021) Strontium isotope evidence for a trade network between southeastern Arabia and India during antiquity. Sci Rep 11:303. https://doi.org/10.1038/s41598-020-79675-3

Sakkir S, Shah JN, Cheruth AJ, Kabshawi M (2015) Phenology of desert plants from an arid gravel plain in eastern United Arab Emirates. J Arid Land 7:54–62. https://doi.org/10.1007/s40333-014-0036-2

Sale PF, Feary D, Burt JA, Bauman A, Cavalcante G, Drouillard K, Kjerfve B, Marquis E, Trick C, Usseglio P, van Lavieren H (2011) The growing need for sustainable ecological management of marine communities of the Persian Gulf. Ambio 40:4–17. https://doi.org/10.1007/s13280-010-0092-6

Samour A, Baskaya MM, Tursoy T (2022a) The impact of financial development and FDI on renewable energy in the UAE: a path towards sustainable development. Sustainability 14:1208

Samour A, Shahzad U, Mentel G (2022b) Moving toward sustainable development: assessing the impacts of taxation and banking development on renewable energy in the UAE. Renew Energy 200:706–713. https://doi.org/10.1016/j.renene.2022.10.020

Scherf A, Abed R, Rullkötter J (2007) Lipid biomarkers as indicators for environmental stress in cyanobacterial mats of Abu Dhabi, United Arab Emirates. Geochim Cosmochim Acta 71:A888

Seddon N, Smith A, Smith P, Key I, Chausson A, Girardin C, House J, Srivastava S, Turner B (2021) Getting the message right on nature-based solutions to climate change. Glob Chang Biol 27:1518–1546. https://doi.org/10.1111/gcb.15513

Sgouridis S, Abdullah A, Griffiths S, Saygin D, Wagner N, Gielen D, Reinisch H, McQueen D (2016) RE-mapping the UAE's energy transition: an economy-wide assessment of renewable energy options and their policy implications. Renew Sust Energ Rev 55:1166–1180. https://doi.org/10.1016/j.rser.2015.05.039

Shahid M (2017) Goats: a threat to biodiversity in the United Arab Emirates. Tribulus 25:4–12

Shahin SM, Salem MA (2015) The challenges of water scarcity and the future of food security in the United Arab Emirates (UAE). Natural. Resour Conserv 3:1–6. https://doi.org/10.13189/nrc.2015.030101

Sherif M, Sefelnasr A, Ebraheem AA, Al Mulla M, Alzaabi M, Alghafli K (2021) Spatial and temporal changes of groundwater storage in the quaternary aquifer, UAE. Water 13:864

Soorae P, Els J, Gardner D, El Alqamy H (2013) Distribution and ecology of the Arabian and Dhofar toads (*Duttaphrynus arabicus* and *D. dhufarensis*) in the United Arab Emirates and adjacent areas of northern Oman. Zool Middle East 59:229–234. https://doi.org/10.1080/09397140.2013.841428

Steffen W, Grinevald J, Crutzen P, McNeill J (2011) The Anthropocene: conceptual and historical perspectives. Philos Trans R Soc A Math Phys Eng Sci 369:842–867. https://doi.org/10.1098/rsta.2010.0327

Tourenq C, Launay F (2008) Challenges facing biodiversity in the United Arab Emirates. Manag Environ Qual Int J 19:283–304

Tourenq C, Khassim A, Sawaf M, Shuriqi MK, Smart E, Ziolkowski M, Brook M, Selwan R, Perry L (2009) Characterisation of the Wadi Wurayah catchment basin, the first mountain protected area in the United Arab Emirates. Int J Ecol Environ Sci 35:289–311

Tourenq C, Brook M, Knuteson S, Shuriqi MK, Sawaf M, Perry L (2011) Hydrogeology of Wadi Wurayah, United Arab Emirates, and its importance for biodiversity and local communities. Hydrol Sci J 56:1407–1422. https://doi.org/10.1080/02626667.2011.631139

Ulrichsen KC (2016) The United Arab Emirates: power, politics and policy-making. Taylor & Francis, London

Umar T, Umeokafor N (2022) Exploring the GCC progress towards United Nations sustainable development goals. Inte J Soc Ecol Sustain Dev 13:1–32. https://doi.org/10.4018/IJSESD.2022010105

Umar T, Egbu C, Ofori G, Honnurvali MS, Saidani M, Shibani A, Opoku A, Gupta N, Goh K (2020) UAE's commitment towards UN sustainable development goals. Eng Sustain 173:325–343

Van Lavieren H, Klaus R (2013) An effective regional marine protected area network for the ROPME sea area: unrealistic vision or realistic possibility? Mar Pollut Bull 32:389–405. https://doi.org/10.1016/j.marpolbul.2012.09.004

van Lavieren H, Burt J, Feary D, Cavalcante G, Marquis E, Benedetti L, Trick C, Kjerfve B, Sale PF (2011) Managing the growing impacts of development on fragile coastal and marine systems: lessons from the Gulf. A policy report. United Nations University - Institute for Water, Environment, and Health. Hamilton, ON, Canada

Vine P, Al-Abed I (1996) Natural emirates: wildlife and environment of the United Arab Emirates. Trident Press, Dublin