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Conserving Ras Al Khaimah's Botanical Diversity

Marina Tsaliki, Landscape Agency – Public Services Department – Ras Al Khaimah

Chloe MacLaren, Rothamsted Research

EXECUTIVE SUMMARY

Ras Al Khaimah is home to a diverse ecosystem of plant species, many of which have medicinal uses and cultural significance in addition to supporting wildlife. As the human population and associated urban development increases in the Emirate, it is essential to ensure the national heritage related to plant diversity is protected. In this policy paper, we present the results of an emirate-wide botanical survey that explores how the plant species, present across Ras Al Khaimah, vary according to the Emirate's geography. In total, 320 plant species were documented in the survey, 293 of which were identified. Some of the recorded species are either uniquely found in the Emirate or are rare and endangered. Four main vegetation types have been identified in the Emirate: coastal and lowland vegetation, plains vegetation, low mountain vegetation, and high mountain vegetation. Within each of these, there are several distinct subtypes that contain unique species and species common to the primary vegetation type.

Additionally, this paper collates all known medicinal plants in Ras Al Khaimah and reports their medicinal uses according to Emirati tradition. 103 of the 320 plants recorded in the botanical survey have known medicinal uses for various ailments. Knowledge of these medicinal uses, however, is at risk of being lost due to changes in lifestyle and the increasing modernization of medicine.

A robust conservation plan should protect all vegetation types identified in this survey. In particular, we recommend that greater attention is paid to three areas of high importance for plant biodiversity: the mountains Jabal Jais and Jabal Sahab (Wadi Sfai) and the mangroves along Ras Al Khaimah's coast. These sites include plant species of high priority only found in a single location, locations with decreasing populations, or both. Conservation should further encompass safeguarding the knowledge and variety of uses of medicinal plants and the areas and seasons in which they can be gathered. We suggest using an approach that: 1) preserves knowledge through the creation of a database of local knowledge and; 2) raises awareness through public education in schools and museums. Conserving wild plants and their respective cultural traditions is critical to the sustainability of Ras Al Khaimah's natural and cultural heritage.

Introduction

Ras Al Khaimah encompasses various natural habitats, including mountain ranges, hills, coastal dunes, mangroves, gravel plains, and desert. These landscapes can seem universally harsh in their aridity or salinity. However, the variations in environmental conditions, such as temperature, water availability, and soil type, that define the habitats allow for a great diversity of flora and fauna. The complete range of species present in Ras Al Khaimah has yet to be fully cataloged and investigated. There is a particular lack of information on the diversity and distributions of plants.

Understanding plants is critical to understanding ecosystems. Plants are at the interface of the physical environment and biological communities: as primary producers, plants convert sunlight, carbon dioxide, and soil nutrients into oxygen and biomass, providing food and air to other organisms. Plants also influence their physical environment by creating shade, intercepting rainfall, stabilizing soil, and cycling nutrients. These effects are particularly critical in locations with harsh physical conditions, like Ras Al Khaimah. Many plants have unique adaptations to high salt levels, high temperatures, and low rainfall and can turn even these inhospitable environments into habitats for other organisms.

For millennia, communities have used plants as resources for food, fodder, fiber, medicines, cosmetics, construction materials, and fuel. The Arabian Peninsula has a particularly strong tradition in the use of medicinal plants. Until recently, such medicinal plants were the only form of treatment known and available in the region (Ghazanfar, 1994). In recent decades, clinics for traditional medicine and herbs have been established, and medicinal plants are still used in Ras Al Khaimah to treat minor ailments or in combination with modern medicine to improve outcomes. Ongoing research has revealed the active medicinal components of these plants, which may lead to more effective use in treatments or the development of new pharmaceutical products.

Plants are vital in providing habitats and resources that support both wildlife and people (Maestre et al., 2012). However, wild plants in Ras Al Khaimah are under threat due to several factors, including the effects of climate change, desertification, overgrazing, invasive species, stone mining, urban development, and road construction (Keblawy, 2014; Abahussain et al., 2002; Ministry of Environment and Water, 2012; Ghazanfar & Osborne, 2010). To understand how these different threats will affect Ras Al Khaimah's plant diversity, we must urgently increase our knowledge of plant species' distribution and habitat requirements across the Emirate. Greater understanding will allow us to identify the plants most at risk and help prioritize areas for conservation, such as landscapes that support high plant diversity or a greater number of rare species.

In this paper, we present the results of an in-depth botanical survey of Ras Al Khaimah. The presence and abundance of plant species were quantified in different locations across the Emirate. A statistical classification was used to identify distinct plant communities - groups of plants that typically co-occur in the same areas. The presence of each community was linked to local geographic conditions, including elevation, slope, incident solar radiation, flow accumulation, and distance from the coast. These geographic conditions were selected due to their relevance to local temperature and water availability, which are critical drivers of vegetation composition, abundance, and diversity in arid areas (Wang et al., 2019). Using geographic information systems (GIS), these geographic conditions were then used to predict the distributions of different plant communities across Ras Al Khaimah. The resulting vegetation map can be used to understand how the distributions of different plant communities intersect with potential threats to their continued survival and thus identify priority areas and management actions for plant conservation.

In addition to the survey of plant distributions, the literature review presents all known traditional remedies and medicinal uses of plants in Ras Al Khaimah. The medicinal uses of plants illustrate the critical role plants have played in Ras Al Khaimah's history. Thus, the Emirate's cultural and natural heritage are fundamentally intertwined. Currently, both plants and their cultural and traditional significance are at risk of being lost: wild plants' habitats are being degraded, and opportunities to pass traditional knowledge between generations diminish with modern lifestyle changes. If action is not taken, this national heritage will soon disappear. Accordingly, this paper seeks to inform priorities for the conservation of Ras Al Khaimah's plants in the wild and provide knowledge of plants' medicinal properties to the Emirate's people.

Context and Background

Three major ecotypes, coastline, desert, and mountains (including wadis), form Ras Al Khaimah's cultural environment, and botanical studies have been conducted throughout the UAE to understand their levels of biodiversity (EWS-WWF in preparation; Gairola et al., 2016; Jongbloed, 2003; Mahmoud et al., 2016; Western, 1989). In the United Arab Emirates, plant species count varies substantially. Western (1989) documented 450-500 species, the World Wildlife Fund notes up to 600 recorded plants, while other authors have detailed more than 800 native and naturalized plant species (Karim & Fawzi, 2007; Feulner, 2011; Shahid, 2014). Feulner (2011, 2014) has presented further in-depth studies focusing primarily on the northern mountains and adding new findings to the list of total species. Many of these plants are highly specialized, given the extreme conditions, and exhibit adaptations to high salt levels, high temperatures, and low rainfall. Along the coast, the mangroves are represented by a single species, *Avicennia marina* (*qurm*[1]). At lower elevations, such as in plains and dunes, common species are *Zizyphus spina-christi* (*sidr*), *Prosopis cineraria* (*ghaf*), and *Vachellia tortilis* (*samr*). In the mountains and wadis, *Vachellia tortilis* is joined by *Moringa peregrina* (*shushu'aFicus salicifolia* and *Ficus johannis* (*teen* species)). The coastal areas and inter-tidal marshes showcase various salt-tolerant scrub, the most common being *Haloxylon salicornicum* (*rimth*).

The recently undertaken International Union for Conservation of Nature (IUCN) Plant Red List Assessment for the UAE states that the greatest prevalence of threatened species occurs across coastal and mountainous areas (IUCN 2020, unpublished data). This is due in part to ongoing urban development, which reduces coastal habitat. Moreover, the limited ecological distribution range of mountainous species places them at risk from local disturbances (e.g., mining, road-building, tourism, infrastructure) and global climate change. The impact of climate change is often more significant in mountainous regions (Pepin et al., 2015). Species in isolated habitats also find it more challenging to shift their distributions in response to changing conditions (Graae et al., 2018).

Plants underpin Ras Al Khaimah's wildlife diversity by providing its various habitats with the resources required to support animal food webs. Consequently, the findings of our botanical survey could be used to determine which areas of Ras Al Khaimah should be considered as protected areas in the future or prioritized for other conservation management actions. Protecting the full range of plant species and vegetation types across Ras Al Khaimah will contribute significantly to the conservation of all other wildlife by safeguarding the Emirate's habitat and resource diversity.

Research and Findings

Botanical Field Survey

A plot sampling methodology that sampled 232 plots was used to assess Ras Al Khaimah's plant diversity. 100m² (10x10m) plots were randomly sampled; data included elevation, last rainfall, ratio of stone, soil/sand cover, and the percent of plot covered by the plant species present (a measure of abundance). Any obvious disturbances were also documented.

[1] The Arabic names of the species are in parenthesis.

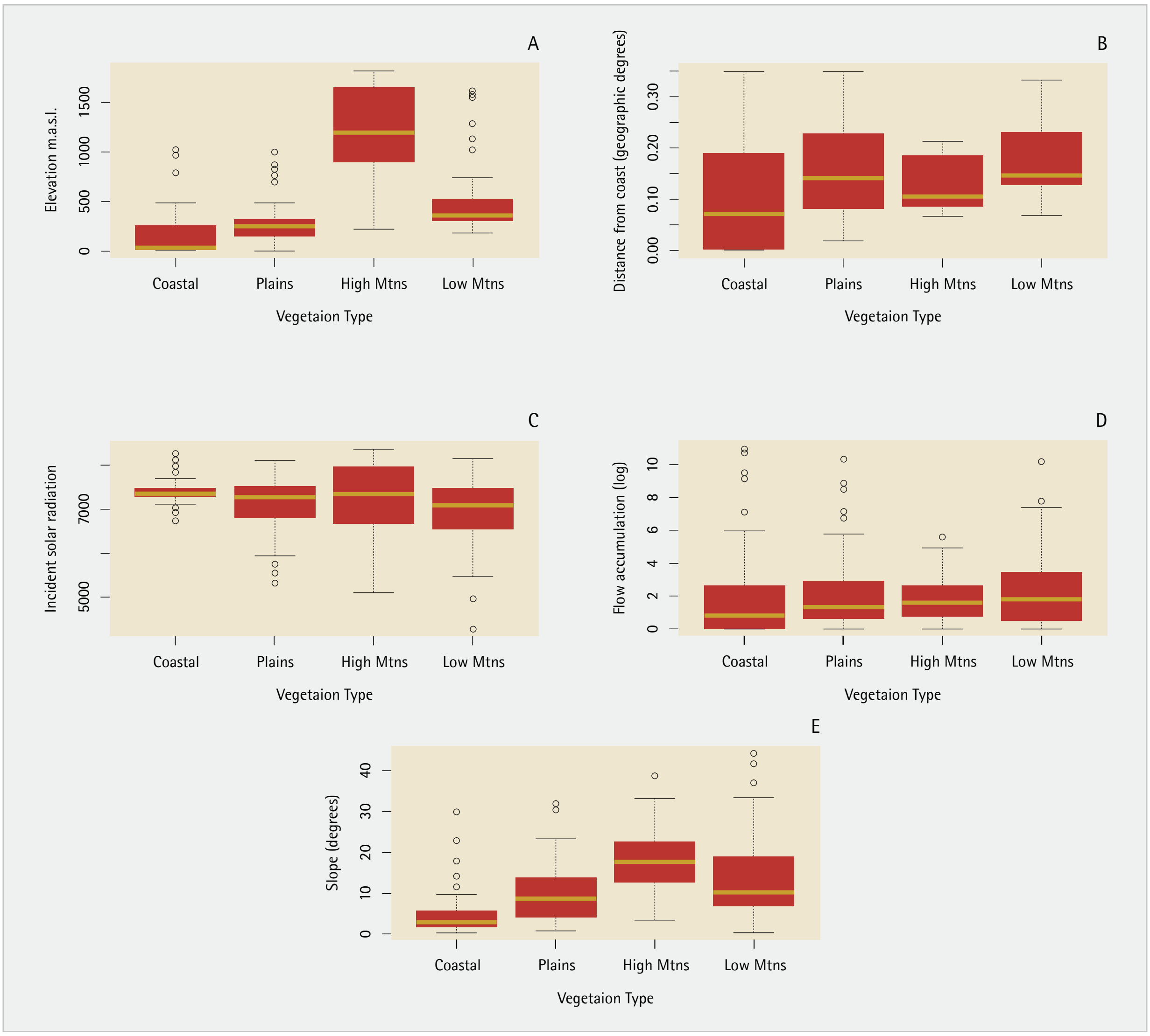
In total, 320 plant species, classified into 217 genera and 67 plant families, were recorded and identified throughout Ras Al Khaimah (see Appendix A for further information; 26 specimens await further identification). Some plant families included more species than others, the most common being the Poaceae (grasses) with 41 species, closely followed by Asteraceae (Daisy family) with 36 species, and Fabaceae (Pea family) with 28 species. Several plants were commonly seen across all habitats and regions, whereas others were more restricted. Examples of common plants found in multiple habitats are *Tephrosia apollinea*, *Lycium shawii*, *Acacia tortilis*, and *Cymbopogon* ssp.. In contrast, *Pycnocycla aucheriana* and *Prunus arabica* are only found at high elevation sites of the northern mountains. Meanwhile, *Leptadenia pyrotechnica* grows in sand dunes and halophytes, a salt-tolerant species, grow in coastal areas and beaches, reaching into the dunes and gradually being replaced by desert-adapted species such as *Dipterygium glaucum*, *Prosopis cineraria*, and *Pennisetum divisum*.

Habitat Mapping

The records of plant species and their cover at each site in the botanical survey allowed, firstly, for the identification of distinct vegetation types (groups of species that typically occur together), and secondly, for an investigation into where the different vegetation types occur in relation to environmental conditions and geography. Cluster analysis was used to identify the vegetation types, and statistical analysis, using the multinomial logistic regression model, investigated the occurrence of vegetation types in specific environments (see Appendix B for more details).

The environmental model was then used to predict vegetation types across Ras Al Khaimah to create a vegetation map, using geographic variables available at an emirate-wide scale: elevation, slope, incident solar radiation, flow accumulation, and distance from the coast. Together, these variables provide a strong indication of variations in temperature and moisture across the landscape. This procedure of cluster analysis, modeling, and mapping is necessary to increase our

Figure 1: The occurrence of the four main vegetation types in relation to geographic environmental variables, (a) elevation, (b) distance from coast, (c) annual incident solar radiation, (d) log flow accumulation, and (e) slope



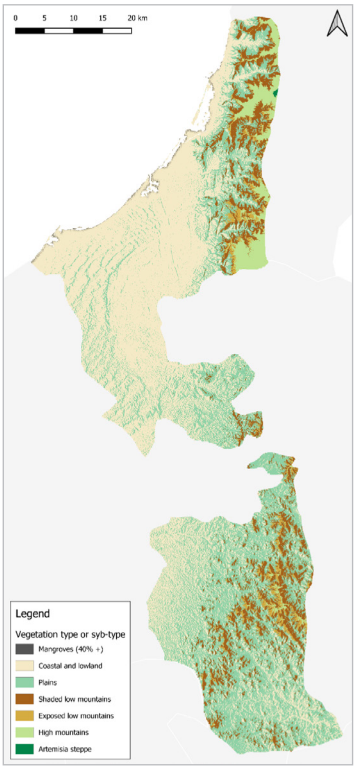
understanding of the plant species of Ras Al Khaimah, their distributions, and their relationship with the physical environment. The information can help determine which areas of the Emirate are most critical for conservation to preserve plant diversity and locally endemic or culturally important plant species.

Four main vegetation types were identified through cluster analysis (Appendix B, Figure B1). These vegetation types can be loosely described by their habitat preferences as "coastal and lowland," "plains," "low mountain," and "high mountain." These four main vegetation types are separated primarily by elevation. Within them, distinct subtypes occur in areas with differences in incident solar radiation (temperature) and flow accumulation (water availability) (see Figure 1). These subtypes contain species common to their primary vegetation type and species only found in more specific environmental conditions. We found elevation, solar radiation, and flow accumulation as explanatory variables to account for the presence of different vegetation types. This finding confirms that temperature and moisture availability are important factors determining which plants can survive in different landscapes.

Each of the four main vegetation types had multiple subtypes, but these could not all be included in the models and map due to the limited number of sample sites within each subtype.[2] The three most distinct subtypes were included because they either occurred in very specific conditions or contained a relatively large number of sites: the coastal mangroves, the high mountain *Artemisia* steppe, and the shaded and exposed subtypes of the low mountains. The four main vegetation types and these three subtypes are, thus, the seven types shown on the map (Figure 2), while more minor subtypes are discussed in the text.

The vegetation types differed in their total cover and the richness of their species variability. Vegetation cover was generally low and rarely reached 50%, with the exception of the mangroves and the Artemisia steppe on the plateau

Figure 2: Map of Ras Al Khaimah showing vegetation types with maximum predicted probability for each 30x30m pixel



of Jabal Jais (Table 1). The lowest vegetation cover was found in the plains between Khatt and Adhen/Ghail, where the number of species ranged from one to 11 per plot.

Mangroves had the highest vegetation cover but the lowest number of species per plot (a mean of two per plot, ranging from one to siz species). The highest numbers of species per plot were found in mountain areas with up to 19 species per plot.

In the following sections, we provide details on each of the four main vegetation types and their subtypes, including their relationship to environmental conditions, their predicted occurrence across Ras Al Khaimah, and their characteristics, such as diversity, cover, and indicator species.

Table 1: Habitat types in relation to environmental factors (elevation, rock, soil substrate, and water features), vegetation cover, and plant species numbers (mean values)

Habitat		Elevation (m)	Rock (%)	Soil substrate (%)	Water features (%)	Vegetation cover (%)	Plant species nr. (mean)	Plant species nr. (range)
Mountain high	1	1526.9	75.9	24.1	0	40.2	8	3-17
Mountain med.	2	966.7	80.4	19.6	0	38.8	10	3-17
Mountain low	3	366.8	68.3	31.7	0	36.7	9	2-16
Wadi	4	333.9	65.3	34.3	0.3	43.1	8	1-19
Dunes/Desert	5	30.2	0	100	0	44	9	2-18
Plains	6	101.2	27.9	72.1	0	35.9	5	1-11
Mangrove/Marsh	7	-11.6	0	27	73	79	2	1-6

[2] This would reduce model predictive power.

1. Coastal and Lowland Vegetation

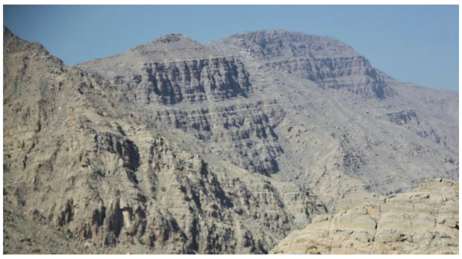
The coastal and lowland vegetation type is generally found in areas of low elevation that receive high solar radiation. This vegetation type has high diversity between sites, as indicated by its many subtypes (Appendix 1). Of the subtypes, the mangrove sites have the most significant distinction. They are dominated by *Avicennia marina*, contain few other species, and occur only in areas very close to the coast. The other coastal subtypes can be distinguished between those found in desert areas (deserts, coastal deserts, saline deserts[3], and *Prosopis* groves) and those found on rocky plains and low hills (*Rhazya* plains and southern wadi sites). Vegetation cover and within-site diversity are variable within the coastal and lowlands vegetation type. The mangrove subtype typically has low diversity and high cover, while the coastal desert subtype has relatively high diversity. Moreover, all desert subtypeshave low vegetation cover.

Figure 3: A coastal mangrove site in Ras Al Khaimah city

2. Plains Vegetation

The plains vegetation type is characterized by the presence of *Vachellia tortilis* and is widespread throughout the plains and lowland wadi areas of Ras Al Khaimah. This type tends to occur in areas with slightly higher moisture availability and a little more shade than the coastal vegetation type but otherwise occupies a similar environment. In general, plains vegetation has relatively low diversity and intermediate vegetation cover. It can be divided into two subtypes. One subtype occurs more frequently in large mountain wadis with higher flow accumulation and lower incident solar radiation and tends to have a greater abundance of *Vachellia tortilis*. The other subtype tends to occur on plains and wadis in hilly areas but is not distinguished by the presence of any particular species.

Figure 4: Vachellia plains near Wadi Bih



3. Low Mountain Vegetation

The low mountain vegetation type occurs in mountainous areas at low elevations and has intermediate diversity and intermediate cover relative to the other main types. It has two distinct subtypes: the first subtype is typically found in more shaded areas with higher moisture availability, while the second subtype is found in drier, more exposed areas with higher solar radiation. The occurrence of the second subtype in exposed slopes was not well predicted by the map as several different vegetation types can occur in similar conditions, primarily the high mountain type and low mountain shaded subtype. Therefore, the model does not predict a high probability of any particular type occurring. If the survey is extended in the future, it may be worth exploring these exposed slopes further to determine which vegetation types can be found in specific locations.

Figure 5: Low to medium elevation mountain slopes above Khatt Village

4. High Mountain Vegetation

The high mountain vegetation type typically occurs at elevations higher than 800 meters above sea level (m.a.s.l)., and is notable for having the highest species diversity of all vegetation types. It can be divided into four subtypes that occur at different elevations. The most distinct of these is the *Artemisia* steppe subtype, which is found exclusively above 1700m (Figure 3). The other three subtypes occur in different bands, between 1300m and 1600m, between 900m and 1200m, and between 600m to 900m. At higher elevations, temperatures drop, and moisture provided by mist may also be more common. It may therefore be easier for a greater abundance and diversity of plants to survive at higher elevations. All high mountain subtypes had relatively high diversity. Among these, the subtype found around 1000m had the highest diversity, while *Artemisia* steppe had the highest vegetation cover.

Figure 6: A high elevation site within the Artemisia steppe subtype on Jabal Jais mountain

[3] The "saline desert" subtype is named for the presence of halophytic species in these sites (indicating saline soils, not coastal salinity).

Endangered Plants and Habitats: Threats and Causes for Reduction and Loss

Endangered Plants and Threats

Potential threats to wild plants in Ras Al Khaimah include habitat loss to development, infrastructure, and extractive activities (such as mining) and habitat degradation from climate change, pollution, overgrazing, and invasive species. The intensity of these threats varies in different parts of the Emirate, but their combined impact on plant life is already apparent. The recently compiled IUCN plant red list for the UAE concluded that five percent of Ras Al Khaimah's native plant species are endangered (unpublished data). Several species found in Ras Al Khaimah are already noted on the global IUCN plant red list as near threatened, vulnerable, or endangered (Table 2).

Mainly at risk are plants with specialized habitat requirements that occur only under specific environmental conditions. The four most endangered species recorded in this survey are *Echiochilon jugatum, Limonium carnosum, Polygala irregularis,* and *Rhanterium epapposum*. These four species inhabit plains and coastal areas where they are subject to overgrazing by camels and goats and habitat loss to urban development. All sites with *Avicennia marina* (the Grey Mangrove, listed as "near threatened") were located close to Ras Al Khaimah city, which may be affected by polluted urban run-off and siltation caused by construction (Ellison & Farnsworth, 1996; Assaf, 2020). However, the mangrove is a species of high importance, storing large amounts of atmospheric carbon dioxide (Donato et al., 2011; WWF, 2020) and being a crucial nesting area or refuge for many bird species, fish, and crustaceans below water.

Olea europaea, *Glossonema varians*, and *Jurinea berardioides* (listed as vulnerable and near threatened respectively by the IUCN) were found only in the high mountain type; thus, they are most likely to be affected by climate change. As global temperatures rise, it is common to observe species sensitive to high temperatures dying out in the lower elevations of their range and becoming confined to increasingly small areas in high mountains. This upward elevational shift in species ranges can eventually lead to extinction when even the summits of the mountains become too warm for sensitive species (Walther et al., 2009; Pauli et al., 2012).

Effects of Climate Change on Plants

Climate change is a significant concern for Ras Al Khaimah and neighboring states, given that diverse and unique vegetation communities occur at high elevations. These communities are at risk of losing suitable habitats as temperatures rise. Notably, the *Artemisia* steppe vegetation type was only observed above 1750m, an elevation reached by only one mountain in the Emirate, Jabal Jais. Anecdotal evidence suggests this vegetation type was also previously present on Jabal Yanis, but it was not found there in this survey. This indicates that an elevational shift has been occurring, and the range of the *Artemisia* steppe vegetation type is retracting. If temperatures continue to rise, *Artemisia* steppe vegetation type may eventually disappear entirely from Ras Al Khaimah. Evidence of upward elevational shift of montane plant species at high altitudes has also been observed in neighboring Oman (MacLaren, 2016).

Some plants with specialized habitats may not yet be threatened but are vulnerable to future habitat loss or changes. These include plants with highly specific habitat requirements. For example, halophytes require inland saline conditions, and parasitic plants require the presence of their hosts, such as *Cistanche tubulosa* and *Cuscuta planiflora*. Plants that are endemic to small geographic regions also need to be kept under observation since changes in climate and habitat can cause population sizes to decrease rapidly and lead the species to extinction. In Ras Al Khaimah, this is the case for *Desmidorchis arabica, Echinops erinaceus, Pulicaria edmondsonii*, and *Pteropyrum scoparium* (El Keblawy, 2014). These species are endemic to Eastern Arabia, and the limited population found in Ras Al Khaimah is declining in their distribution range.

Table 2: Plant species categorized as threatened in the United Arab Emirates, according to the 2019 IUCN assessment

Species	IUCN category
Avicennia marina	NT
Corchorus depressus	NT
Eciochilon callianthum	VU
Echiochilon jugatum	EN
Glossonema varians	NT
Halopyrum mucronatum	VU
Jurinea berardioides	NT
Limonium carnosum	EN
Nannorrhops ritchieana	NT
Olea europaea	VU
Polygala irregularis	EN
Rhanterium epapposum	EN
Rosularia adenotricha	NT
Triraphis pumilio	VU

Note: The IUCN Red List categories applied here, in order of declining extinction risk, are: CR = Critically Endangered (not applicable to any species), EN = Endangered, VU = Vulnerable, and NT = Near Threatened.

Priority Areas for Conservation

Thus far, the results of our survey and knowledge of current threats suggest that the *Artemisia* steppe sites on Jabal Jais and possibly Jabal Yanis, as well as the mangrove areas along the coast, require the most urgent conservation efforts to protect their restricted areas of remaining habitat. Concurrently, continued observation of other vegetation types, with particular attention paid to rare and endemic species, is recommended to monitor whether further action should be taken. In addition, we can advance our understanding of the threats to different plant species and vegetation types in Ras Al Khaimah by combining the vegetation map provided in this paper with maps of human activities such as urbanization, farming, road construction, and mining. The overlap between the ranges of each vegetation type and these threats could then be assessed to prioritize the types of vegetation that most urgently need protection from specific threats. Appropriate identification of conservation management actions that would be most effective to sustain a high wild plant diversity across Ras Al Khaimah could then be undertaken.

Medicinal Plants of Ras Al Khaimah

Within the UAE, many native plants have known medicinal and traditional uses (Sajjad et al., 2017; Sakkir et al., 2012). The literature provides descriptions of over 100 plant species found in Ras Al Khaimah and used to treat and cure illnesses (Table 3). All plants are native or have adapted to growing in the prevailing harsh conditions for hundreds of years. All plant forms – trees, shrubs, flowering plants, and grasses – are represented. Medicinal practices use differing plant parts (e.g. flowers, leaves, roots, bark), and preparation may include drying, boiling, mashing, and exuding oils or plant sap. The prepared medicine might be used by inhaling smoke, rubbing creams onto the affected areas, or eating and swallowing ointments or pastes. The main illnesses and ailments treated with the plants were diarrhea, toothache, skin rashes, muscle and bone pains, fever, coughs, and general pain relief. Plants were also used to comfort during and strengthen after childbirth, relieve menstruation issues, and treat liver and kidney failure, cataracts, vomiting, and bruising.

As part of the UAE's history and cultural heritage, the preservation of traditional medicinal knowledge is of high relevance. For centuries, knowledge of herbal medicine was passed on verbally from one generation to the next, in most cases, by women to their daughters or nieces. The young women would watch and accompany the mothers into the field, learning when and where to collect the appropriate plant parts and how to process them further. None of the information was preserved in writing. Nowadays, knowledge of plants and their uses is being lost due to the reliance on modern medicine and effective treatment in hospitals. Lifestyle changes have led to a lack of time and interest from the younger generations. Furthermore, plants are not as readily available anymore (potentially due to the environmental pressures described above), making them harder to find when the need arises. Therefore, the in-depth knowledge of plant cures and treatments is gradually vanishing.

Table 3: A subset of native plants collected and used to treat common ailments

Concern	Treatment by Plant Species
Skin problems	*Cocculus pendulus, Euphorbia larica, Lysimachia arvensis, Periploca aphylla*
Childbirth (prepartum, delivery, & postpartum)	*Capparis cartilaginea, Dactyloctenium aegyptium, Haplophyllum tuberculatum, Moringa peregrina, Pergularia tomentosa*
Coughs and asthma	*Nerium oleander, Pycnocycla aucheriana, Rhazya stricta, Suaeda vermiculata*
Infections and disinfection	*Blepharis ciliaris, Ficus cordata, Suaeda aegyptiaca, Tetraena simplex, Ziziphus spina-christi*
Wounds	*Aerva javanica, Calotropis procera, Chrozophora oblongifolia*
Fever	*Arnebia hispidissima, Artemisia sieberi, Malva parviflora, Sisymbrium irio*
Bone fractures and muscle pain	*Cleome amblyocarpa, Dodonaea viscosa, Olea europaea, Prosopis cineraria, Tephrosia apollinea*
Digestive system	Asphodelus tenuifolius, Cistanche tubulosa, Cynomorium coccineum, Emex spinosa, Fagonia indica, Lavandula subnuda, Ochradenus arabicus, Senna italica, Sonchus oleraceus

Recommendations

Protecting Ras Al Khaimah's Diversity

Any plant conservation strategies or management plans for Ras Al Khaimah should aim to safeguard the full range of plant species in the Emirate. This would maximize the diversity of resources and habitats available to support other wildlife and conserve the richness of medicinal plants that have helped sustain Ras Al Khaimah's habitats throughout history (Heneidy et al., 2018). The results of the botanical survey presented here indicate that multiple distinct vegetation types occur under different environmental conditions across the Emirate; hence, protecting plant diversity will require conservation efforts targeted at a range of diverse landscapes and environments.

Certain plants and vegetation types in Ras Al Khaimah could be prioritized for conservation due to their significant value for biodiversity or vulnerability to extinction. For example, the high mountain vegetation type, particularly the Artemisia steppe subtype, is highly diverse and contains several species restricted to this habitat and not found in other vegetation types. Furthermore, the land area available for this vegetation type is small, as few parts of Ras Al Khaimah reach the necessary altitudes.

Mangrove Protection

The coastal mangrove subtype is another conservation priority. As noted previously, all examples of this subtype are close to Ras Al Khaimah city and thus potentially vulnerable to the impact of poor water quality (e.g., siltation and pollution) caused by urban development and urban activities. Although this vegetation type has a relatively low number of plant species, its provision of habitat to aquatic wildlife and contribution to coastal protection is substantial. The keystone species, *Avicennia marina* or the Grey Mangrove, is considered a "near threatened" species by the IUCN. Restrictions on development near mangrove sites and regulations around urban water management to ensure high water quality would contribute to the conservation of coastal mangrove ecosystems (Assaf, 2020; Lopez-Portillo et al., 2017).

One possible strategy for plant conservation could be creating protected areas in Ras Al Khaimah, within which human activities such as construction and agriculture are restricted to levels that allow plant diversity to continue to thrive. Protected areas can help to conserve plant diversity by limiting or prohibiting activities that disturb or destroy plants and their habitats. The UAE comprises a total of 43 protected areas recognized by the federal government and numerous emirate-level protected areas (not yet designated by the federal government) and private reserves (IUCN 2020 unpublished data). Even though Ras Al Khaimah has one of the highest biological diversity among the emirates, to date, none of these protected areas lie within the Emirate.

Many habitats are of high biodiversity value because of both the recorded plants and wildlife in general. Mangroves, high elevation mountain areas, and interior desert habitats include many plants, mammals, insects, fish, and amphibians that would benefit from protected areas. For example, all 47 species of reptiles known to the UAE occur in Ras Al Khaimah (Whelan, RAK Wildlife Project, personal communication). A multitude of mammals such as *Caracal caracal schmitzi* (Arabian Caracal), *Vulpes cana* (BlaBlanford'sx), and *Gerbillus dasyurus* (WagWagner'srbil) have been documented. In addition, many new insect species are currently being discovered in Ras Al Khaimah (Howarth et al., 2020).

Both the high mountain and coastal mangrove vegetation types are likely to be threatened by climate change (AGEDI, 2015). An increase in air temperature may be reducing the area of the mountains that is sufficiently cool and moist enough to support the ecosystem's plant species (MacLaren, 2016), while sea level rises and increases in the frequency of intense storms can impact mangroves. Although global action is required to mitigate climate change, Ras Al Khaimah could take an active leadership role in this regard by committing to and investing in low carbon infrastructure, technologies, and lifestyles. The more nations that step forward to become part of the solution, the faster the world will reduce carbon emissions to levels that are safe to sustain biodiversity and ecosystems.

Overall, a variety of potential actions could be taken in Ras Al Khaimah to improve the protection of its natural environments and wildlife. The results of the botanical survey presented here emphasize that these efforts need to target multiple distinct domains to fully conserve Ras Al Khaimah's plant diversity. Specifically, high mountain and coastal ecosystems may be in the most urgent need of action to safeguard their ecosystems from the impact of current human activities and climate change.

Preserving Medicinal Plants and Their Uses

Efforts are already underway to address the risk of heritage and knowledge loss around plant medicinal properties. A government-led project has been initiated to document the local uses and knowledge. The project includes two main aims: firstly, a review of the literature and compilation of all available information related to the native plants, their uses, and components; and secondly, the implementation of an in-depth survey within the local communities, using a standardized questionnaire. The collected information will build the medicinal plant database for Ras Al Khaimah. This database will ideally be used as a living document, where information is added continuously and knowledge exchanged with relevant authorities and research institutions. This knowledge collection will be accompanied by laboratory analysis of local plants with known uses.

The Zayed Centre for Herbal Research (ZCfHR) in Abu Dhabi has started examining the medicinal properties of local plants, which mainly came from samples in the desert and lowland habitats (ZCfHR, 2005). The Ras Al Khaimah government project will add to this research by including mountain species, most of which have not been analyzed but are used in local medicine in numerous ways. Scientific insights into the actual medicinal components will complement the known uses and open opportunities for modern medicinal production and use.

A further step towards keeping the heritage alive is through education, raising awareness, and showcasing the knowledge. School curricula should include a more extensive variety of plant-related learning units, taking children outdoors and involving them in gardening projects. Exhibitions, museums, and botanical gardens can exhibit plants, plant products, information panels, and introduce traditional uses. Information amenable to being shared on social media, such as through video clips, could be used to share local stories of reliance on plants and of daily lives that are entwined with the natural environment.

Conserving the traditional knowledge of plants without preserving the plants themselves, however, would be a hollow victory. According to reports from locals, medicinal plants are no longer as readily available or accessible as they were previously. The limited availability emphasizes that habitats and plant diversity are under threat from development and disturbances. A more substantial conservation effort to protect Ras Al Khaimah's vegetation types, as described above, will also be vital to conserving native medicinal plants. In turn, efforts to raise awareness of the medicinal values of plants could strengthen public motivation to support and contribute to the conservation of wild plant diversity. Conserving both the plant diversity and the knowledge of their medicinal use together will contribute to an ecologically and culturally rich future for Ras Al Khaimah.

Authors

Dr. Marina Tsaliki is Senior Plant Research and Conservation Specialist at the Public Services Department (Government of Ras Al Khaimah) in Ras Al Khaimah, UAE. Her current work focuses on the native plant diversity of the Emirate and the initiation of several projects protecting the flora.

Dr. Chloe MacLaren is a plant ecologist who has previously worked on plant conservation in Oman with the National Field Research Centre for Environmental Conservation and the Oman Earthwatch Programme. She is currently based at Rothamsted Research in the United Kingdom, where she applies plant ecology to increase sustainability in agriculture.

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Appendix A

Table A1: Native plant species of Ras Al Khaimah (TBC = plant identification to be confirmed). Indicator species are marked with a green tick. Indicator species are plants that are both common to this vegetation type and not commonly found in other vegetation types, and thus can be used in the field as a guide to which vegetation type is present (see Appendix B for more detail)

Family	Plants	Habitat	Indicator species
Acanthaceae	*Avicennia marina*	Coastal	✓
	Blepharis ciliaris	Low mountains and wadis	
Aizoaceae	*Aizoon canariense*	Low mountains and wadi	✓
	Sesuvium verrucosum	Coastal	
	Zaleya pentandra	Plains	✓
Amaranthaceae	*Aerva javanica*	Plains	
	Amaranthus graecizans	Plains	
	Amaranthus hybridus	Plains	
	Arthrocnemum macrostachyum	Plains	
	Caroxylon imbricatum	Coastal and plains	
	Chenopodiastrum murale	Desert and plains	
	Cornulaca monacantha	Desert and plains	✓
	Halocnemum strobilaceum	Coastal and desert	
	Halopeplis perfoliata	Desert and plains	
	Haloxylon salicornicum	Plains	
	Suaeda aegyptiaca	Coastal, plains, and dunes	✓
	Suaeda vermiculata	Coastal	✓
Apiaceae	*Ammi majus*	High mountains	
	Pimpinella eriocarpa	Wadis and mountains	
	Pycnocycla aucheriana	Mountains and wadis	
Apocynaceae	*Calotropis procera*	Plains and dunes	✓
	Desmidorchis arabica	Mountains and wadis	✓
	Glossonema varians	Mountains	
	Leptadenia pyrotechnica	Dunes and plains	✓
	Nerium oleander	Wadis	✓
	Pentatropis nivalis	Wadis and mountains	
	Pergularia tomentosa	Wadis	
	Periploca aphylla	Mountains and wadis	✓
	Rhazya stricta	Wadis	
Arecaceae	*Nannorrhops ritchiana*	Wadis	
	Phoenix dactylifera	Wadis	✓
Aspleniaceae	*Asplenium ceterach*	High mountains	
Asteraceae	*Aegopordon berardioides*	High mountains	
	Anthemis odontostephana	High mountains	
	Artemisia sieberi	High mountains	✓

Asteraceae	*Atractylis cancellata*	Wadis	
	Atractylis carduus	Wadis	
	Centaurea pseudosinaica	Low mountains and wadis	
	Centaurea wendelboi	High mountains	✓
	Echinops erinaceus	Wadis	
	Filago desertorum	Desert and plains	
	Helichrysum glumaceum	High mountains	✓
	Ifloga spicata TBC	Low mountains and wadis	
	Iphiona scabra	Wadis	✓
	Jurinea carduiformis	High mountains	
	Lactuca dissecta	Wadis	
	Launaea bornmuelleri	High mountains	✓
	Launaea capitata	Desert	✓
	Launaea massauensis	Mountains and wadis	
	Launaea mucronata	Desert	
	Pentanema divaricatum	Wadis	
	Phagnalon schweinfurthii	High mountains	✓
	Pulicaria arabica	Wadis	
	Pulicaria edmondsonii	Mountains and wadis	✓
	Pulicaria glutinosa	Mountains and wadis	✓
	Reichardia tingitana	Wadis	✓
	Rhanterium epapposum	Plains (abandoned agricultural sites)	
	Senecio glaucus	Desert and wadis	
	Sonchus oleraceus	Mountains and wadis	✓
	Urospermum picroides	Wadis	
	Vernonia arabica	Mountains and wadis	
	Zoegea purpurea	High mountains	✓
Boraginaceae	*Anchusa aegyptiaca*	Mountains and wadis	
	Arnebia hispidissima	Desert and wadis	
	Buglossoides sp. TBC	High mountains	
	Echiochilon callianthum	High mountains	
	Echiochilon jugatum	Desert, coastal, and plains	
	Echiochilon persicum	Wadis and mountains	✓
	Heliotropium brevilimbe	Wadis	✓
	Heliotropium kotschyii	Desert and plains	✓
	Heliotropium lasiocarpum TBC	Wadi	
	Lappula spinocarpos	Wadi	
	Moltkiopsis ciliata	Dunes	✓
	Myosotis ramosissima	High mountains	

Boraginaceae	*Ogastemma pusillum*	Wadi	
	Trichodesma ehrenbergii	Mountains and wadis	
Brassicaceae	*Clypeola aspera*	High mountains	
	Clypeola jonthlaspi	High mountains	
	Diplotaxis harra	Mountains and wadis	
	Eremobium aegyptiacum	Desert	✓
	Erucaria hispanica	Plains and wadis	
	Farsetia sp.	Wadi	
	Farsetia stylosa	Wadi	
	Morettia parviflora	Wadi	
	Notoceras bicorne TBC	Wadi	
	Physorhynchus chamaerapistrum	Plains and mountains (along agricultural sites)	
	Savignya parviflora TBC	Wadi	
	Sinapis arvensis	Desert and plains (ephemeral)	
	Sisymbrium irio	Wadis and plains	
Capparaceae	*Capparis cartilaginea*	Mountains and wadis	
	Capparis spinosa	Mountains and wadis	
Caprifoliaceae	*Lomelosia olivieri*	High mountains	
Caryophyllaceae	*Cometes surattensis*	Wadis	
	Dianthus crinitus	High mountains	
	Gymnocarpos decandrus	Mountains and wadis	
	Gymnocarpos sclerocephalus	Wadis	
	Paronychia arabica	Desert and wadis	✓
	Silene apetala	Mountains and wadis	
	Silene villosa	Desert	
	Spergularia flaccida	High mountains	
Cistaceae	*Helianthemum lippii*	Mountains and wadis	✓
	Helianthemum salicifolium	High mountains	
Cleomaceae	*Cleome amblyocarpa*	Desert	
	Cleome droserifolia	Mountains	
	Cleome quinquenervia	Wadi	
	Cleome rupicola	Wadi	
	Cleome pallida	Desert	✓
Convolvulaceae	*Convolvulus acanthocladus*	Mountains	✓
	Convolvulus deserti	Wadi	
	Convolvulus prostratus	Desert	
	Convolvulus virgatus	Mountains and wadis	✓
	Cuscuta planiflora	High mountains	✓
	Ipomoea pes-caprae (naturalised)	Coastal	
Crassulaceae	*Rosularia adenotricha*	High mountains	

Crassulaceae	*Umbilicus horizontalis*	High mountains	
Cucurbitaceae	*Citrullus colocynthis*	Mountains, plains, wadis, and desert	
	Cucumis prophetarum	Wadi	
Cynomoriaceae	*Cynomorium coccineum*	Desert and coastal	
Cyperaceae	*Cyperus conglomeratus*	Desert	
	Cyperus rotundus	Desert	✓
Ephedraceae	*Ephedra foliata*	Desert	
	Ephedra pachyclada	High mountains	✓
Euphorbiaceae	*Chrozophora oblongifolia*	Mountains and wadis	
	Chrozophora plicata	Desert	
	Euphorbia granulata	Wadi	✓
	Euphorbia larica	Mountains and wadis	✓
Fabaceae	*Acacia ehrenbergiana*	Wadis	
	Argyrolobium roseum	Wadis	
	Astragalus fasciculifolius	Mountains and wadis	✓
	Astragalus hauarensis	Desert	
	Crotalaria aegyptiaca	Wadis	
	Hippocrepis areolata	Plains and dunes	
	Hippocrepis constricta	Mountains and wadis	
	Indigofera arabica	Wadis	
	Indigofera colutea TBC	Desert	
	Indigofera intricata	Desert and plains	
	Indigofera semitrijuga	Desert and plains	
	Leobordea platycarpa	Desert and wadis	
	Lotus garcinii	Desert	
	Lotus halophilus	Desert	
	Medicago laciniata	Plains and desert	
	Melilotus indicus TBC	Wadi	
	Ononis serrata TBC	Desert	
	Prosopis cineraria	Desert and plains	✓
	Prosopis farcta	Wadis and desert	
	Prosopis juliflora	Plains, desert, and coastal	✓
	Pseudolotus villosus	High mountains	
	Rhynchosia minima	Wadis and desert	
	Rhynchosia schimperi	Desert	
	Senna italica	Mountains and wadis	
	Taverniera cuneifolia	Wadi	
	Tephrosia apollinea	Mountains, wadis, and plains	✓
	Tephrosia nubica	Wadis	
	Tephrosia uniflora	Plains	
	Trigonella stellata	Wadis	

	Vachellia farnesiana	Desert	
	Vachellia flava TBC	Wadi	
	Vachellia tortilis	Plains, wadi, and desert	✓
Gentianaceae	*Centaurium pulchellum TBC*	High mountains	
Geraniaceae	*Erodium laciniatum*	Mountains, wadis, and plains	
	Erodium neuradifolium	Mountains, wadis, and plains	
	Geranium mascatense	Wadis	✓
Gisekiaceae	*Gisekia pharnaceoides*	Desert	
Iridaceae	*Moraea sisyrinchium*	High mountains	
Ixioliriaceae	*Ixiolirion tataricum*	High mountains	
Juncaceae	*Juncus rigidus*	Wadis	
Lamiaceae	*Lavandula subnuda*	Mountains and wadis	✓
	Leucas inflata	Mountains and wadis	
	Salvia aegyptiaca	Mountains and wadis	✓
	Salvia macilenta	Wadis	
	Salvia macrosiphon	Mountains and wadis	
	Teucrium stocksianum	High mountains	✓
Linaceae	*Linum corymbulosum*	High mountains	
Malvaceae	*Abutilon pannosum*	Wadis	
	Corchorus depressus	Wadis	
	Corchorus triocularis	Wadis	
	Grewia erythraea	Wadis	
	Hibiscus micranthus	Wadis	
	Malva parviflora	Wadis, desert, and plains	✓
Meliaceae	*Azadirachta indica (cultivated)*	Plains	
Menispermaceae	*Cocculus pendulus*	Wadis	
Moraceae	*Ficus johannis*	High mountains	✓
	Ficus salicifolia	Wadis and plains	✓
Moringaceae	*Moringa peregrina*	Wadis	✓
Neuradaceae	*Neurada procumbens*	Desert and plains	✓
Nyctaginaceae	*Boerhavia diffusa*	Wadis	
	Boerhavia elegans	Wadis	
Oleaceae	*Olea europaea*	Mountains and wadis	✓
Orobanchaceae	*Cistanche tubulosa*	Coastal	
	Orobanche cernua	High mountains	✓
Phyllanthaceae	*Andrachne aspera*	Wadis	
	Andrachne telephioides	Wadis	
	Phyllanthus rotundifolius	Plains (abandoned agricultural sites)	
Plantaginaceae	*Misopates orontium*	Mountains and wadis	
	Nanorrhinum acerbianum	Wadis	

Plantaginaceae	*Nanorrhinum hastatum*	Madis	
	Plantago afra	Wadis	
	Plantago amplexicaulis	Desert	
	Plantago boissieri	Desert	✓
	Plantago ciliata	Wadis and desert	
	Plantago ovata	Mountains, wadis, and desert	✓
	Schweinfurthia papilionacea	Wadis and plains	
Plumbaginaceae	*Dyerophytum indicum*	Wadis	
	Limonium carnosum	Desert and coastal	
Poaceae	*Aeluropus lagopoides*	Coastal and plains	✓
	Aristida abnormis	Desert and wadis	
	Aristida adscensionis	Mountains, wadis, and deserts	
	Aristida sp. (migiurtina)	Mountains	
	Brachypodium distachyum	High mountains	✓
	Bromus lanceolatus	Wadi	
	Cenchrus ciliaris	Mountains, wadis, desert, and plains	✓
	Cenchrus divisum	Desert and wadis	✓
	Cenchrus pennisetiformis	Mountains, wadis, and desert	
	Cenchrus setaceus	Wadis	
	Cenchrus setiger	Wadis	
	Chloris virgata	Wadis	
	Coelachyrum piercei	Desert	✓
	Cutandia memphitica	Desert	
	Cymbopogon sp.	Mountains and wadis	✓
	Cynodon dactylon	High mountains	
	Dactyloctenium aegyptium	Desert	
	Dactyloctenium scindicum	Wadis	
	Dichanthium annulatum	Mountains and wadis	✓
	Dichanthium foveolatum	Wadis	
	Digitaria sanguinalis	Wadis	
	Eragrostis barrelieri	Desert and wadis	
	Eragrostis papposa TBC	Wadis	
	Halopyrum mucronatum	Desert	✓
	Hyparrhenia hirta	Desert and wadis	
	Phalaris minor	Mountains	
	Phragmites australis	Wadis	
	Piptatherum holciforme	Wadis	
	Rostraria pumila	High mountains	
	Saccharum ravennae	Wadis	✓

Poaceae	*Setaria verticillata*	Desert	
	Sporobolus ioclados TBC	Desert	
	Sporobolus spicatus	Plains	
	Stipagrostis ciliata	Desert	
	Stipagrostis plumosa	Mountains, wadis, and desert	✓
	Stipellula capensis	Desert	
	Tetrapogon villosus TBC	Wadis	✓
	Tragus racemosus	Desert	
	Tricholaena teneriffae	Wadis	
	Triraphis pumilio TBC	High mountains	
Polygalaceae	*Polygala erioptera*	Desert and wadis	
Polygonaceae	*Calligonum comosum*	Desert	
Polygonaceae	*Pteropyrum scoparium TBC*	Desert	
	Rumex nervosus TBC	Desert	
	Rumex pictus	Desert	✓
	Rumex spinosus	Wadis	
	Rumex vesicarius	Mountains and wadis	✓
Primulaceae	*Lysimachia arvensis*	Mountains and wadis	✓
	Lysimachia linum-stellatum	Mountains and wadis	
Pteridaceae	*Cosentinia vellea*	Mountains and wadis	
	Hemionitis pteroides	Mountains and wadis	
	Onychium divaricatum	Mountains and wadis	
Ranunculaceae	*Ranunculus muricatus TBC*	Wadis	
Resedaceae	*Ochradenus arabicus*	Mountains and wadis	✓
	Ochradiscus aucheri	Wadis	
	Reseda aucheri	Wadis	
Rhamnaceae	*Ziziphus spina-christi*	Wadis and plains	✓
Rosaceae	*Prunus arabica*	High mountains	✓
Rubiaceae	*Callipeltis cucullaris*	Mountains and wadis	
	Galium ceratopodum	Wadis	
	Galium setaceum	Mountains and wadis	
	Galium tricornotum	Wadis	
	Plocama aucheri	Mountains and wadis	
	Plocama hymenostephana	Mountains and wadis	
Rutaceae	*Haplophyllum tuberculatum*	Wadis	
Salvadoraceae	*Salvadora persica*	Desert and plains	
Sapindaceae	*Dodonaea viscosa*	Mountains and wadis	✓
Scrophulariaceae	*Anticharis arabica*	Mountains and wadis	
	Anticharis glandulosa	Wadis	
	Scrophularia arguta	Wadis	
	Scrophularia deserti	Desert	

Solanaceae	*Datura stramonium*	Wadis (abandoned sites)	
	Lycium shawii	Mountains, wadis, and desert	
	Scrophularia arguta	Wadis	
	Solanum incanum	Mountains and wadis (abandoned sites)	
Tamaricaceae	*Tamarix aucheriana*	Coastal and plains	
	Tamarix senegalensis	Plains	
Typhaceae	*Typha domingensis*	Wadis	
Urticaceae	*Forsskaolea tenacissima*	Mountains, wadis, and plains	✓
	Parietaria alsinifolia	Dunes	
Violaceae	*Viola cinerea*	Mountains and wadis	
Xanthorrhoeaceae	*Asphodelus tenuifolius*	Mountains, wadis, and plains	
Zygophyllaceae	*Fagonia bruguieri*	Mountains, wadis, and plains	✓
	Fagonia indica	Wadis and plains	✓
	Tetraena qatarensis	Plains and desert	✓
	Tribulus arabicus	Plains	
	Tribulus pentandrus	Desert and wadis	
	Tribulus terrestris	Plains and wadis	

Appendix B

Detail on Classification, Modelling, and Mapping Methods

Vegetation Classification

The vegetation data collected from the field survey of Ras Al Khaimah consisted of visual estimates of the percent cover of each plant species present at each survey site. To classify this data into vegetation types, agglomerative cluster analysis based on the Bray-Curtis dissimilarity measure was used (Kent 2012), undertaken in R (R Core Team 2017). This approach sequentially pairs sites with the most similar vegetation composition, as is illustrated in the resulting dendrogram (Figure B1). The Bray-Curtis dissimilarity measure takes into account differences in which species are present in each site, and the abundance (cover) of each species.

The cluster dendrogram was divided into main vegetation types where there were clear distinctions between groups, i.e. long vertical bars between branch nodes. However, these groups were further divided into subtypes as inspection of the data revealed substantial variation within the main types. The level of division for the subtypes was guided by maximising the overall number of indicator species across groups (species that are found to occur with a significantly higher constancy and abundance in one cluster compared with any other; Peck, 2010). If the number of indicator species is low, it suggests either that clusters are formed of sites with relatively different compositions (so fewer species are found consistently in each cluster), or that relatively similar sites have been split into too many clusters (and each species is likely to be found in more than one cluster). A higher number of indicator species thus indicates a more optimal grouping. The indicator species were identified using the Dufrene-Legendre indicator species analysis of the the labdsv package in R.

This analysis produced 16 subtypes in total, too many for a predictive model given the sample size and available explanatory variables. Therefore, we decided only to map the main vegetation types and the three most distinct subtypes: the mangroves, the Artemisia steppe, and the shaded/exposed low mountain subtypes. It was possible to include these in the model given that they either occurred under very specific conditions or contained relatively large numbers of sites.

Geographic Environmental Variables

The geographic environmental variables in this study consisted of elevation, solar radiation, flow accumulation, slope, and distance from coast. All variables except distance from coast were obtained from a digital elevation model (DEM) with a 30mx30m resolution of the region from the ASTER version 3 dataset (US/Japan Aster Science Team 2001). Slope, solar radiation, and flow accumulation were calculated from the DEM in QGIS (QGIS 2018), and the distance from coast was also calculated from a coastline map of the region. These calculations produced rasters of each explanatory variable, i.e. a map layer with a value of elevation, slope, flow accumulation, solar radiation, and distance from coast. These rasters were then used to calculate the probability of different vegetation types based on the models described below.

Other variables that may have improved the accuracy of this map are soil type and NDVI (Normalized Difference Vegetation Index) imagery, neither of which were available during this study. Evidence suggests that soil type affects vegetation type, given that vegetation in the coastal vegetation type and plains type tended to vary in response to the amount of ground covered by either rock or soil/sand, which affects the nutrients and water available to plants at a site. Soil types can also affect variables such as pH and salinity, which further affect which species can survive. Thus, it may be of interest to explore the response of vegetation to soil type if the information can be obtained in the future. NDVI imagery is data on reflected green light from the earearth'srface, and given that different vegetation types tend to reflect different wavelengths, this can be used to identify which vegetation type is present in a given location.

Multinomial Logistic Regression to Predict Vegetation Type Based on Environmental Variables

A multinomial logistic regression model was used to calculate the probability of a site belonging to a particular vegetation type based on its environmental variables. The model was calculated in the software R (R Core Team 2017) using the nnet package. Before inclusion in the model, explanatory variables were tested for collinearity (as this can result in over-fitting of the model or the effects of collinear variables masking one another) and slope was removed from the model as it correlated with elevation and flow accumulation: higher sites tended to be steeper, and the bottoms of wadis with higher flow tended to be flatter.

Explanatory variables were also transformed where necessary to meet the assumption of a linear relationship between the explanatory variables and the response. Flow accumulation and distance from coast were transformed to logarithmic values for inclusion in the model to reflect that the impact of these variables reduces as their value increases; for example, an increase from very low water availability to moderate water availability would be expected to affect vegetation more than an increase from moderate to high water availability. Additionally, distance from coast was capped at a distance of 0.01 geographical degrees given that salinity was not expected to have an effect beyond this distance.

The final model equation was thus:

> *vegetation type ~ elevation + solar radiation + log(flow accumulation) + log(distance from coast)*

A multinomial model produces coefficients for each variable representing the effect of that variable on the log-odds of a site belonging to a vegetation type. These coefficients can be used to predict the probabilities of a specific vegetation type occurring under a specific set of environmental conditions, based on the following equations. These convert the log-odds to probabilities based on the fact that the probabilities must sum to one. First the probability of a reference vegetation type is calculated (it does not matter which type is the reference type):

$$\Pr(Y_i = K) = \frac{1}{1 + \sum_{k=1}^{K-1} exp^{\beta_k \cdot x_i}}$$

Equations to work out the probability of all other vegetation types (1 to K-1):

$$\Pr(Y_i = 1) = \frac{e^{\beta_1 \cdot x_i}}{1 + \sum_{k=1}^{K-1} exp^{\beta_k \cdot x_i}}$$

Where:

K = the reference vegetation type from the multinomial model

Pr(Yi = 1) = the probability that pixel i has vegetation type *1*

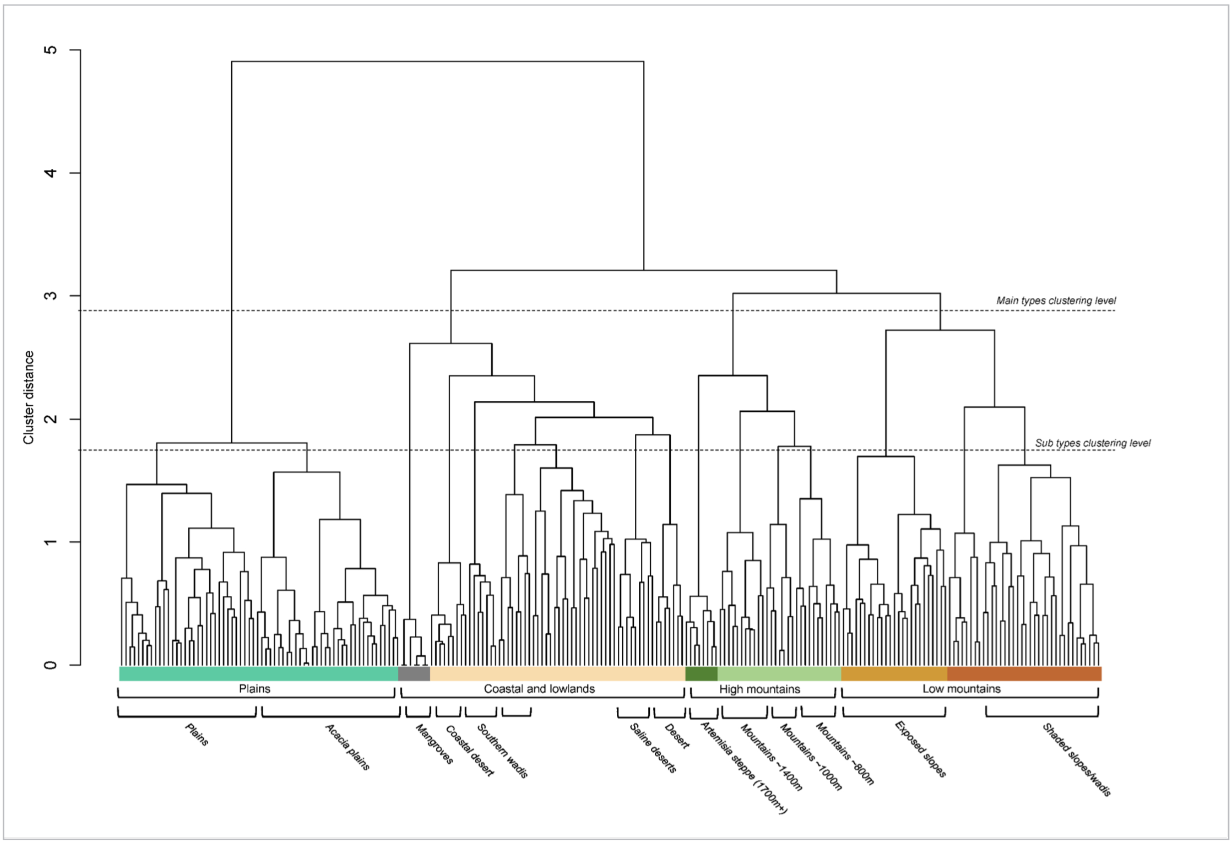
exp = exponent

β = the set of model coefficients for vegetation type *k*

x = the set of explanatory variables associated with pixel *i*

To produce the vegetation maps of Ras Al Khaimah, these equations were coded into the 'Ra'ter calcalculator'ol in QGIS, to calculate the probability of each pixel belonging to each vegetation type.

Figure B1: The cluster dendrogram illustrating the relatedness of each site based on vegetation composition, and the groupings of the sites in the main vegetation types and the subtypes.



Note: The colored bars in the dendrogram highlight the types and subtypes displayed on the map (Figure 2), using the same colour coding.

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P.O. Box 12050, Ras Al Khaimah, United Arab Emirates
Tel: +971 7 233 8060 | Fax: +971 7 233 8070
E-mail: info@alqasimifoundation.rak.ae | www.alqasimifoundation.com