School of Molecular and Life Sciences

Assessing the current distribution of Southwestern Australian shallow-water reef fish assemblages in relation to management bioregions, and the change in these assemblages over time

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AUTHORS DECLARATION

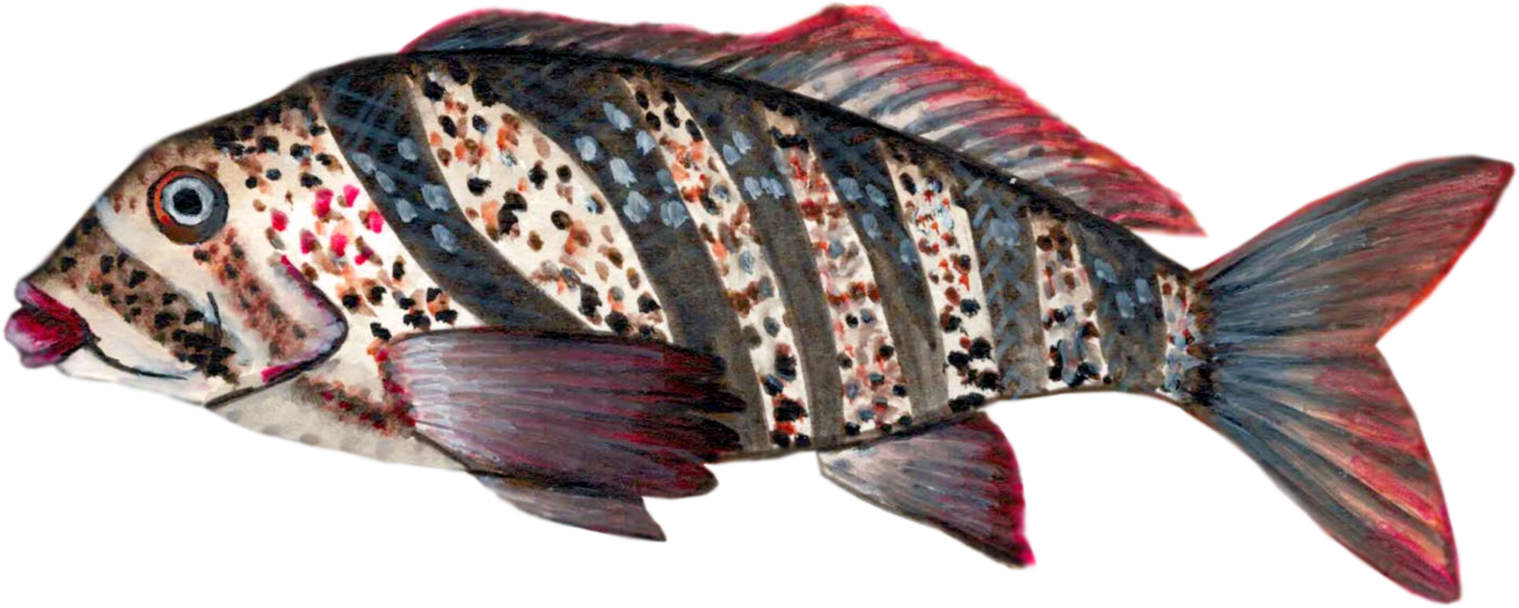
To the best of my knowledge and belief, this thesis contains no material previously published by another person except where due acknowledgments have been made. This thesis contains no material which has been accepted for the award of any other degree or diploma at any university. All artwork and cover pages in this thesis were painted and edited by me, Savita Goldsworthy.

Animal Ethics:

The research presented and reported in this thesis was conducted in compliance with the National health and Medical research Council Australian code for the care and use of animals for scientific purposes 8th edition (2020). All required animal ethics observational approvals were obtained prior to commencing research and was conducted with the approval from the Curtin University Animal Ethics Committee, Approval Number: AEC_2015_01.

Signed: Savita Goldsworthy

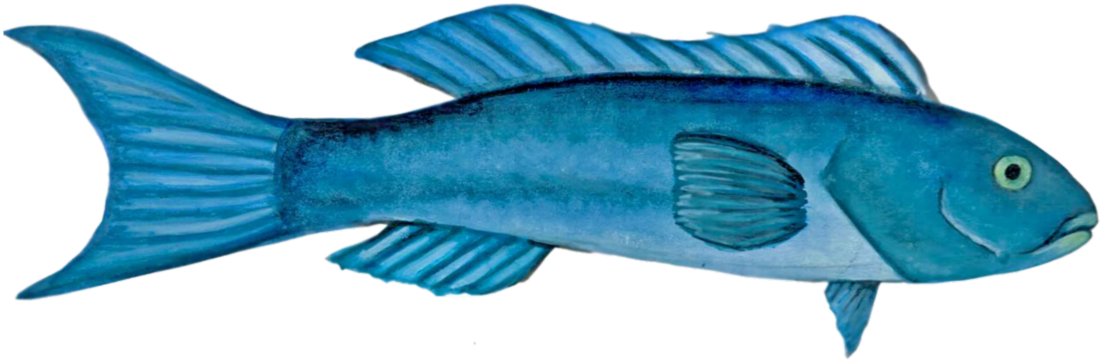
Date: November 2020



Watercolour of a red-lipped morwong (*Goniistius rubrolabiatus*) by Savita Goldsworthy

ABSTRACT

Assessing the current distribution of South-Western Australian shallow-water reef fish assemblages in relation to management bioregions, and the change in these assemblages over time



Watercolour of a herring cale (*Olisthops cyanomelas*) by Savita Goldsworthy

Globally, variations in climate are driving changes in the distribution and composition of marine assemblages (Sunday et al. 2012; Poloczanska et al. 2013; Cheung et al. 2012). In light of these changes, and the growing need to conserve and protect the marine environment, there is an increasing focus on the development of management strategies that protect whole ecosystems (Barr and Possingham 2013; Morrone 2015). The effectiveness of these strategies relies on accurate distributional data (DEFRA 2007) and tracking changes in the composition of marine assemblages over time (Molinos et al. 2015). In Southwest Australia (SWA) there is limited research that documents the distributional patterns of marine fauna and flora over large temporal and spatial scales.

The data presented and interpreted within this thesis aimed to document the current distribution of shallow-water reef fish along ~2000 km of coastline in SWA and provides insights into how these assemblages have changed over the last 14 years. Data was collected from seven regions in SWA, from Geraldton in the north to Esperance in the south-east, which encompassed the subtropical to temperate transition of coastal assemblages.

In Chapter 2 I investigated whether the shallow-water reef fish of SWA have distinctive compositions that represent bioregions and compare these groupings to the current IMCRA and fisheries management regions. In Chapter 3 I assessed the responses of shallow-water reef fish assemblages to 14 years of climatic changes. In both Chapter 2 and Chapter 3 I also identified the characteristic species, environmental and habitat variables that are driving these assemblage patterns.

Distributional data collected using diver-operated stereo-video systems (stereo-DOVs) in 2015 from the seven regions sampled indicated that the shallow-water reef fish formed four distinct assemblages. The boundaries of these assemblages differed from the current three management bioregions of the area, suggesting that four regions may more effectively capture species patterns of SWA. This research also highlighted the importance of sea surface temperature (SST) and macroalgae cover (*Ecklonia radiata*, non-*Ecklonia* canopy and understorey algae cover) as assemblage drivers. Each of the four assemblages were characterised by a high number of short-range endemic species that have a heightened vulnerability to climate change and fishing pressure (Chapter 2).

To monitor the responses of shallow-water reef fish over 14 years of climatic variability, surveys were conducted using stereo-DOVs over the seven regions of SWA at three time points (2006, 2015 and 2019). Shallow-water reef fish assemblages changed over the 14-year period with variations in the thermal niche, endemism and trophic level of species present. In addition, environmental and habitat variables such as SST and macroalgae were important drivers of assemblage change through time. Species of importance to recreational and commercial fishing in SWA were responsive to these environmental changes, with some increasing in abundance for example the subtropical *Choerodon rubescens* (baldchin groper) and *Glaucosoma hebraicum* (dhufish), and others decreasing, e.g. the temperate *Achoerodus gouldii* (western blue groper) and *Bodianus frenchii* (foxfish) (Chapter 3).

Shallow-water reef fish in SWA form distinct assemblages, which are changing in correlation with environmental and habitat variables. Geraldton and Esperance individually contain unique fish assemblages, which are distinct from all other regions along the SWA coastline. Despite this, both Geraldton and Esperance are currently managed as part of the wider Central West Coast and Western Australian South Coast management bioregions, respectively. Esperance is bordered by the Great Australian Bight, defining the geographical limit of some shallow-water endemic species and Geraldton is a transition zone where tropical and temperate species overlap. The fish assemblages of these regions have started to change since 2006 and understanding the direction and magnitude of this change may have direct implications for ecosystem functioning and the protection of species, particularly endemics.

ACKNOWLEDGMENTS

This thesis would not have been completed without the support and guidance from a number of people including supervisors, colleagues, friends and family, and it really has highlighted the importance of collaboration to deliver research that is well beyond what could be achieved individually.

Firstly, to my supervisors Ben Saunders and Euan Harvey who have supported and guided me throughout this entire project. I would especially like to thank them for taking me on as a student even though I am from another country and they initially knew very little about me. Thank you for constantly driving me to achieve my best and ensuring I learnt as much as I could along this journey, as well as always being available for meetings and coffee. Your academic integrity and good science have given me the skills and knowledge to build my own career in the scientific world, I am excited to see what the future may hold and the development of projects to come.

A project this size required the assistance of a number of people for both fieldwork and data analysis, it really would have been difficult to collect all the data required for this research by myself. I would especially like to thank Jack Parker for all his help organising field trips and, in the field, assisting with statistical analysis and identifying fish! Thank you for always answering my questions. Thank you also to the 2019 dive team; Euan Harvey, Ben Saunders, Brae Price, Karl Schramm, Rowan Kleindienst, Damon Driessen, Laura Fullwood and Logan Hellmrich. I also wish to acknowledge everyone who provided field support during previous survey years before I joined at Curtin University.

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The support I received from people outside of the university must also be acknowledged. Thank you to my managers at The Boatshed Restaurant, Claire and

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Finally, I would like to acknowledge financial support for the 2019 fieldwork surveys from the Sea World Reef and Rescue Foundation Inc. (SWRRFI) and the Winifred Violet Scott Charitable Trust. I was also personally supported by an Australian Government Research Training Programme (RTP) to cover the costs of my course fees at Curtin University.

A school of swallowtails (*Centroberyx Lineatus*) And old wives (*Enoplosus Armatus*) during a dive In Albany (Southwest Australia). Photo: Jack Parker

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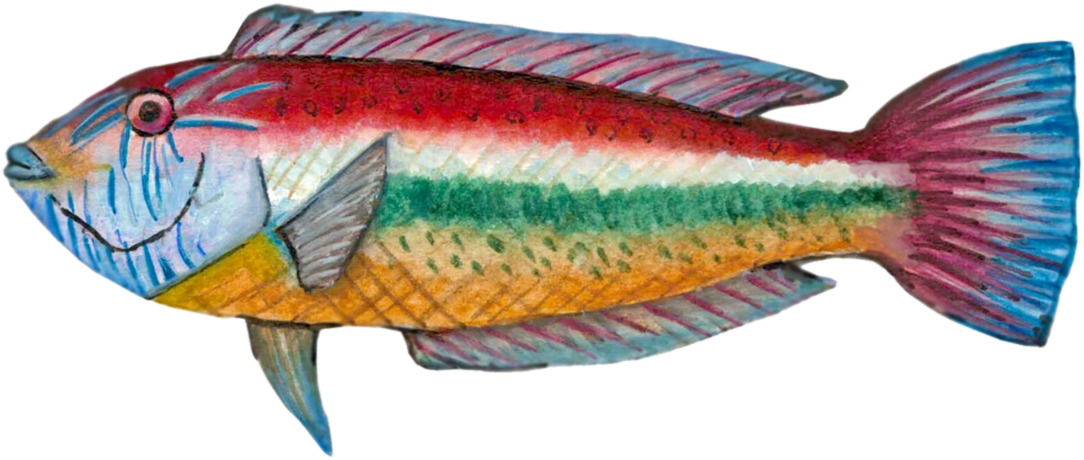
STATEMENT OF CONTRIBUTIONS



Watercolour of a southern Maori wrasse (*Ophthalmolepis lineolatus*) by Savita Goldsworthy

Chapter 2

Published: Goldsworthy, S. D., Saunders, B. J., Parker, J. R. C., Harvey, E. S. (Marine Ecology Progress Series 2020). Spatial assemblage structure of shallow-water reef fish in Southwest Australia.

Author Contribution: SG, BS, JP, ES collected the data. SG, BS and EH designed the study with assistance from JP. SG analysed and executed the data analyses and designed and created the figures and tables. SG wrote and edited the manuscript. BS, EH and JP provided comments and edits on the manuscript. All co-authors reviewed and commented on the manuscript and accepted the final version.

Chapter 3

Prepared for submission: Goldsworthy, S. D., Saunders, B. J., Parker, J. R. C., Shalders, T. C., Bennett, S., Harvey, E. S. (Nature Climate Change 2020). Responses of shallow-water reef fish in a global hotspot over 14 years of climatic changes.

Author Contribution: SG, BS, JP, TS, SB, EH collected the data. SG, BS, EH designed the study with assistance from JP, TS and SB. SG analysed and executed the data analyses and designed and created the figures and tables. SG wrote and edited the manuscript. BS, JP, TS, EH and SB provided comments and edits on the manuscript. All co-authors reviewed and commented on the manuscript and accepted the final version.

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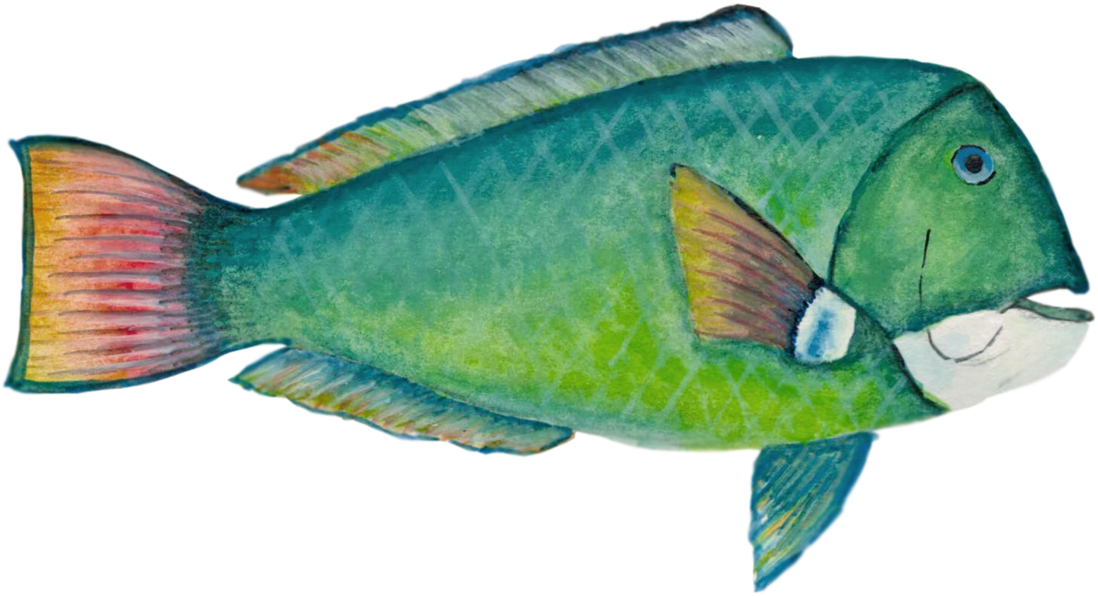
LIST OF ABBREVIATIONS

AIC_C	Corrected Akaike Information Criterion
AODN	Australian Ocean Data Network
CAP	Canonical Analysis of Principal coordinates
dbRDA	Distance-based Redundancy Analysis
DISTLM	Distance-based Linear Modelling
GSR	Great Southern Reef
IMCRA	Integrated Marine and Coastal Regionalisation of Australia
MPAs	Marine Protected Areas
nMDS	Non-metric Multidimensional Scaling
PERMANOVA	Permutational Multivariate Analysis of Variance
PERMDISP	Permutational Analysis of Multivariate Dispersions
SE	Standard Error
SIMPER	Similarity Percentages
SST	Sea Surface Temperature
stereo-DOV	Diver Operated stereo-video System
SWA	Southwest Australia

CHAPTER 1

General Introduction



Watercolour of a baldchin groper (*Choerodon rubescens*) by Savita Goldsworthy

Preface

This general introduction provides broad background information relating to this thesis, details the study area and discusses previous studies in this region. This section also identifies the aims and objectives of each data chapter, poses the research question and illustrates the layout of this thesis.

1.1 Management of the Marine Environment

1.1.1 Marine Protected Areas and ‘Hotspot’ Regions

The marine environment provides many essential ecosystem services that the human population is dependent on (Barbier, 2017; Weatherdon et al., 2016). Humans rely on marine ecosystems for food security, commercial and recreational fishing, tourism and the provision of raw materials (Barbier, 2017; Palumbi et al., 2009). As a consequence, marine ecosystems are increasingly being exploited as a way of sustaining an increasing human population (Barbier, 2017; Weatherdon et al., 2016). The combined impacts of anthropogenic activities are affecting marine communities and changing the abundance and distribution of species and habitats (IPCC, 2014). Successful management of marine resources requires a strategy that protects entire communities, while also incorporating essential human uses such as fishing, tourism and recreation (Atkins et al., 2011).

Throughout the world, a number of marine regions are considered biodiversity ‘hotspots’. Hotspots contain a concentrated diversity of animals and plants, many of which are endemic to that area (Phillips, 2001). Marine Protected Areas (MPAs) are commonly used as a management tool to protect these regions (Mumby et al., 2006; Palumbi, 2002) and have been shown to improve ecosystem functioning within an area (Palumbi et al., 2009; Salm et al., 2006). However, single or scattered MPAs are generally not an effective management tool for protecting species and habitats, particularly following disturbances. Individual or isolated MPAs do not manage migration or species dispersal, and similarly they do not consider range shifts (Roberts et al., 2003; Salm et al., 2000). As a consequence, there is a shift towards management plans and policies that are ecosystem-based and composed of connected networks (Barr & Possingham, 2013; Wood et al., 2008).

1.1.2 Bioregionalisation

Creating a management system of connected networks relies on accurate species distributional data, and once developed can assist conservation efforts and regional planning (Olson et al., 2001). ‘Bioregionalisation’ involves dividing a geographic area into distinct bioregions, which take into account species and habitat distributions, ecological processes and human usage (Commonwealth of Australia, 2006). Bioregionalisation allows for whole ecosystem management and a network of representation, enabling the management or protection of the entire biodiversity of a geographical area, whether at the local, state, or national level (Olson et al., 2001). Bioregionalisation as a management strategy can optimise the prioritisation and allocation of resources and funding, allocation of no take zones and protection of endangered species (Moore et al., 2010; Valavanis et al., 2004; Ward et al., 1999). This has been refined in terrestrial systems (Jenkins & Joppa, 2009; Warry & Hanau, 1993), but when compared to its terrestrial counterpart, the marine environment is underrepresented in management policy and planning (Chape et al., 2005), possibly due to its vast size and general inaccessibility.

The concept of bioregionalisation is beginning to be adopted globally in marine systems, as recognition of the importance of ecosystem-based management grows among scientists and policy makers (Morrone, 2015). For example, the Netherlands, United Kingdom and Australia have developed and adopted individual regional planning frameworks to aid in marine ecological management, whilst also balancing human usage and economic gain (Barr & Possingham, 2013, DEFRA, 2007; IDON, 2015). Managing an area by bioregions may protect the essential services that marine ecosystems provide, which are relied upon by the surrounding ecological communities and human population (Morrone, 2015). For bioregional management to be effective and useful, the allocation of these regions relies on establishing the current distributions of species (Lyne & Last, 1996), and should accurately represent the communities within them (Stewart et al., 2003).

1.1.3 Bioregionalisation of Southwest Australia

The bioregionalisation of an area allows for the development and employment of broadscale management practices, and provides a basis for the conservation of biodiversity within marine systems. Marine management and conservation relies on accurate biological data alongside the implementation of policy and guidelines. Therefore, bioregionalisation encourages the synthesis of biological data, international agreements and policy makers (Spalding et al., 2007). Due to the fluctuation of the marine environment with differing ocean currents, weather conditions and seasons, ecological boundaries in the oceans may shift (Spalding et al., 2007). Climate change is predicted to have a profound impact on the marine environment, destabilising the natural oceanographic boundaries, and therefore, embedding climate change adaption into bioregional management is essential. The integration of climatic research into the bioregionalisation of an area will assist in the establishment of an adaptive ecosystem management approach, which will aid the protection of marine biodiversity as the climate changes (Olson et al., 2001).

Australia has adopted the bioregional approach to manage its marine environment (Commonwealth of Australia, 2006) and aims to have over 35% of its waters protected within MPAs (Barr & Possingham, 2013). To facilitate this management strategy, the Integrated Marine and Coastal Regionalisation of Australia (IMCRA) was developed, which arranged the marine environment of Australia into 60 mesoscale regions integrating benthic and physical information (Commonwealth of Australia, 2006). In SWA, IMCRA 4.0 defined two provincial regions; the Southwest Transition and the Southwest IMCRA Province, and three mesoscale bioregions; the Central West Coast, The Leeuwin-Naturaliste and the Western Australian South Coast. Commercial fisheries management in SWA utilises an ecosystem-based approach to form a planning system that balances economic use and conservation (Fletcher et al., 2010, 2012), combining fisheries value, exploited fish stocks and associated habitats (Gaughan & Santoro, 2018). Fisheries in this area are managed within two regions: the West Coast and the South Coast (Gaughan & Santoro, 2018). In SWA, these IMCRA and Fisheries bioregions form the basis for species management and conservation.

1.2 The Global Changing Climate

1.2.1 Anthropogenic and climatic impacts

Throughout the world, climatic and anthropogenic pressures are driving changes in the composition of marine assemblages and the distribution patterns of fish (for example: Chen et al., 2011; Poloczanska et al., 2013; Wernberg et al., 2013). The implications and consequences of these changes for marine communities are a current focus of global marine research. By detailing shifts in the abundance and geographical ranges of species, we can begin to quantifying the ecological, economic and social impacts of these changes (Bell et al., 2018; Bertrand et al., 2019; Brander et al., 2017; Sumaila et al., 2011; Fredston-Hermann et al., 2020a). Anthropogenic pressures include commercial and recreational fishing (Cooke & Cowx, 2004; Myers & Worm, 2003), increased agricultural run-off (Cloern, 2001) and a rise in atmospheric CO_2 (IPCC, 2014). Unprecedented increases in anthropogenic greenhouse gas emissions, which are driven by recent economic and population growth, contribute to global climatic changes. These climatic changes are having an impact on the marine environment, leading to variations in ocean chemistry and an increase in anomalous warm-water events (known as marine heatwaves) across the world (Oliver et al. 2020). Globally, pressures from anthropogenic and climatic impacts are projected to increase (IPCC, 2014; Weatherdon et al., 2016) and changes in the distribution and composition of marine species will continue to occur, causing possible shifts in ecosystem structure.

1.2.2 Environmental and habitat drivers of assemblage distribution

Environmental and habitat variables drive the distribution of marine assemblages and changes can lead to a decrease in resilience or alterations in the composition of communities (Perry et al., 2005; Galaiduk et al., 2013; Bennett et al., 2015; Vergés et al., 2014; Wernberg et al., 2016). Previous studies have highlighted the importance of sea surface temperature (SST) as a dominant environmental factor, which can influence the distribution, abundance and size of marine species (Dayton et al., 1999; Lüning, 1984; Seabra et al., 2015). SST is increasing globally (Thomson et al., 2015), and predictions indicate that this will continue unless the emission of greenhouse gasses into the environment is decreased (IPCC, 2014). Warmer ocean temperatures are correlated with changing marine assemblages (Brander et al., 2003; Rijnsdorp et al., 2009), including regime shifts (Bennett et al., 2015; Wernberg et al., 2016) and the tropicalisation of communities (Figueira & Booth, 2010; Cheung et al., 2012; Vergés et al., 2014). Species 'cold range edges' track climate change to a greater degree than their 'warm range edges' (Fredston-Hermann et al, 2020a), indicating the potential for range increases of species. Changes in SST can also facilitate a shift in marine habitats, which in turn drives the distribution of assemblages (Galaiduk et al., 2017; Harvey et al., 2013; Smale & Wernberg, 2013). Species distributions can also be influenced by oceanography, such as currents and weather events, by aiding dispersal or migration (Adey & Steneck, 2001; Caputi et al., 1996; Phillips, 2001; Figueira & Booth, 2010).

1.3 Southwest Australia

Southwest Australia (SWA) has a complex coastline ranging from a subtropical north to a temperate south (Fox & Beckley, 2005), with large areas of rocky coasts, abundant kelp forests and sandy beaches (Phillips, 2001). This heterogeneity creates distinct ecological habitats and niches, which comprise of differing algal assemblages and canopy-forming macroalgae (Galaiduk et al., 2017; Toohey et al., 2007), substratum type (Jenkins & Wheatley, 1998), vertical relief (Harman et al., 2003) and SST (Caputi et al., 1996; Langlois et al., 2012), which leads to unique fish assemblages along the SWA coast (Ford et al., 2017; Galaiduk et al., 2017; Langlois et al., 2012). The major oceanographic feature of the region is the southward flowing Leeuwin Current that transports warm water down the coastline, creating a gradual SST gradient that facilitates the migration and survival of tropical fauna south of their usual range (Pearce & Walker, 1991). In this region, and extending across the whole of southern Australia, lies the important temperate 'Great Southern Reef' (GSR), which provides substantial socio-economic and ecological value to the surrounding area and human population (Bennett et al., 2016)**.**

1.3.1 Affiliation and endemic influence

The coastline of SWA is an old, oligotrophic area that has remained relatively stable and isolated for the past 40 million years (Langlois et al., 2012; McGowran et al., 1997). SWA is an intermixing zone, with tropical affiliated species at their southern limit, temperate species at their northern end and a linking unique subtropical fish fauna that

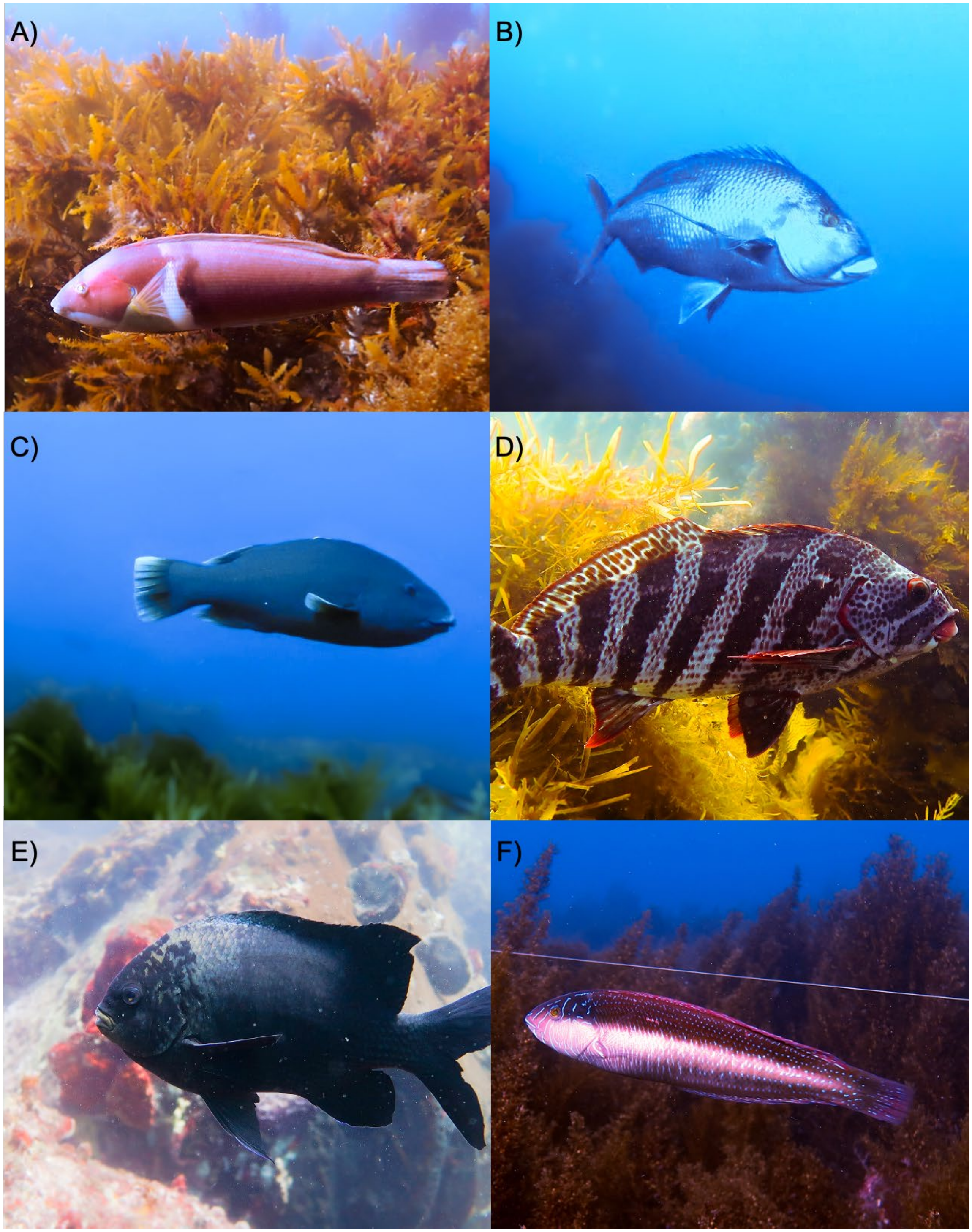


Figure 1.1. Examples of typical Australian endemic shallow-water reef fishes in Southwest Australia (SWA). (A) Male western king wrasse (*Coris auricularis*); (B) queen snapper (*Nemadactylus valenciennesi*); (C) blue groper (*Achoerodus gouldii*); (D) red-lipped morwong (*Goniistius rubrolabiatus*); (E) mcculloch's scalyfin (*Parma mccullochi*); and (F) Maori wrasse (*Ophthalmolepis lineolatus*)

is neither temperate nor tropical in distribution (Hutchins, 1994, 2001). The shallow waters of Western Australia contains approximately 1500 species of fish (with 19.5% estimated to be endemic), whose distributions are correlated with the SST gradient produced by the Leeuwin Current (Fox & Beckley, 2005; Hutchins, 2001). Short-range endemic species occur across small areas of less than 10,000 km^2 (Harvey, 2002), and in SWA these species may be indicator or keystone species (species with a higher than expected influence on an assemblage) within the marine community (Fletcher et al., 2010; Ford et al., 2017; Helfield & Naiman, 2006). Changes in species distributions (particularly endemics) along the SWA coastline should be monitored to aid in predicting future movements, which will enable the continuing development of proactive and effective management of fish assemblages (Harvey et al., 2013; Simpson et al., 2011).

1.3.2 Climatic changes in Southwest Australia

Matching global climatic trends, variations in SST have occurred in SWA (Feng et al., 2013; Pattiaratchi & Hetzel, 2020; Pearce & Feng, 2013). In 2011, the region experienced a marine heatwave with temperatures increasing ~2-4^{o}C above the long-term monthly average (Pearce & Feng, 2013). This rapid increase in temperature drove a change in marine habitats and facilitated the tropicalisation of fish assemblages (Bennett et al., 2015; Smale & Wernberg, 2013; Wernberg et al., 2016). This was characterised by warm-water fishes shifting south, leading to an increase in abundance of these species further down the coast than previously recorded (Parker et al., 2019; Shalders et al., 2018). Canopy cover in the region declined by up to 40% with this altered state maintained over time (Bennett et al., 2015; Wernberg et al., 2013). Species and their associated habitats are intrinsically linked, and changes in either may result in differing species interactions throughout the community (Bennett et al., 2015; Saunders et al., 2014; Smale & Wernberg, 2013).

1.4 The Need for Continued Monitoring and Research

1.4.1 Research gaps

Temperate ecosystems are relatively understudied when compared to their tropical counterparts (Barrett et al., 2007). Globally, and locally in SWA, climatic changes have been observed (Cheung et al., 2012) and are predicted to continue (Hobday & Lough, 2011; IPCC, 2014; Meehl et al., 2007). These climatic variations have resulted in changes to marine assemblages and species distributions which have already been documented (Parker et al., 2019; Perry et al., 2005; Vergés et al., 2016) (Fig. 1.2). Successful marine conservation and management strategies require high quality, accurate distributional data on assemblages (DEFRA, 2007). As a consequence, monitoring species' responses to environmental changes over appropriate spatial and temporal scales is important to track species ranges, and validate management and conservation techniques (Fredston-Hermann et al., 2020a). Distributions of fish assemblages along the SWA coast have been documented at single time periods (Ford et al., 2017; Fox & Beckley, 2005; Hutchins, 2001; Last et al., 2011), or over a time series for a single taxonomic family (Cure et al., 2015; Parker et al., 2019; Shalders et al., 2018; Tuya et al., 2009). Therefore, knowledge about how whole assemblages respond to climatic changes over large spatial and temporal scales is limited.

1.4.2 The current distribution of shallow-water reef fish

To adequately manage species in a continually changing environment, it is important to determine the accuracy of current regional management (Fig. 1.2). I address this in Chapter 2 of this thesis, which identifies the composition and distribution of shallow-water reef fish assemblages in 2015 and how these differ from existing bioregional management along the SWA coastline (Fig. 1.2). This chapter also investigates the primary environmental and habitat variables that influence the distribution of fish assemblages, and identifies characteristic species of each distinct assemblage (Fig. 1.1). Bioregionalisation of SWA was defined by studies in the early 2000s (Commonwealth of Australia, 2006; Fox & Beckley, 2005; Hutchins, 2001). However, climatic changes in this region over the past two decades suggest that these descriptions would benefit from current validation. Data was collected from surveys conducted in 2015 using diver-operated stereo-video systems to record the abundance of shallow-water reef fishes and describe their associated habitat. This information is crucial for management and planning strategies in this ecological, economically and socially important region.

1.4.3 Responses of shallow-water reef fish to climatic changes

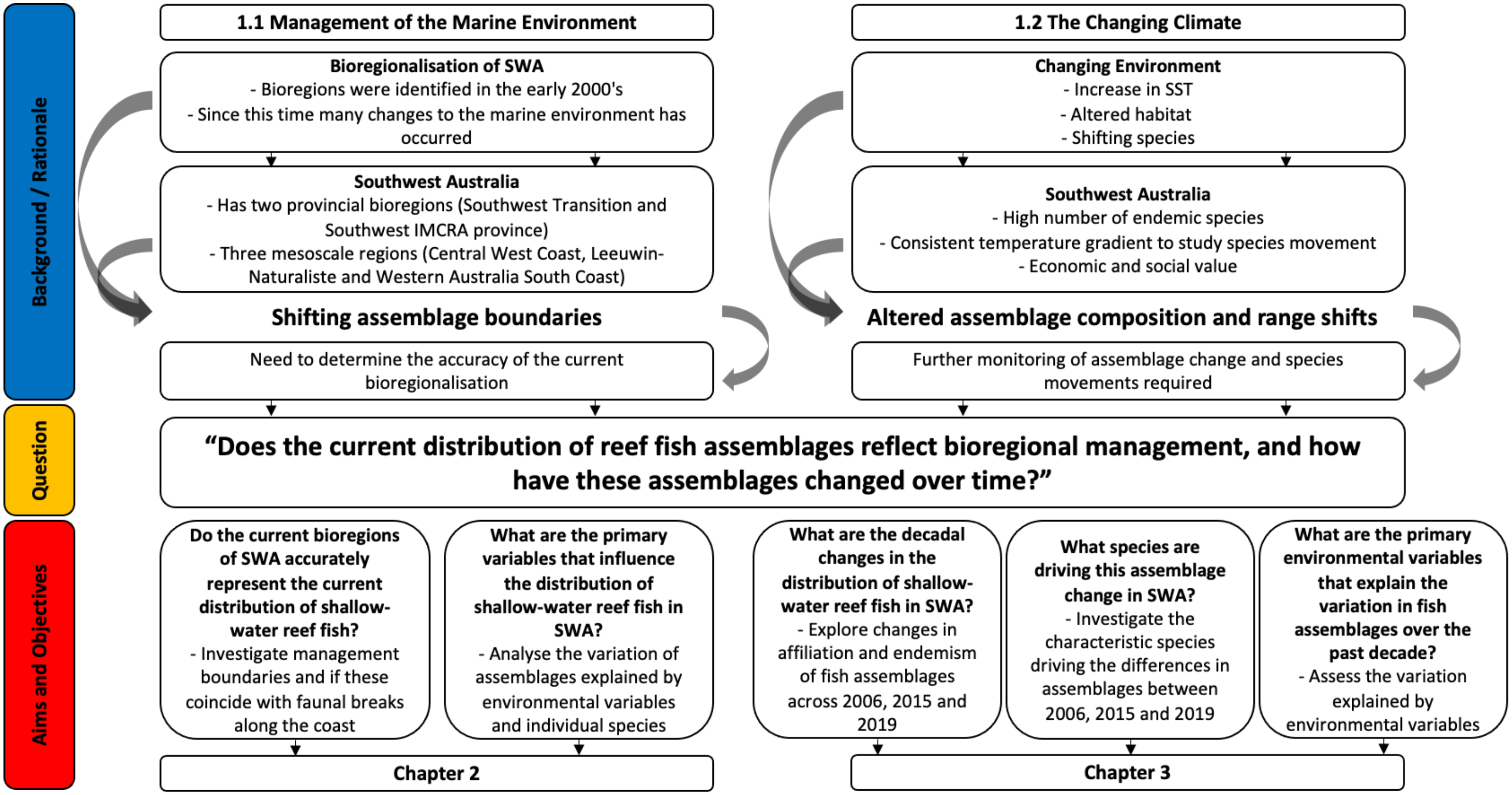
Monitoring species over large temporal and spatial scales is important to determine the extent of community responses to a changing environment (Dayton et al., 1999;

Molinos et al., 2015, Figueira & Booth, 2010), aiding in predicting future community shifts and allowing an adaptive, flexible management policy and strategy (Fig. 1.2). Throughout the world, shifting species ranges, tropicalisation and regime shifts have been documented, and are correlated with a change in SST and other habitat variables. Previous studies have mainly targeted individual species or families, with few studies looking at changes in whole fish assemblages over a large temporal and spatial scale. Along the temperate southeast coast of Australia the occurrence and survival of tropical fishes has been documented in correlation to increasing ocean temperature (Booth et al., 2007; Figueira & Booth, 2010). However, research is limited along Australia's southwest coastline. Chapter 3 of this thesis assesses changes in shallow-water reef fish assemblages over 14 years (2005-2019) of climatic variations in SWA (Fig. 1.2). I also address changes in the climatic affiliation, endemism and trophic level of shallow-water reef fish, identify characteristic species, and primary environmental and habitat variables that are driving assemblage changes over time (Fig. 1.1). This chapter encompasses a changing climate and variation in SST and links these to the responses of the fish community.

1.5 Research Question and Thesis Structure

1.5.1 Research question

The overall objective of this thesis was to assess the current distribution of SWA shallow-water reef fish assemblages in relation to management bioregions, and the change in these assemblages over time. The question that defines the direction and aims of this thesis is "Does the current distribution of reef fish assemblages reflect bioregional management, and how have these assemblages changed over time?" (Fig. 1.2). This question will be addressed in the two data chapters, with research in this thesis focussing on assemblages of shallow-water reef fish. The primary aim of the second chapter was to determine if the regions sampled along the SWA coast represented distinct fish assemblages or grouped into other arrangements, and to evaluate how these groupings differed from the present bioregionalisation of SWA (Fig. 1.2). The third chapter analysed how these shallow-water reef fish communities have responded to over a decade of climatic changes, with an emphasis on regional changes in the affiliation, endemism and trophic level of species (Fig. 1.2).



1.1 Management of the Marine Environment

Bioregionalisation of SWA
- Bioregions were identified in the early 2000's
- Since this time many changes to the marine environment has occurred

Southwest Australia
- Has two provincial bioregions (Southwest Transition and Southwest IMCRA province)
- Three mesoscale regions (Central West Coast, Leeuwin-Naturaliste and Western Australia South Coast)

Shifting assemblage boundaries

Need to determine the accuracy of the current bioregionalisation

1.2 The Changing Climate

Changing Environment
- Increase in SST
- Altered habitat
- Shifting species

Southwest Australia
- High number of endemic species
- Consistent temperature gradient to study species movement
- Economic and social value

Altered assemblage composition and range shifts

Further monitoring of assemblage change and species movements required

"Does the current distribution of reef fish assemblages reflect bioregional management, and how have these assemblages changed over time?"

Do the current bioregions of SWA accurately represent the current distribution of shallow-water reef fish?
- Investigate management boundaries and if these coincide with faunal breaks along the coast

What are the primary variables that influence the distribution of shallow-water reef fish in SWA?
- Analyse the variation of assemblages explained by environmental variables and individual species

Chapter 2

What are the decadal changes in the distribution of shallow-water reef fish in SWA?
- Explore changes in affiliation and endemism of fish assemblages across 2006, 2015 and 2019

What species are driving this assemblage change in SWA?
- Investigate the characteristic species driving the differences in assemblages between 2006, 2015 and 2019

What are the primary environmental variables that explain the variation in fish assemblages over the past decade?
- Assess the variation explained by environmental variables

Chapter 3

Figure 1.2. Conceptual diagram outlining the general structure of this thesis. Chapter 2 has been published and chapter 3 has been written for publication.

1.5.2 Thesis structure

This thesis is structured into four chapters, a general introduction, two data chapters and a general discussion. The two data chapters (Chapters 2 and 3) are written as stand-alone manuscripts. Chapter 2 has been published in Marine Ecology Progress Series (https://doi.org/10.3354/meps13445), and as such, the accepted manuscript is included here. Chapter 3 has been prepared for submission to Nature Climate Change. As stand-alone chapters, there is some repetition within each, particularly in the Materials and Methods sections.

In this thesis, I begin by investigating the current distribution of shallow-water reef fish assemblages in SWA (Chapter 2). I then determine the responses of these assemblages to over a decade of climatic changes (Chapter 3). In the general discussion at the end of this thesis (Chapter 4), I relate the findings back to the over-arching research question and to previous studies, and discuss the implications of this study in conservation and management strategies in SWA. I also explore the limitations of this thesis and identify future areas of research that could advance this data set.

CHAPTER 2

Spatial assemblage structure of shallow-water reef fish in Southwest Australia

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Watercolour of a male (right), female (below) and juvenile (left) western king wrasse (*Coris auricularis)* by Savita Goldsworthy

Preface

This Chapter has been published in the peer-reviewed journal *Marine Ecology Progress Series* Inter-Research (doi: https://doi.org/10.3354/meps13445) and has therefore been formatted according to their specific guidelines. However, to keep consistency across this thesis, references have been formatted to the APA style.

The main objective of this first data chapter was to document the unique assemblages of shallow-water reef fish in SWA, determine driving environmental and habitat variables, and identify characteristic species of each distinct assemblage.

2.1 Abstract

Bioregional categorisation of the Australian marine environment is essential to conserve and manage entire ecosystems, including the biota and associated habitats. It is important that these regions are optimally positioned to effectively plan for the protection of distinct assemblages. Recent climatic variation and changes to the marine environment in Southwest Australia (SWA) have resulted in shifts in species ranges and changes to the composition of marine assemblages. The goal of this study was to determine if the current bioregionalisation of SWA accurately represents the present distribution of shallow-water reef fishes across 2000 km of its subtropical and temperate coastline. Data was collected in 2015 using diver-operated underwater stereo- video surveys from seven regions between Port Gregory (north of Geraldton) to the east of Esperance. This study indicated that (1) the shallow-water reef fish of SWA formed four distinct assemblages along the coast: one Midwestern, one Central and two Southern Assemblages; (2) differences between these fish assemblages were primarily driven by sea surface temperature, *Ecklonia radiata* cover, non-*Ecklonia* canopy cover, understorey algae cover, reef type and reef height; and (3) each of the four assemblages were characterised by a high number of short-range Australian and Western Australian endemic species. The findings from this study suggest that four, rather than the existing three bioregions would more effectively capture the shallow-water reef fish assemblage patterns, with boundaries having shifted southwards likely associated with ocean warming.

2.2 Introduction

2.2.1 Marine bioregionalisation

‘Bioregionalisation’, or accurately specifying distinct bioregions, is important for both marine and terrestrial conservation planning. Once defined, these regions can be used to build a planning framework for an area that is representative and comprehensive (e.g. Ray & McCormick-Ray, 1992; Salm et al., 2000). Managing an area by bioregions allows for whole ecosystem conservation and management (Olson et al., 2001), which is recognised as an optimal management practice for regions of high biodiversity in terrestrial systems (e.g. Warry & Hanau, 1993; Jenkins & Joppa, 2009). In contrast to terrestrial bioregional planning, the marine environment is underrepresented in management systems, despite a number of regions having high biodiversity and a high concentration of species and endemics (Phillips, 2001). As a consequence of this underrepresentation, a shift towards management strategies that conserve and protect entire marine ecosystems is occurring (Wood et al., 2008; Barr & Possingham, 2013). The concept of marine bioregionalisation has been expanding since the late 1990s (Agardy, 1999), with it being suggested that these regions should be of a suitable size to assist in managing the dynamic marine environment, encompass multiple use and no-take areas and enable the protection of associated habitats (Day, 2002; GBRMP Authority, 2004). This concept is being adopted globally (Morrone, 2015) to balance and manage resource use and conserve marine biodiversity and habitats. For example, the Netherlands are developing a regional management plan and framework to enhance the economic value of the North Sea while protecting and managing the ecology and habitat (IDON, 2015). Similarly, the United Kingdom has adopted a spatial management plan of their entire marine area via the White Bill, allowing plans for interactions between ecological and economical uses (DEFRA, 2007). Australia has also adopted a bioregional approach and aims to have over 35% of its waters protected within this system (Barr & Possingham, 2013).

In 1991 (Last et al., 2011), Australia established the National Representative System of Marine Protected Areas based on bioregional marine planning. To facilitate and ensure establishment of this management strategy by 2012, the Integrated Marine and Coastal Regionalisation of Australia (IMCRA) was developed (Commonwealth of Australia, 2006). These maps arranged the marine environment into 60 mesoscale bioregions on the Australian continental shelf. In Southwest Australia (SWA), there are three identified mesoscale bioregions under the current iteration (Commonwealth of Australia, 2006): (1) the Central West Coast; (2) The Leeuwin-Naturaliste; and (3) the Western Australian South Coast. The goal of IMCRA is to ensure these bioregions are ecologically structured and useful for resource planning and conservation of species and their habitats in Australia (Commonwealth of Australia, 2006).

Commercial fisheries in SWA are managed according to slightly different management regions, building upon the IMCRA mesoscale bioregions. In this region, fisheries management utilises the risk-based ecosystem-based fisheries management approach to form a regional management and planning system (Fletcher et al., 2010; 2012), which observes the linkage between fisheries value and individual exploited fish stocks as well as effects on habitat and individual species (Gaughan & Santoro, 2018). Currently, SWA commercial fisheries are managed within two bioregions: the West Coast and the South Coast. Bioregions in Australia form the basis of marine management and planning to balance biodiversity preservation and sustainable resource use. As a consequence, the bioregions should accurately represent the marine communities within them (Stewart et al., 2003) and be adaptable to consider changes in the distribution of species.

2.2.2 Australia’s biodiversity

Australia’s marine biodiversity has long been recognised as unique (Kriwoken, 1996; Wernberg et al., 2011), with its waters containing a number of internationally accredited biodiversity marine ‘hotspots’ (regions with a high biodiversity and concentration of species and endemics) (Phillips, 2001; Wernberg et al., 2011). Hotspots are areas usually isolated in space and time and are useful to prioritise the conservation and management of a region. The most famous Australian marine hotspot is the Great Barrier Reef, which is home to approximately 1150 fish species and tropical coral reef communities (Allen, 2008; Wood et al., 2008). SWA is also a global biodiversity hotspot (e.g. Lüning, 1991; Bolton, 1994; Bennett et al., 2016), recognised for its high species richness and endemism and estimated to have 30− 40% of the world’s macroalgae diversity within its coastal waters (Bolton, 1994). The ‘Great Southern Reef’ of SWA provides substantial socio-economic and ecological value to the surrounding communities that depend on this reef system (Bennett et al., 2016).

SWA has a complex coastline ranging from a subtropical north to a temperate south (Fox & Beckley, 2005). The waters of Western Australia contain approximately 3000 species of marine fish (Hutchins, 2001), with 19.5% of these species estimated to be short-range endemics (Fox & Beckley, 2005), defined as species that occur naturally across small areas less than 10 000 km^2 (Harvey, 2002). The coastline of SWA is highly heterogeneous, with abundant rocky coasts, kelp forests and sandy beaches, and is subjected to oceanographic influence, such as ocean currents that may facilitate the migration of species (Adey & Steneck, 2001; Phillips, 2001). The southward flowing Leeuwin Current has a major influence on SWA coastal waters, transporting warmer water from the north and ensuring the survival of tropical fauna along the coast (Pearce & Walker, 1991). The Leeuwin Current and the corresponding sea surface temperature (SST) gradient from north to south makes SWA an ideal area to study the distribution and assemblage structure of shallow-water reef fish (Wernberg et al., 2010; Langlois et al., 2012). Algal assemblages and canopy-forming macroalgae (Levin & Hay, 1996; Galaiduk et al., 2017), substratum type (Jenkins & Wheatley, 1998), vertical relief (Harman et al., 2003) and SST (Pörtner et al., 2010; Langlois et al., 2012) all contribute to creating distinct ecological habitats and niches that give rise to unique fish assemblages within a geographic area. The relationship between species, habitat and SST, along with other environmental variables can aid in defining bioregions, which can be used in conservation and management, allowing prioritisation of resources and funding (Ward et al., 1999; Valavanis et al., 2004; Moore et al., 2010).

Bioregions in SWA were identified by studies completed in the early 2000s (e.g. Hutchins, 1994; 2001, Fox & Beckley, 2005; Commonwealth, of Australia 2006). However, in the past 2 decades, climatic variations including changes in salinity, ocean currents and temperature have been predicted and documented (Hobday & Lough; 2011, Cheung et al., 2012), which has resulted in regime shifts (Bennett et al., 2015b; Wernberg et al., 2016), shifts in species ranges, changes in the composition of fish and other marine assemblages (e.g. Bennett et al., 2015b; Shalders et al., 2018; Parker et al., 2019) and changes in fishing effort (Gaughan & Santoro, 2018). To adequately manage and protect species and habitats in a changing environment, it is important to determine if the current bioregionalisation of SWA represents the present distribution of shallow-water reef fish communities.

The goal of this study was to determine whether the defined bioregionalisation of SWA accurately represents the current distribution of shallow-water reef fish communities. Quantifying the accuracy of SWA's bioregionalisation can inform management to ensure bioregions accurately represent shallow-water reef fish assemblages and contribute to accurate protection of hotspot regions. The aims of this study were to (1) assess whether seven regions sampled each represent distinct fish assemblages or group into a smaller number of clusters representing bioregions; (2) assess whether any distinct bioregions observed align to the established SWA IMCRA and fisheries management regions; and (3) identify the primary environmental variables that influence the distribution of shallow-water reef fish and the fish species that characterise the fish assemblages within the distinct bioregions in SWA.

2.3 Materials and Methods

2.3.1 Study area and experimental design

Surveys of shallow-water reef fish assemblages were completed across SWA following a hierarchical experimental design (Saunders et al., 2014; Shalders et al., 2018; Parker et al., 2019). A total of seven coastal regions in SWA were sampled, designed to incorporate the subtropical to warm-temperate transition, and warm temperate SWA coastline. Locations were selected to ensure they encompassed the temperature gradient that exists along the coast and the heterogeneous habitats of SWA. The seven regions spanned 2000 km of coastline, ranging from Geraldton (28.7797° S, 114.6144° E) in the north, through Jurien Bay (30.3070° S, 115.0372° E), Perth (31.9505° S, 115.8605° E), South-West Capes (34.0887° S, 114.9975° E), Albany (35.0269° S, 117.8837° E) and Bremer Bay (34.3979° S, 119.1897° E), to Esperance (33.8613° S, 121.8914° E) in the southeast of Western Australia (Fig. 2.1). In total, four locations were selected within each region, four reef sites were chosen within each location and 12 transect lines (25 m long × 5 m wide) were surveyed within each reef site. This resulted in data being collected from 1344 transects across 112 reef sites between December 2014 and July 2015. While collecting data over a six-month period may have resulted in seasonal changes in the recorded fish assemblages, most reef-dwelling fish species are site-associated (Sale, 1991), and therefore the recorded assemblages were likely to be stable between seasons (Holbrook et al., 1994). Samples were separated by distance based on a hierarchical spatial scale. The seven regions were separated by

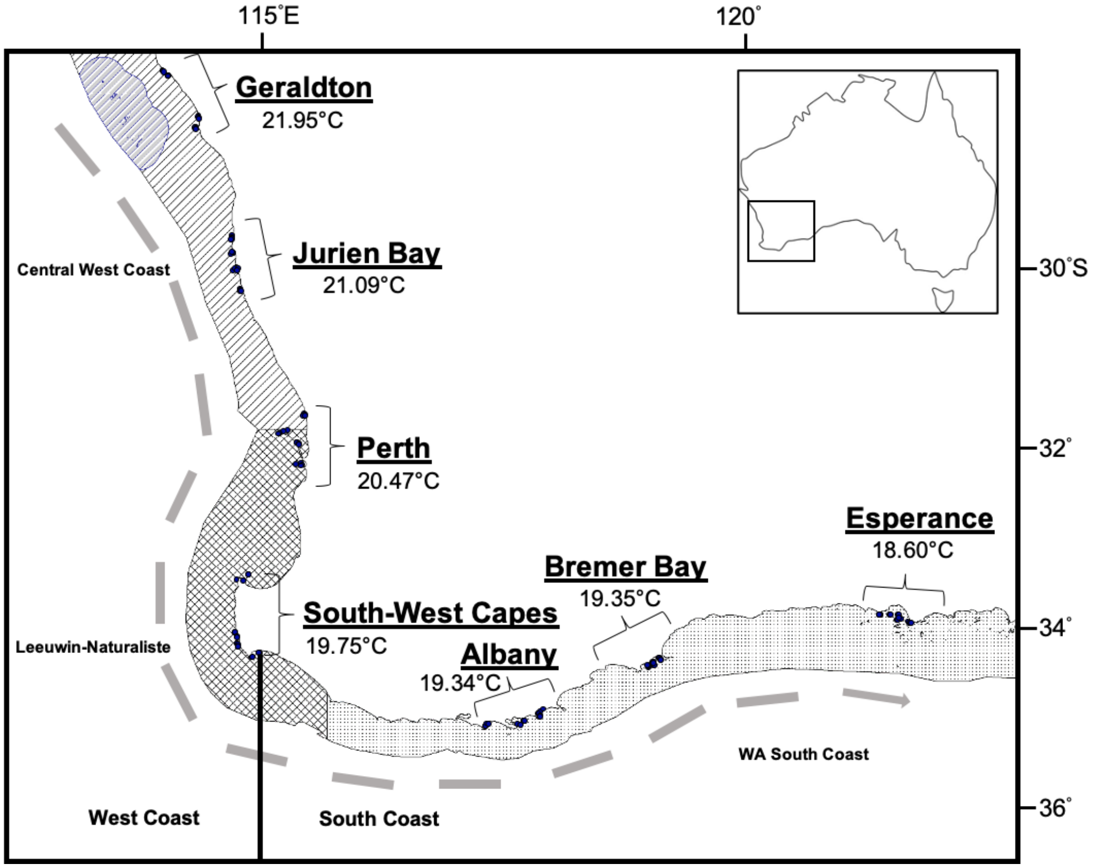

Figure 2.1. Survey design in Southwest Australia (SWA) showing the seven regions (1: Geraldton; 2: Jurien Bay; 3: Perth; 4: South-West Capes; 5: Albany; 6: Bremer bay; 7: Esperance) and mean sea surface temperature for each region during the study period. Within each region the locations of each reef site (n = 112) are illustrated. Grey arrow along the coast: direction of the Leeuwin Current and the corresponding temperature gradient; hatching and shading: the three Integrated Marine and Coastal Regionalisation of Australia mesoscale regions: Central West Coast, Leeuwin-Naturaliste and the Western Australian South Coast; dark line heading south from the South-West Capes: the two fisheries management areas of SWA

1000s to 100s of km, locations within each region by 10s of km and reef sites within each location by kilometres to 100s of metres. Transects within each reef site were separated by at least 10 m. Sampling targeted shallow, complex reefs between 4 and 12 m deep and encompassed a coastline spanning 7° of latitude and 10° of longitude.

2.3.2 Survey method

To record and survey the shallow-water reef fish and benthic habitats, SCUBA divers maneuvered a diver-operated stereo-video system (stereo-DOV) along the 25 × 5 m transects. The use of 25 m transect lengths was chosen due to the patchiness of the complex shallow-water reefs sampled. Each transect was swum by a pair of SCUBA divers with one diver operating the stereo-DOV. Stereo-DOVs were designed to improve the precision of length and distance estimates and minimise inter-observer variability (Harvey & Shortis, 1995; Harvey et al., 2002; Harvey et al., 2004; 2010). The stereo-video system used in this research was constructed from two Sony HDR CX700 video cameras in underwater housings, fixed 700 mm apart and inwardly converged at 8° to maximise the area for measurement (Shalders et al., 2018; Parker et al., 2019). The system was calibrated before and after each set of field work using the software CAL (Seager, 2014), which ensured accurate calculation of transect dimensions and length measurements throughout the entire study area (Harvey & Shortis; 1998, Shortis & Harvey, 1998; Harvey et al., 2004).

2.3.3 Video analysis

Video recordings created a permanent record of each transect, allowing for post-survey analysis of fish and benthic habitat. The video footage was analysed using the software package Event-Measure (stereo) (www.seagis.com.au) with an observer identifying, counting and measuring the lengths of fish seen within each transect. Rules established within the software prevented fish that were more than 7 m away from the camera or 2.5 m away from the centre of the transect line (outside the transect) from being counted or measured (Harvey et al., 2004). Fish that were only visible in one camera, due to obstruction of the field of view by algae or substrate, were still counted if the analyst was certain that the fish were within transect boundaries.

2.3.4 Habitat analysis

The same video footage was also used to quantify the benthic habitat. Video imagery was analysed in a Visual Basic program in Microsoft Excel modified from that described by Holmes (2005). Following the procedures from Saunders et al. (2014), five equally spaced frames were selected within each 25 m transect and analysed. Each frame was non-overlapping and showed an extensive view of the habitat, which allowed categorisation as a horizontal image. It was then assigned a reef type, either limestone or granite, and reef cover was approximated and assigned a categorical value from 1−6 within each frame: (1) 0−25% reef and 75−100% sand, (2) 21−50% reef and 50−75% sand, (3) 50% reef and 50% sand, (4) 50−75% reef and 25−50% sand, (5) 75−100% reef and 0−25% sand or (6) 100% reef. Reef height was also estimated from the field of view and categorised with a value from 1−4: (1) platform reef, (2) small (<1 m in height boulders or outcrops), (3) large (1−3 m in height boulders or outcrops), or (4) massive (> 3 m in height out- crops). Reef slope was estimated and assigned a value from 1−5 based on (1) gentle slope (< 30°), (2) steep slope (30−70°), (3) vertical wall (70−110°), (4) overhanging wall (>110°) and (5) overhead overhanging reef or cave. Benthic habitat was also estimated at each frame for *Ecklonia radiata* canopy, non-*Eclonia* canopy cover, understorey algae cover (foliose and turfing algal forms) and hard coral cover, and were given a rank from 0−6, with (0) no cover, (1) <1%, (2) 1−10%, (3) 10−25%, (4) 25−50%, (5) 50−75% and (6) > 75% cover. Seagrass presence or absence was also recorded for each frame. The Australian Ocean Data Network (AODN) open access to ocean data portal (AODN, 2020) was used to determine mean SST at each study location. The AODN uses a single-sensor, multi-satellite 'SSTfnd' product that is derived from observations on all available NOAA satellites to produce a 0.02° grid. The mean temperature value was calculated from all available temperature recordings to give a single temperature value for each location over the year 2015.

2.3.5 Statistical analysis

A species list was generated, and the geographic affiliation and endemism of each species compiled. Geographic affiliation information was gathered primarily from the literature (e.g. Fairclough et al., 2011) (Supplementary Information: *Overall Species Table*) with additional data obtained from FishBase (Froese & Pauly, 2019). Endemism data were collected from Fishes of Australia (Museums Victoria) (Bray et al., 2017–

2020) with supplementary information from FishBase (Froese & Pauly, 2019). Species that could not be accurately distinguished to species level with high certainty were grouped to family level for statistical analysis. These included *Pempheris* spp., *Siphonognathus* spp. and *Trachinops* spp. *Kyphosus* species could be differentiated via video but were classified into two distinct groups based on their morphology: *K. cornelli/ biggibus/vaigiensis* and *K. sydneyanus/gladius*.

2.3.5a SWA's faunal structure and endemism

For each of the 28 locations, the overall abundance of fish was represented graphically. Temperature affiliation of each species (temperate, subtropical and tropical), along with the contribution of Western Australian and Australian endemics, Indo-Pacific species and 'other' species (species with global distributions) were illustrated using stacked bar plots.

2.3.5b SWA's distinct shallow-water reef fish assemblages

Multivariate statistical analysis was used to analyse the spatial distribution patterns of shallow- water reef fish in SWA and was performed using the PRIMER v.7.0 software package (Anderson et al., 2008). Prior to transformation, raw transect assemblage data were summed to site level (n = 112 across the SWA coast; Fig. 2.1). Dispersion-weighting was then applied to transform and down-weight overly dispersed species and those with large abundance fluctuations in the data set. This transformation gave species with similar abundances within each site (i.e. stable species) greater weight in the analysis but still ensured that the data remained quantitative by allowing all species to contribute to overall patterns (Clarke et al., 2006). A Bray-Curtis similarity coefficient was implemented in a resemblance matrix constructed using the site data, as it does not consider species with joint absences evidence for similarity (Bray & Curtis, 1957; Clarke ,1993). To determine if an overall significant difference in the shallow-water reef fish assemblages occurred across regions and locations along the SWA coast, the resemblance matrix was tested using a two-factor permutational multivariate analysis of variance (PERMANOVA) (Anderson, 2001). This design included region (fixed factor; seven levels) and location (random factor, nested in region; 28 levels). Prior to the PERMANOVA analysis, the Bray-Curtis resemblance matrix was tested for homogeneity of multivariate dispersions on the factor 'region' using the 'PERMDISP' function in PRIMER, as PERMANOVA models are sensitive to these dispersions (Anderson, 2004).

A canonical analysis of principal coordinates (CAP) was used to project each site (n = 112) into high-dimensional space using the seven regions of SWA as a factor for groups. The CAP procedure is constrained to hypotheses described a priori and is used to show maximum differences between levels of a chosen factor. This procedure may have more power than PERMANOVA in certain situations in multivariate space where the overall dispersion in the data conceals real dispersion among groups (Anderson & Willis, 2003). The resulting leave-one-out allocation success of observations (region) table was used to analyse which regions were clearly separated from others. CAP was also used to assess alternative ways by which the fish assemblages of the seven sampled regions could be arranged into ‘assemblage structures’. The ‘assemblage structures’ arrangements assessed were (1) the two fisheries management zones, (2) the three mesoscale regions of SWA (Fig. 2.1) and (3) assemblages comprising three, four, five and six distinct groupings. CAP analyses were implemented for each of these six different assemblage structures and the resulting plots and leave-one-out allocation success tables were examined to determine which structure best represented the distinct assemblages of shallow-water reef fish species in SWA. To directly compare and support the results of the six CAP analyses, corrected Akaike’s information criterion (AIC_C) was calculated for each assemblage structure using the equation:

$$N \log (SS_{residual} / N) + 2v \, [N / (N - v - 1)]$$

where N is the sample size (i.e. 112 sites) and v is the number of groups within each assemblage structure. The AIC_C results are directly comparable between the six CAP analyses, and the assemblage structure with the lowest AIC_C was considered to be the best representation of the current distribution of shallow-water reef fish assemblages along the SWA coastline.

Species that typified each distinct region as determined by the CAP analysis with the lowest AIC_C value were examined using SIMPER (Clarke & Warwick, 2001) and ranked by their percentage contribution (% contrib).

2.3.5c Contribution of habitat and SST to SWA's distinct shallow-water reef fish assemblages

To analyse the contribution of habitat (reef cover, reef type, reef height, reef slope, *E. radiata* cover, non-*Ecklonia* canopy cover, understorey algal cover, hard coral cover and seagrass presence) and SST on distinct fish assemblage structures, a distance-based multivariate linear model (DISTLM) analysis was run using the PERMANOVA+ package (Anderson, 2004; Anderson et al., 2008). This procedure selected habitat and temperature variables that best explained the variation in shallow-water reef fish assemblages along the SWA coast. Prior to analysis, the mean for categorical variables was calculated for each site to give measures of habitat at each of the 112 study sites. Correlations between explanatory variables were viewed in Draftsman Plots, as models based on regression are sensitive to these correlations. All correlations were < 0.9, allowing all variables to be available for inclusion in the analysis. Normality was assessed visually via histogram plots, and as a result, reef height was log transformed. The final DISTLM model was constructed using the BEST selection procedure (fits all possible models) and the AIC_C selection criterion (Chambers & Hastie, 1992). The BEST selection procedure was used to formulate the optimum model, as this evaluated selection criteria for all possible combinations of variables (Anderson et al., 2008). AIC_C was the most suitable for this procedure, as it reduced the bias from linear regression (Sugiura, 1978) and refined model selection by correcting for small sample sizes (Hurvich & Tsai, 1989). Analysis using DISTLM was based on the Bray-Curtis resemblance matrix of the dispersion-weighted shallow-water reef fish assemblage data. A distance-based redundancy analysis (dbRDA) was used to present the optimum model created by the DISTLM, with the dbRDA performing an ordination of the assemblage data that is constrained to the significant habitat and temperature variables.

2.4 Results

2.4.1 SWA's faunal structure and endemism

Across the 28 locations, the most speciose family was the Labridae, with 28 species comprising 26% of the total number of fish recorded, followed by Pomacentridae (14 species) with 12% of the total number of fish. Of the 119 species recorded, 32% (38

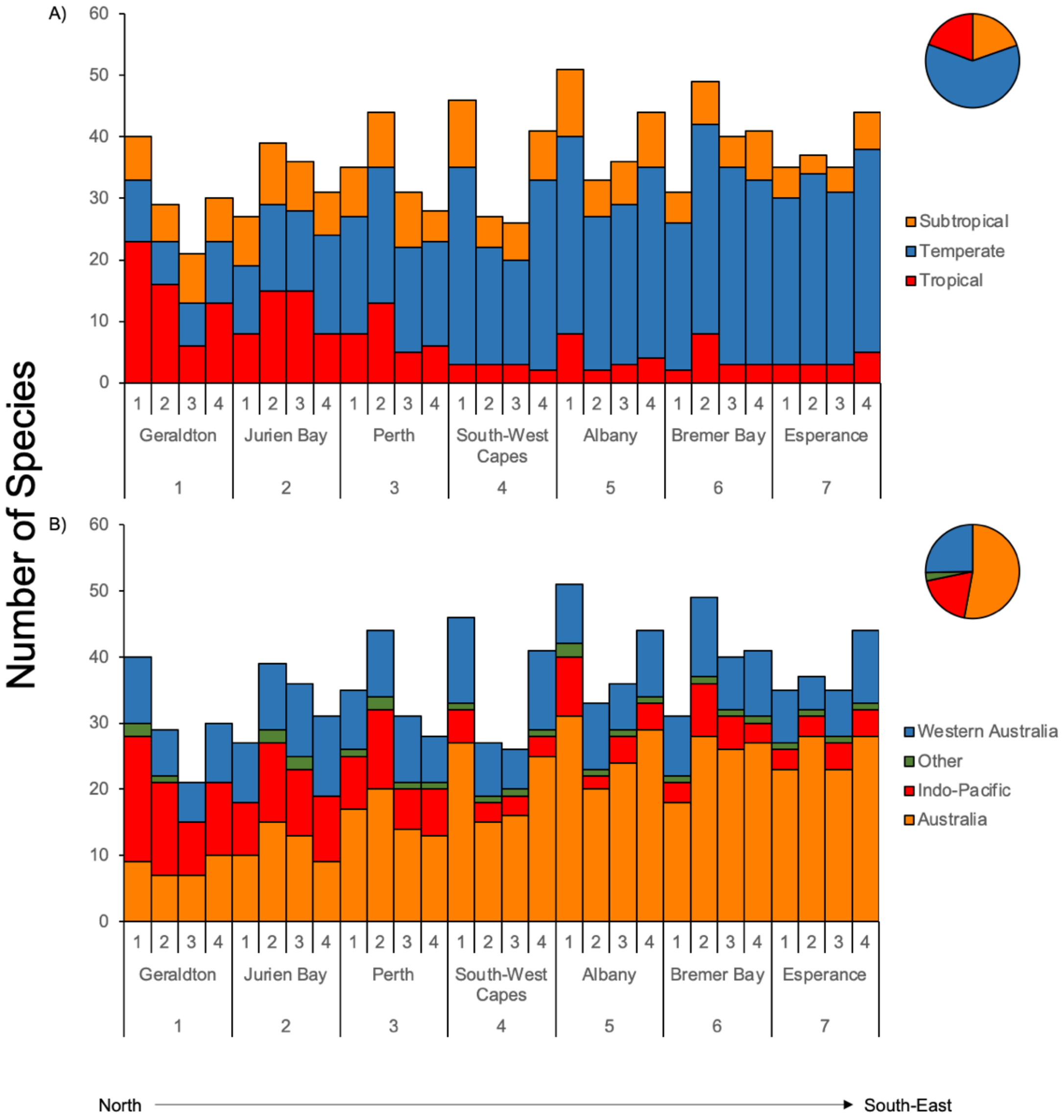

Figure 2.2. (A) Temperature affiliation (tropical, subtropical, temperate) and (B) endemism (Australia, Western Australia, Indo-Pacific and other) of shallow-water reef fish species in each of the 28 locations along the Southwest Australian (SWA) coast (n = 119 species); insets show the percentage of temperature affiliation (A) and endemism (B) within the total fish fauna of SWA

species) had an Indo-Pacific distribution, 66% (79 species) were endemic to Australia and 2% (2 species) were categorised as ‘other’ having global distributions. Of the 79 Australian endemic species, 21% (25 species) were short-range endemics only occurring in Western Australia. Overall, 29% (34 species) had a tropical affiliation, 17% (20 species) were subtropical and 54% (65 species) had a temperate distribution. All locations contained species from each climatic affiliation and each endemic category (Figs. 2.2A & 2.2.B). The full species list can be found in Supplementary Information: *Overall Species Table*, along with the abundance of each species across the entire survey area, observation frequency (% of sites present), temperature affiliation and endemism level.

Across the ~2000 km survey area, species richness remained relatively stable, with no significant increases or decreases in any location. Numbers of Indo-Pacific species were higher in the Midwest and Central regions of Geraldton, Jurien Bay and Perth (9−22 species) than in the lower West Coast and Southern locations of South-West Capes, Albany, Bremer Bay and Esperance (4−13 species) (Fig. 2.2B). Australian endemic species showed the opposite trend, with a higher number of species in Southern and lower West Coast locations (10−24 species) than in Midwest and Central locations (4−12 species) (Fig. 2.2B). Western Australian endemics did not appear to follow any pattern, with numbers remaining relatively stable across all locations (7−14 species).

2.4.2 SWA’s distinct shallow-water reef fish assemblages

Table 2.1. Results of a two-factor nested Permutational Multivariate Analysis of Variance on dispersion-weighted transformed densities of shallow-water reef fish species across the seven regions in Southwest Australia (SWA). Region is a fixed factor; location is nested within region

Source	df	MS	Pseudo-*F*	Unique perms	p
Region	6	18184.0	5.2986	9873	0.0001
Location(region)	21	3431.9	1.6051	9564	0.0001
Residuals	84	2138.1			
Total	111				

PERMANOVA showed a significant difference in shallow-water reef fish assemblages across the seven regions and 28 locations (Table 2.1: Location $(\text{Region})_{21,84}$, MS = 3432, Pseudo-F = 1.61, $p < 0.001$). This indicated distinct groupings of fish assemblages across the ~2000 km coast of SWA. CAP analysis also showed significant differences in fish assemblages across the seven regions (Fig. 2.3A; trace statistic = 4.53, $p < 0.001$) which supported the results from the PERMANOVA test. The percentage of overall correct classification was high (83%), and the leave-one-out allocation success rates were > 93% for the regions of Geraldton and Esperance, indicating that the composition of the shallow-water reef fish assemblages of these regions is unique (Table 2.2). Misclassification of sites occurred between Jurien Bay and Perth, showing a similarity of fish assemblage composition between these two regions (Table 2.2). The South-West Capes, Albany and Bremer Bay had a lower allocation success rate (< 87.5%) and sites were misclassified across these three regions, suggesting that the composition of the fish assemblage at these regions is similar (Table 2.2). These groupings were supported by the CAP plot (Fig. 2.3A), which showed a distinct separation of sites within the Geraldton and Esperance regions, grouped together the regions of Jurien Bay and Perth, and showed no distinction between the South-West Capes, Albany and Bremer Bay regions.

Table 2.2. Leave-one-out allocation success rate (%) of observation to region (m [number of PCO axes] = 41, n [sample size] = 112), for seven regions of Southwest Australia (SWA)

Region	Geraldton	Jurien Bay	Perth	South-West Capes	Albany	Bremer Bay	Esperance	Total	Success (%)
Geraldton	15	0	1	0	0	0	0	16	93.75
Jurien Bay	0	12	4	0	0	0	0	16	75.00
Perth	0	1	14	1	0	0	0	16	87.50
South-West Capes	0	0	2	12	1	1	0	16	75.00
Albany	0	0	1	3	11	1	0	16	68.75
Bremer Bay	0	0	0	0	2	14	0	16	87.50
Esperance	0	0	0	1	0	0	15	16	93.75

Further CAP analyses were performed to determine which of the six ‘assemblage structures’ arrangements (the fisheries management zones, IMCRA mesoscale regions and assemblages with three, four, five and six groupings) best represented the current distribution of shallow-water reef fish assemblages (Figs. 2.3, S.2.1 & S.2.2). The resulting plot and leave-one-out allocation success rates (Tables 2.3 & 2.4, Figs S.2.1 & S.2.2) indicated that the distribution of SWA’s shallow-water reef could be arranged into at least three distinct assemblages along the coast (Fig. 2.3B, trace statistic = 1.64, $p < 0.001$; Fig. 2.3C, trace statistic = 2.29, $p < 0.001$).

Table 2.3 Leave-one-out allocation success rate (%) of observations to assemblage (m [number of PCO axes] = 12, n [sample size] = 112), for three assemblages of Southwest Australia (SWA): Midwest (Geraldton), Central (Jurien Bay and Perth) and Southern (South-West Capes, Albany, Bremer Bay and Esperance)

Assemblages	1	2	3	Total	Success (%)
Midwest	15	1	0	16	93.75
Central	0	32	0	32	100.00
Southern	0	1	63	64	98.44

AIC_C results compared among each assemblage arrangement supported the results of the CAP analysis (Table S.2.1). The lowest AIC_C value was calculated for the ‘three assemblage’ structure ($AIC_C = 387.879$), closely followed by the ‘four assemblage’ structure ($AIC_C = 387.955$). These four assemblages are the Midwest, which contains the Geraldton region, the Central assemblage, which consists of Jurien Bay and Perth, a Southern region that contains the South-West Capes, Albany and Bremer Bay and a second Southern assemblage that consists of the Esperance region. It was also of interest to analyse how well the two fisheries management zones and three IMCRA mesoscale regions represented the current distribution of shallow-water reef fish in SWA (Figs. S.2.1 & S.2.2). The leave-one-out allocation success rates were low, indicating that the fish assemblage composition did not conform well to the management areas (Figs. S.2.1 & S.2.2), and the AIC_C values were higher compared to the ‘three assemblage’ and ‘four assemblage’ arrangement (fisheries $AIC_C = 391.024$; IMCRA $AIC_C = 389.889$).

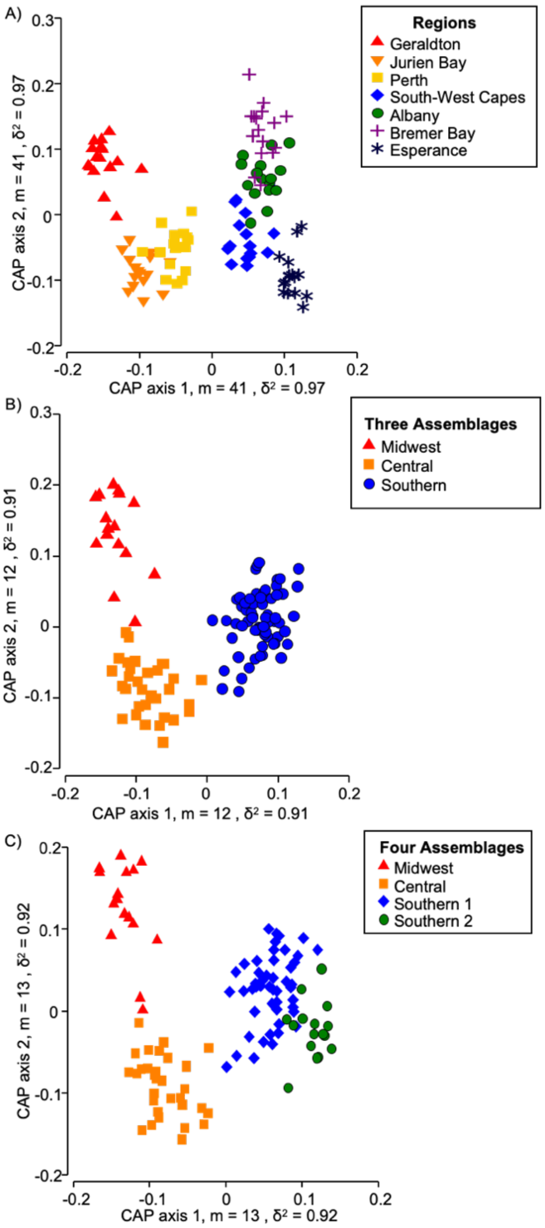

Figure 2.3. Canonical Analysis of Principal Coordinates (CAP) plots of shallow-water reef fish assemblages using (A) the 7 regions of Southwest Australia (SWA): Geraldton, Jurien Bay, Perth, South-West Capes, Albany, Bremer Bay, Esperance (m [number of PCO axes] = 41, n [sample size] = 112) as a factor of groups; (B) the 3 assemblage structure: Midwest (Geraldton), Central (Jurien Bay and Perth) and Southwest (South-West Capes, Albany, Bremer Bay and Esperance) (m = 12, n = 112) as a factor of groups; and (C) the 4 assemblage structure; Midwest (Geraldton), Central (Jurien Bay and Perth), Southwest 1 (South-West Capes, Albany and Bremer Bay) and Southwest 2 (Esperance) (m = 13, n = 112) as a factor of groups. Ordinations are based on the Bray-Curtis resemblance matrix using dispersion-weighted shallow-water reef fish abundance data; assemblage structures (3 or 4) were based on corrected Akaike's Information Criterion (AIC_c) values and the leave-one-out allocation success to observation values

Table 2.4. Leave-one-out allocation success rate (%) of observation to assemblage (m = [number of PCO axes] = 13, n [sample size] = 112), for four assemblages of Southwest Australia (SWA): Midwest (Geraldton), Central (Jurien Bay and Perth), Southern 1 (South-West Capes, Albany and Bremer Bay) and Southern 2 (Esperance)

Assemblage	Midwest	Central	Southern 1	Southern 2	Total	Success (%)
Midwest	15	1	0	0	16	93.75
Central	0	31	1	0	32	96.88
Southern 1	0	1	45	2	48	93.75
Southern 2	0	0	1	15	16	93.75

The top five species in each assemblage, ranked by their percentage contribution (% contrib), were identified by the SIMPER analysis (Table 2.5). The Midwest assemblage contained the region of Geraldton and was characterised by mostly tropical- and subtropical-affiliated species. The highest percentage contributor was the tropical Indo-Pacific species *Plectorhinchus flavomaculatus* (goldspotted sweetlips), followed by the subtropical Western Australian endemics *Parma occidentalis* (western scalyfin) and *Choerodon rubescens* (baldchin groper). Jurien Bay and Perth made up the Central assemblage and were characterised by a combination of subtropical and temperate species. The greatest contributing (%) species was *Notolabrus parilus* (brownspotted wrasse), a temperate Australian endemic, followed by the temperate Western Australian endemic *Parma mccullochi* (Mcculloch's scalyfin) and the subtropical *Coris auricularis* (western king wrasse, a Western Australian endemic). The Southern assemblage consisted of the South-West Capes, Albany and Bremer Bay regions and was predominantly characterised by temperate species such as the Australian endemic *Olisthops cyanomelas* (herring cale) and the Western Australian endemics *P. mccullochi* and *Pseudolabrus biserialis* (red-banded wrasse).The Esperance region formed the second Southern assemblage, which also consisted mainly of temperate Australian endemic species including *N. parilus* and *Achoerodus gouldii* (western blue groper).

Table 2.5. Species identified by SIMPER as characteristic of each of the four distinct groups (Midwest, Central, Southern 1, Southern 2) defined in the canonical analysis of principal coordinates of shallow-water reef fish in Southwest Australia (SWA)

Species	Average abundance	Average similarity	Similarity /SD	Contribution (%)	Cumulative abundance (%)
Midwest assemblage					
Average similarity: 28.37					
Plectorhinchus flavomaculatus	1.00	5.64	0.90	19.87	19.87
Parma occidentalis	0.83	4.16	1.27	14.67	34.53
Kyphosus cornelii / bigibbus / vaigiensis	0.66	2.95	0.95	10.40	44.94
Choerodon rubescens	0.65	2.89	0.92	10.17	55.11
Cheilodactylus rubrolabiatus	0.53	2.52	0.78	8.90	64.01
Central assemblage					
Average similarity: 32.67					
Notolabrus parilus	1.96	10.28	2.22	31.48	31.48
Parma mccullochi	1.42	5.59	1.22	17.12	48.59
Coris auricularis	0.86	3.20	1.33	9.81	58.40
Chelmonops curiosus	0.65	2.50	0.81	7.66	66.06
Kyphosus cornelii / bigibbus / vaigiensis	0.69	2.05	0.77	6.27	72.33
Southern assemblage 1					
Average similarity: 25.18					
Parma mccullochi	0.98	3.62	1.12	14.38	14.38
Notolabrus parilus	0.87	2.87	1.10	11.40	25.78
Ophthalmolepis lineolatus	0.59	2.52	0.75	10.02	35.81
Pseudolabrus biserialis	0.82	2.50	1.08	9.92	45.73
Olisthops cyanomelas	0.59	1.72	0.75	6.84	52.57

Species	Average abundance	Average similarity	Similarity /SD	Contribution (%)	Cumulative abundance (%)
Southern assemblage 2					
Average similarity: 39.18					
Notolabrus parilus	1.33	6.80	1.88	17.35	17.35
Achoerodus gouldii	1.13	3.99	1.52	10.19	27.54
Ophthalmolepis lineolatus	0.83	2.78	1.03	7.09	34.63
Scorpis aequipinnis	0.79	2.70	0.84	6.89	41.52
Chelmonops curiosus	0.56	1.74	0.83	4.44	66.46

2.4.3. Contribution of habitat and SST to SWA's distinct shallow-water reef fish assemblage

DISTLM analysis generated a final model that explained 25.5% of the variation in shallow-water reef fish assemblages using six environmental variables ($R^2 = 0.255$, $AIC_C = 886.820$, Table S.2.3): SST, *Ecklonia radiata* cover, non-*Ecklonia* canopy cover, understorey algae cover, reef type and reef height. Individual marginal tests (Table S.2.2) showed that SST explained the highest proportion of variation (15.5%), followed by reef type (11.6%) and reef height (6.9%). The best model resulting from DISTLM is illustrated in Fig. 2.4A, using the dbRDA procedure overlaid with partial correlations of the explanatory environmental variables. The strength and direction of the correlation of each of the six variables included in the final model to the dbRDA axes are shown by the length and direction of the vectors. The first two dbRDA axes explained 61.9 and 14.8% of the variation in the fitted model, respectively and together accounted for 19.6% of total variation in the distribution and density of SWA's shallow-water reef fish (Fig. 2.4A). SST was positively correlated to the first dbRDA axes (Fig. 2.4A, Table 2.6) in a similar direction to the species *P. occidentalis*, *C. rubescens*, *P. flavomaculatus* and *K. cornelli/biggibus/vaigiensis; Ophthalmolepis lineolatus, Scorpis aequipinnis, O.*

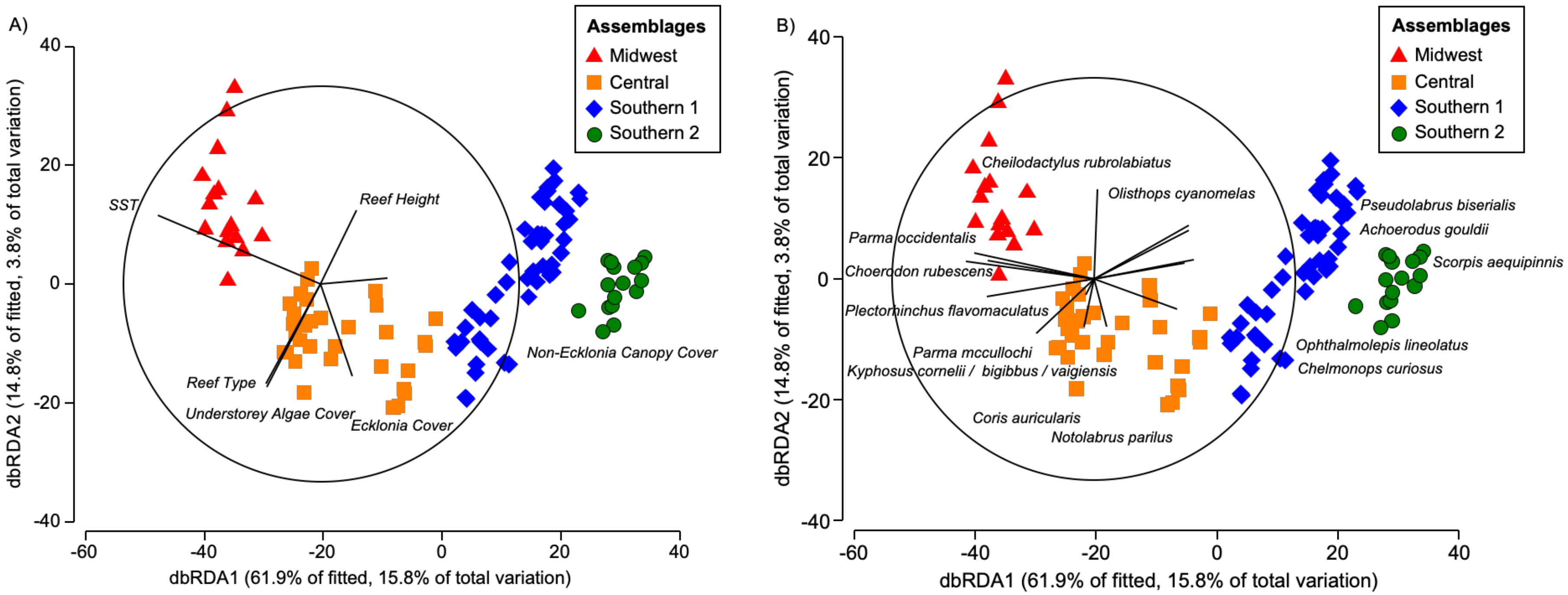

Figure 2.4. Distance-based Redundancy Analysis (DBRDA) ordination of first and second fitted axes relating to (A) environmental and habitat variables and (B) characterising species of shallow-water reef fish over the entire study area in Southwest Australia (SWA). Vectors: strength and direction of multiple partial correlations for the environmental and habitat variables, and Pearson's correlations for characterising species, to the first and second RDA

cyanomelas and *P. biserialis* were negatively correlated to this axis (Fig. 2.4B, Table 2.6) as was non-*E. radiata* (canopy) cover. *Cheilodactylus rubrolabiatus* was negatively correlated to the second dbRDA axis (Fig. 2.4B, Table 2.6) while *N. parilus* was positively correlated. Understorey algae cover, reef type and *E. radiata* cover was also positively correlated to the second dbRDA axis (Fig. 2.4B, Table 2.6)

Table 2.6. Correlations to the first, second and third distance-based redundancy analysis (dbRDA) axes of selected environmental variables (Multiple Partial Correlations) and characterising shallow-water reef fish species (Pearson Correlations) of Southwest Australia (SWA)

Environmental variable	dbRDA1	dbRDA2	dbRDA3
Reef type	0.278	0.482	0.522
Reef height	–0.175	–0.362	0.179
Ecklonia cover	–0.160	0.451	0.262
Non-Ecklonia cover	–0.340	–0.056	–0.412
Understorey algae cover	0.271	0.510	–0.666
2015 Mean sea surface temperature	0.821	–0.345	–0.031
Species variable			
Achoerodus gouldii	–0.498	–0.094	–0.072
Cheilodactylus rubrolabiatus	–0.018	–0.444	–0.022
Choerodon rubescens	0.527	–0.091	–0.078
Kyphosus cornelii / bigibbus / vaigiensis	0.530	0.087	–0.115
Notolabrus parilus	0.048	0.238	–0.388
Olisthops cyanomelas	–0.473	–0.267	–0.151
Ophthalmolepis lineolatus	–0.415	0.152	0.136
Parma occidentalis	0.594	–0.126	0.002
Plectorhinchus flavomaculatus	0.634	–0.085	–0.150
Pseudolabrus biserialis	–0.473	–0.241	–0.173
Scorpis aequipinnis	–0.453	–0.077	–0.021

2.5 Discussion

The shallow-water reef fish of SWA formed four distinct assemblages along the ~2000 km coastline: a Midwestern, a Central and two Southern assemblages (Fig. 2.5). The differences between these assemblages were predominantly driven by six environmental variables: SST, *Ecklonia radiata* cover, non-*Ecklonia* canopy cover, understorey algae cover, reef type and reef height. Along the SWA coastline, the fauna composition changed from one with a high number of tropical and subtropical species to one dominated by warm temperate species. Each of the four assemblages were characterised by species endemic to both Australia and Western Australia.

The spatially fine-scale quantitative data collected here suggest that intricate distribution patterns exist within the assemblages of shallow-water reef fish along the SWA coastline. These assemblages form unique regions and are composed of a high number of short-range endemic species, with ranges less than 10 000 km^2 (Harvey, 2002). Shallow-water reef fish of SWA can be clustered into four distinct fish assemblages (see Section 3.2 and Fig. 2.5). Hutchins (2001) however, grouped the SWA fish fauna into one continuous region, while Fox & Beckley (2005) further divided this region into two distinct faunal groupings with a division south of Perth. The results of this study confirmed these and further divisions of the SWA coast. The AIC_C values were essentially equivalent for the 'assemblage structure' arrangement with four or three groupings, which indicated that three groups were also a good representation of the distribution of shallow-water reef fish. The three grouping arrangement included a Midwest (Geraldton), Central (Jurien Bay and Perth) and Southern assemblage (South-West Capes, Albany, Bremer Bay and Esperance). However, the clear distinction of sites within Esperance, supported by the leave-one-out allocation success table and previous studies (Harvey et al., 2013), demonstrated the separation of assemblages within this region. Harvey et al. (2013) noted the uniqueness of the Esperance region with its diverse Monacanthidae and Labridae fauna, coupled with long-lived 'K-selected' species. These species have a heightened vulnerability to fishing and bycatch pressures due to their large body size, late maturity and longevity (Le Quesne & Jennings, 2012). The characteristic species within the Esperance region highlights the importance of independent management of this assemblage, which is taken into consideration within the 'four assemblage structure' bioregional arrangement.

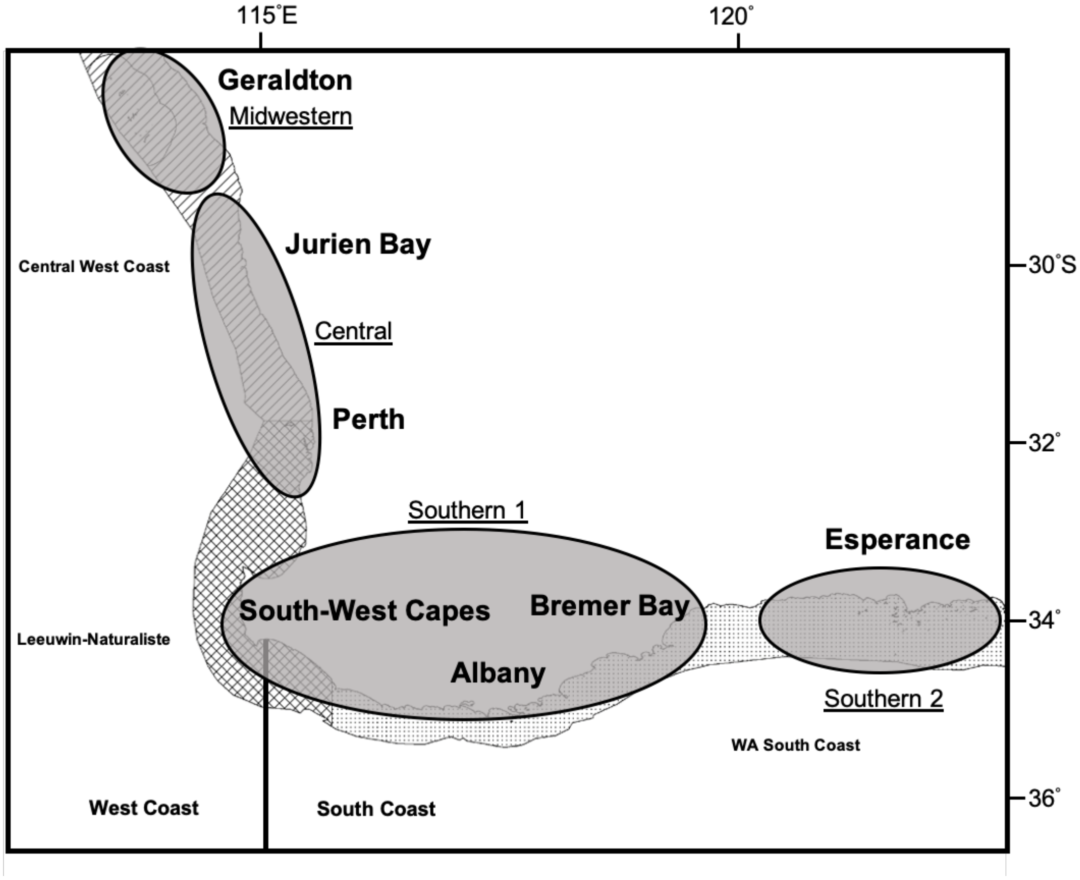

Figure 2.5. Proposed improved bioregional boundaries according to the distribution of shallow-water reef fish in Southwest Australia (SWA) with the four bioregions: Midwestern, Central, Southern 1 and Southern 2. For reference, the three Integrated Marine and Coastal Regionalisation of Australia mesoscale regions (Central West Coast, Leeuwin-Naturaliste and Western Australian south Coast) are illustrated by hatching and shading, and the two fisheries management areas of SWA are delineated by the dark line heading south from the South-West Capes

2.5.1 Bioregional management

Bioregionalisation as a management tool has been adopted not only in Australia (Heap et al., 2005; Last et al., 2005; Commonwealth of Australia, 2006), but also internationally in the United Kingdom and other parts of Europe (DEFRA, 2007; Raakjær et al., 2012) for fisheries management (Fletcher et al., 2010; 2012), reserve selection (Fox & Beckley, 2005; Last et al., 2011) and resource allocation (Day, 2002). The continuing development of bioregions has highlighted the importance of high-quality, accurate, distributional data on marine biota worldwide.

However, movement of species ranges and changes to species interactions have been documented both globally (Perry et al., 2005; Vergés et al., 2014) and locally in SWA (Wernberg et al., 2016). Changes in the composition of fish and other marine assemblages have also been recorded along the SWA coast (e.g. Cure et al., 2018; Shalders et al., 2018; Parker et al., 2019). The length of the SWA coastline, along with climatic changes and increasing SST, make this region an ideal area to study changes in the distribution of fish assemblages, with corresponding implications for management being globally applicable (Day, 2002; DEFRA, 2007; Morrone, 2015). Environmental and climatic changes are occurring globally (e.g. Perry et al., 2005), and continued monitoring of the distribution of fish assemblages worldwide is essential to inform bioregional management, planning and to manage resource allocation.

The existing IMCRA (Commonwealth of Australia, 2006) and fisheries management (Gaughan & Santoro, 2018) regions in SWA do not effectively align with the current distribution of shallow-water reef fish assemblages, and this may have a negative impact on their practicality (Fig. 2.5). The data showed that the South-West Capes region formed a group within the Southern assemblage, but currently it is managed within the West Coast fisheries bioregion. IMCRA defines this region individually due to the unique oceanic currents occurring in this area (Commonwealth of Australia, 2006). The Esperance region contained a unique assemblage of shallow-water reef fish, yet it is currently managed as part of the broader Western Australian South Coast region. Aspects of this uniqueness may be compromised by managing this region at the broader scale. Whilst the results illustrated the current assemblage patterns of SWAs' shallow-water reef fish, it is important to note that IMCRA considers a larger area, and holistically considers all marine species and geological data from both the continental shelf and slope (Commonwealth of Australia, 2006).

2.5.2 Environmental variables

This study also identified that SST, *E. radiata* cover, non-*Ecklonia* canopy cover, understorey algal cover reef type and reef height were the most important drivers of fish assemblages on shallow, rocky reefs in SWA, with SST being the primary driver. Previous international and local studies have documented SST as a dominant environmental driver of the distribution and composition of marine assemblages (Lüning, 1984; Dayton et al., 1999), and have demonstrated tropicalisation and movement of species poleward correlated with change in SST (Dornelas et al., 2014; Vergés et al., 2014). For example, Perry et al. (2005) described the shifting distributions of North Sea fishes in both latitude and depth as a response to changing SSTs, and with the predicted change in climate, this movement is expected to continue.

Locally in SWA, the Leeuwin Current has a major influence along the coast, which maintains a consistent temperature gradient from north to south. This current is also responsible for the transition from tropical- through to subtropical- and temperate-affiliated marine species (Hutchins, 2001). Furthermore, it facilitates the extension and survival of tropical fauna further south than their usual range (Pearce & Walker, 1991). However, with increasing SST the Leeuwin Current may further aid this poleward shift of warm-water species, increasing the vulnerability of cool-water species with geographical range restrictions (Shalders et al., 2018; Parker et al., 2019). In 2011, SWA experienced a marine heatwave which increased SSTs across the study area. Studies following this rise in temperature documented rapid regime shifts to tropical- and subtropical-affiliated seaweeds, fish and other marine organisms (Bennett et al., 2015a,b; Wernberg et al., 2016). The shifting boundaries of shallow-water reef fish reported in this study may be driven by disturbances such as the 2011 heatwave, as the Leeuwin Current promotes distributional changes of fish assemblages and their associated habitats. Increasing SSTs may also act as a surrogate for changes in habitat; e.g. a shift from kelp forests to one dominated by turfs and other algal forms (Bennett et al., 2015a), and therefore habitat variables are also important for defining species distributions (Harvey et al., 2013; Saunders et al., 2014; Galaiduk et al., 2017).

Macroalgae, especially *E. radiata* and non-*Ecklonia* canopy cover, was also a prominent driver of the distribution of shallow-water reef fish assemblages. This result was similar to previous studies along this coastline (Harvey et al., 2013, Galaiduk et al., 2017). For example, using a multivariate regression tree model, Galaiduk et al. (2017) found macroalgae to explain 13% of the variation of fish assemblages, while earlier work in the Esperance region also found these organisms to be a driver of fish assemblage structure (Harvey et al., 2013). With changing climate, the effect on canopy seaweeds in SWA is uncertain, and they may undergo rapid and irreversible changes (Wernberg et al., 2011; Bennett et al., 2015b). Effects may be magnified due to their sessile nature, limited reproductive movement and hence recovery potential (Wernberg et al., 2016). Understorey algae cover was also defined in our model as a driver of fish assemblage distributions, and a shift from canopy to understorey algae dominance may benefit certain fish species while hindering others. An increase in understorey algae has been correlated with a shift in species characteristic of subtropical and tropical waters (Wernberg et al., 2016), as this algae may increase food and habitat availability for grazing herbivores such as pomacentrids (Norman & Jones, 1984; Jones & Norman, 1986; Saunders et al., 2013) and parrotfishes (Bennett et al., 2015b). In contrast, a shift from canopy to understorey algae may have detrimental effects on temperate species such as *Olisthops cyanomelas* that rely on canopy seaweeds for food and habitat (Shepherd & Baker, 2008). The changing climate and associated effects on habitat may have a current and continued impact on the distribution of fish species, particularly short-range endemic habitat specialist species such as *Parma mccullochi* and *O. cyanomelas.*

2.5.3 Climatic affiliation and endemism

Over the 2000 km of coastline studied, the shallow-water reef fish assemblages of SWA changed from one with a large number of tropical, Indo-Pacific species in our northern study sites to one dominated by short-range temperate Australian endemics in the southern study sites. This pattern of affiliation and endemism is supported by other studies along this coastline (Wilson & Allen, 1987; Hutchins, 1994; 2001; Fox & Beckley, 2005). This high level of endemism may be attributed to the long isolation of the Australian continent and unique oceanography, such as the Leeuwin Current, which characterises the area (Adey & Steneck; 2001, Phillips, 2001). The four distinct shallow-water reef fish assemblages described in this study were dominated by species endemic to Australia, with many being confined to only Western Australia.

While the demography of many fish species in SWA is unknown or unstudied, individual families and species have been examined due to their longevity and vulnerability to climate change. *Choerodon rubescens* (baldchin groper), characteristic of the Midwest assemblage, and *Achoerodus gouldii* (western blue groper), found in the Southern assemblage, are wrasses of the Labridae family and are notable due to their importance in both commercial and recreational fishing. However, as targeted species with slow growth and high longevity (max. 70yr), they are vulnerable and susceptible to overfishing (Nardi et al., 2006; Coulson et al., 2009). Labridae species were abundant in this study, with many being short-range endemics. A recent study detailed the increase of tropical and subtropical SWA Labridae species in 2015 that were absent or rare in 2006, which was correlated with a change in climate and a marine heatwave in 2011 (Parker et al., 2019). Similarly, several long-lived Pomacentridae species are also only found in Western Australia, such as *Parma occidentalis* and *P. mccullochi*, and these species have been affected by climatic changes with an increasing abundance of warm-water species (Shalders et al., 2018). Endemic species of Western Australia are abundant and characteristic of the distinct assemblages, but as endemics, these species are more vulnerable to extinction than wider ranging species. It is important that changes in their distribution and abundance are monitored, especially given the geographic constraints of the SWA coastline to further southern shifts of South Coast species and assemblages.

2.5.4 Conclusions and recommendations

The shallow-water reef fish fauna of SWA is species-rich, and this study identified that it has a spatial structure that forms four distinct assemblages along the coast. This key finding is in contrast with both the current IMCRA and Southwest Australian Fisheries Management bioregions, indicating that the present bioregionalisation of SWA may not be the best representation of the current distribution of shallow-water reef fish species. Determining the spatial structure of assemblages can support and inform bioregional and ecosystem-based fisheries management for any area worldwide (Browman & Stergiou, 2004). Bioregions can also aid in conserving entire ecosystems and monitoring distributional changes and extinctions, particularly of small-range endemic species (Briggs & Bowen, 2012; Colton & Swearer, 2012). Both ecological and fisheries bioregionalisation of any region should accurately represent the current distribution of species that inhabit the area. This adaptable approach will improve management and protection of valuable and dynamic marine ecosystems and the vulnerable, unique marine species.

SWA is experiencing species movements and environmental changes that correspond with changes occurring in other regions worldwide (e.g. Perry et al., 2005, Parker et al., 2019). The survey and statistical methods of this study were designed to be replicable, and the approach can be applied to any marine area to determine the effectiveness of current regional planning and conservation. This study illustrates that changes in the distribution of fish assemblages has implications for bioregional boundaries, and similar changes are likely to continue to occur globally (Hobday & Lough, 2011). It also demonstrates that continued monitoring, alongside adaptive and flexible management, is key to ensure that bioregions and protected areas are effectively placed. Correct placement of these areas will improve the conservation of species and their habitats and allow managers in any region worldwide to allocate resources optimally.

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CHAPTER 3

Responses of shallow-water reef fish in a global hotspot over 14 years of climatic changes

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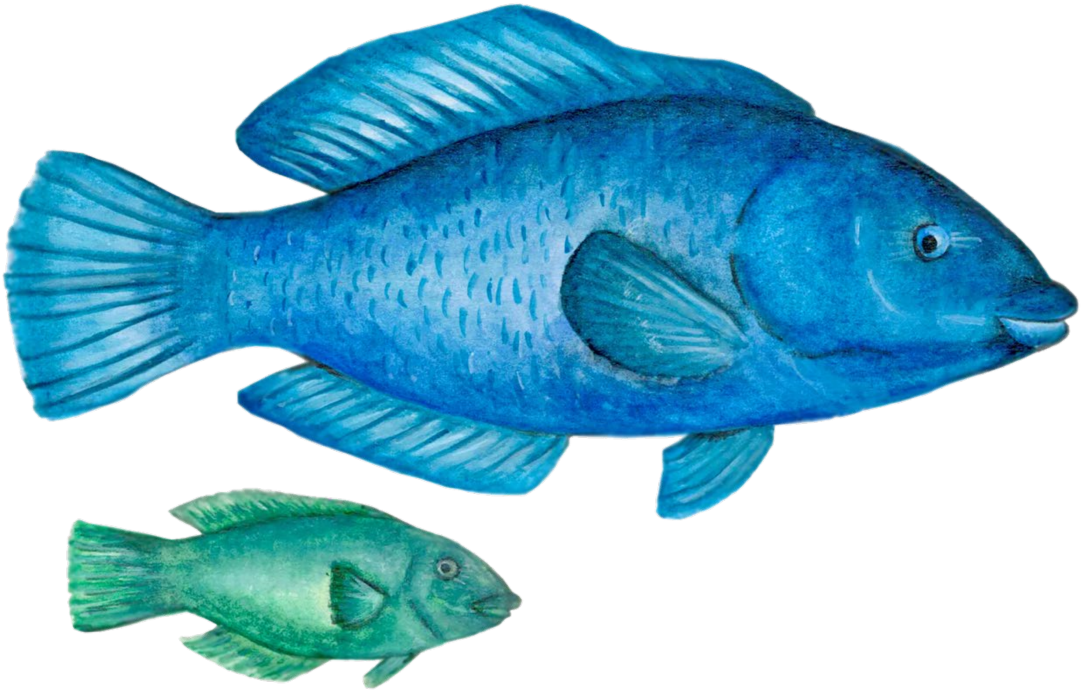

Watercolour of an adult (above) and juvenile (below) western blue groper (*Achoerodus gouldii*) by Savita Goldsworthy

Preface

This Chapter has been prepared for publication in the peer-reviewed journal *Nature Climate Change* and has therefore been formatted according to their specific guidelines However, to keep consistency across this thesis, references have been formatted to the APA style.

The main objective of this second data chapter was to determine assemblage composition changes between 2006, 2015 and 2019. This chapter also identifies primary environmental and habitat variables, and characteristic species that were driving this change.

3.1 Abstract

Species across the world are shifting their distributions in response to climate change. We report how regional patterns of shallow-water reef fish assemblages in Southwest Australia change over 14 years in response to a marine heatwave and rapid ocean warming. Warm-water fish assemblages experienced the largest compositional differences between 2006 and 2015 but stabilised by 2019. Cool-water fish assemblages displayed a more gradual, but continuous, change from 2006 to 2019. Overall, changes in shallow-water reef fish assemblages corresponded to variations in ocean temperature and to changes in canopy and understorey algae cover. Southwest Australia forms part of the ‘Great Southern Reef’ and is a biodiversity hotspot with many short-range endemics. This research highlights previously unrecognised differences in the trajectory of assemblages over 2000 km of coastline, with important implications for food security, culture and livelihoods in this important region.

3.2 Main Text

Climatic warming and extreme weather events are driving changes in the composition and distribution of marine assemblages (for example: Poloczanska et al., 2013; Sunday et al., 2012; Wernberg et al., 2013). To survive in a changing environment, marine species either adapt to new conditions, modify their distribution or become extinct (Sumaila et al., 2011). However, relatively slow environmental changes are required for species adaptation and in contrast, rapid or extreme disturbances may lead to sudden shifts in species distribution and ecosystem structure (Molinos et al., 2015; Wernberg et al., 2013).

Temperature is a fundamental driver of assemblages, influencing the distribution, abundance and size of species (Brander et al., 2003; Goldsworthy et al., 2020; Rijnsdorp et al., 2009; Seabra et al., 2015; Fredston-Hermann et al., 2020a). Marine studies across the world have documented the redistribution of species (Poloczanska et al., 2013), and the tropicalisation (Vergés et al., 2014, 2016) and shifting range edges of assemblages (Fredston-Hermann et al., 2020, 2020b), in association with changes in ocean temperature. These assemblage changes may particularly hinder short-range endemic species (species with ranges less than 10,000 km^2 (Cheung et al., 2009; Harvey, 2002)), or fish with geographic constraints, which may even risk extinction as their ranges contract or shift (Cheung et al., 2009). Other habitat variables, such as the percent cover and density of canopy-forming seaweeds and seagrasses, are also important drivers of fish abundance and distribution (Galaiduk et al., 2017; Harvey et al., 2013). Consequently, shifts in the distribution and structure of habitat forming species may affect associated assemblages (Nagelkerken et al., 2016). It has already been demonstrated that climate change can modify the abundance and dominance of habitat forming species (Wernberg et al., 2013) with potential cascading effects on fish assemblages. Compared to terrestrial ecosystems, temperature variability in the marine environment is low (Steele, 1985) and species have evolved under relatively stable conditions, particularly in the southern hemisphere (DeMets et al., 2010). As a consequence, even minor environmental changes may cause large and unpredictable responses in marine species (Sunday et al., 2012; Pinsky et al., 2020).

Southwest Australia (SWA) has a heterogeneous coastline ranging from a subtropical north to a temperate south (Fox & Beckley, 2005; Phillips, 2001). The major oceanographic feature of the area is the southward flowing Leeuwin Current, which transports warm water poleward along the coast ensuring the survival of tropical fauna further south than their usual range (Pearce & Walker, 1991). Approximately 1500 species of marine fish inhabit the shallow waters of Western Australia (Hutchins, 2001) and their distributions correlate to the sea surface temperature (SST) gradient along the coastline that is generated by the Leeuwin Current (Langlois et al., 2012). A high proportion (approximately 19.5%) of these species are endemic to Western Australia (Fox & Beckley, 2005; Goldsworthy et al., 2020). Over the past two decades, the

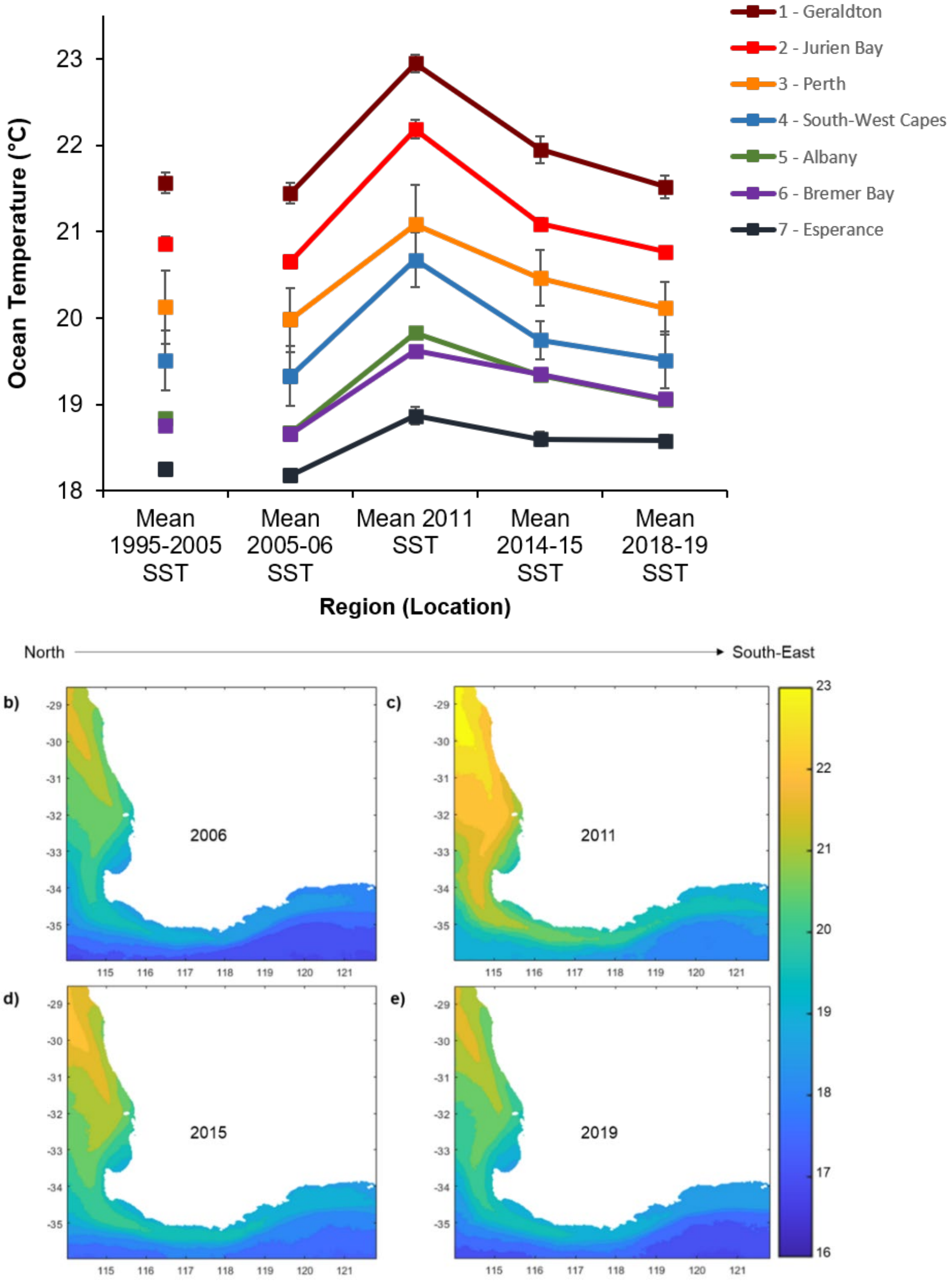

Figure 3.1. Ocean temperature in SWA: (A) Mean sea surface temperature (SST) of each study region (n = 7) surveyed (Geraldton, Jurien Bay, Perth, South-West Capes, Albany, Bremer Bay and Esperance) (± 95% Confidence Interval); for the initial 2006 study, the 2011 marine heatwave, the 2015 survey, the 2019 survey and prior to the beginning of the survey (1995-2005); (B) Gradient heatmap of SST during the initial 2006 study; (C) Gradient heat map of SST during the 2011 marine heatwave; (D) Gradient heat map of SST during the 2015 study; and (E) Gradient heat map of SST during the most recent 2019 study

marine environment of SWA has undergone rapid changes, with these differences varying between regions along the coast (Cheung et al., 2012). In 2011, the region experienced a marine heatwave which drove water temperatures 2-4°C higher than the long-term monthly average (Pearce & Feng, 2013). This rapid rise in SST resulted in a decline in the canopy cover of macroalgae (Bennett et al., 2015; Wernberg et al., 2013, 2016) and facilitated a southerly shift of some warm-water affiliated fishes (Bennett et al., 2015; Parker et al., 2019; Shalders et al., 2018).

Like many temperate ecosystems, SWA is relatively understudied in comparison to warmer environments around Australia (Barrett et al., 2007). Previous studies that have targeted SWA have documented the distribution of fish assemblages for a single period (Fox & Beckley, 2005; Goldsworthy et al., 2020; Hutchins, 2001; Last et al., 2011), or over a temporal scale for a single taxonomic family (Parker et al., 2019; Shalders et al., 2018). Little is known about the extent of change in reef fish assemblages over large spatial and temporal scales.

Shallow-water reef fish assemblages in SWA were monitored three times within a 14-year period (2006, 2015 and 2019) to understand their response to changes in SST. Seven regions encompassing approximately 2000 km of coastline were sampled, ensuring that sites incorporated the subtropical to warm-temperate transition (Fig. 3.7). Furthermore, we addressed changes in the thermal affinity, endemism and trophic groups of shallow-water reef fish assemblages and identified the species responsible for driving the differences between sampling years within each region. We also identified the primary environmental and habitat variables that were influencing any changes in the shallow-water reef fish assemblages.

Faunal diversity

To gather abundance and distributional data on shallow-water reef fish along the SWA coastline we used diver-operated stereo-video systems (stereo-DOVs) (Goetze et al., 2019; Harvey et al., 2002) to sample fish assemblages, from Geraldton in the north to Esperance in the south-east (Fig. 3.7). In total, 112 reef sites were surveyed, first in 2006, with sites resampled in 2015 and 2019. Across 2006, 2015 and 2019 we identified and counted 121,385 individual fish from 147 species and 50 families (Supplementary Information: *Overall Species Table*). Species richness (*S*) significantly

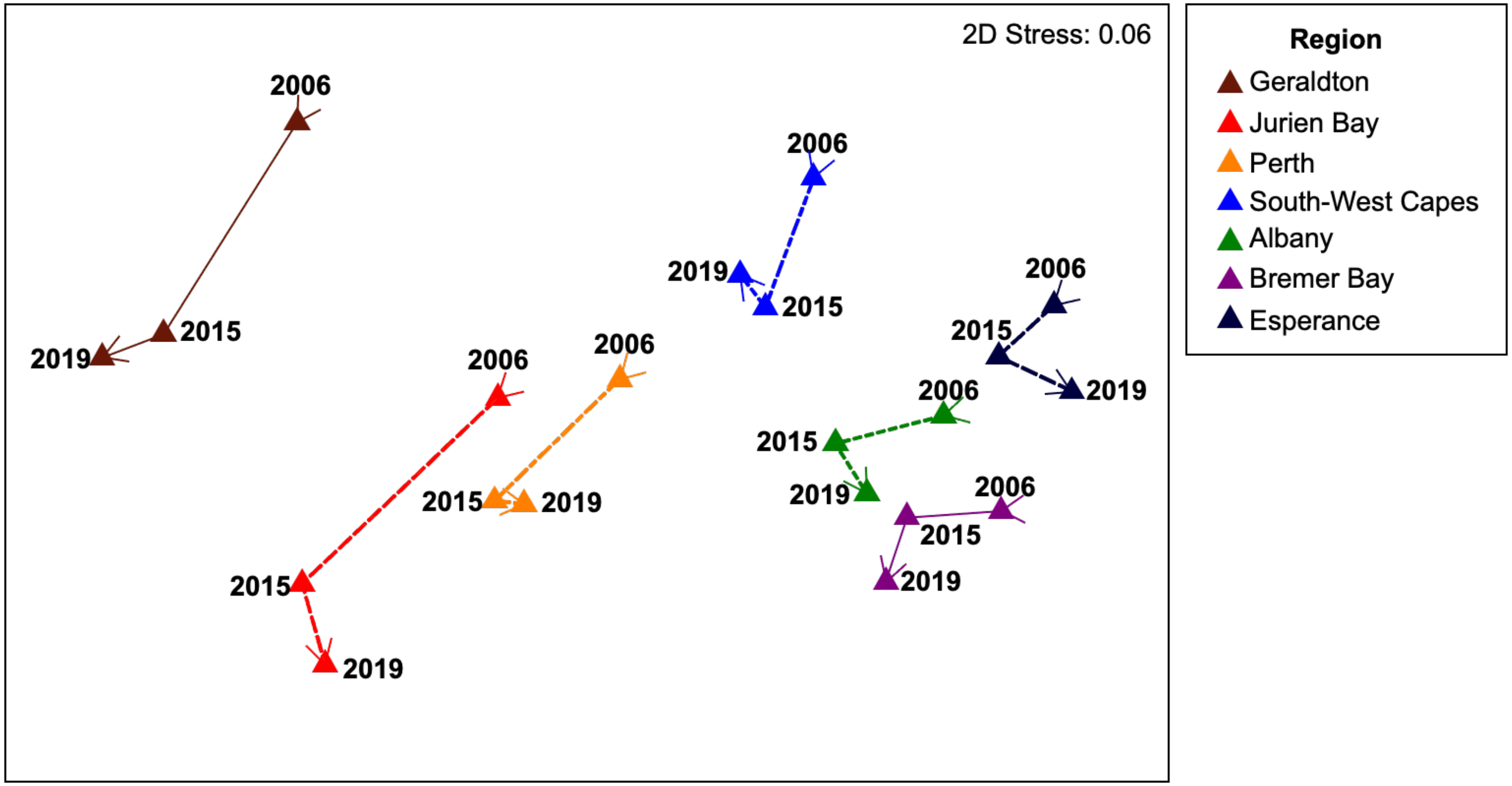

Figure 3.2 Assemblage change through time: NMDs showing the region centroids of shallow-water reef fish densities for each of the seven regions surveyed (Geraldton, Jurien Bay, Perth, South-West Capes, Albany, Bremer Bay and Esperance) and each sampling year (2006, 2015 and 2019). There was a significant interaction between year and region ($p < 0.001$) and all regions differed significantly, as did assemblages between 2006 and 2015 and 2006 and 2019 within each region (post-hoc tests: $p < 0.05$). The lines joining each sampling year with each region show the trajectory through time of the fish assemblage at each region

increased between 2006 and 2015 ($t = 5.261$, $p < 0.01$), and between 2006 and 2019 ($t = 5.995$, $p < 0.01$), with the number of species staying similar between 2015 and 2019. There was a significant increase in the Shannon-Wiener Diversity Index (*H'*) between 2006 and 2015 ($t = 2.116$, $p < 0.05$), and between 2006 and 2019 ($t = 2.311$, $p < 0.05$).

Ocean temperature

Ocean temperature data was linked to each reef site to illustrate changes in water temperature throughout the study period (Fig. 3.1). SST was lowest during the 2006 survey and highest during the marine heatwave in 2011 (Figs. 3.1a, 3.1b & 3.1c). By the time of the 2015 survey, SST had reduced, but remained warmer than 2006 and the 1995-2005 mean (Figs. 3.1a & 3.1d). In 2019, SST returned to a temperature similar to 2006, and lower than the 1995-2005 mean for Geraldton, Jurien Bay and Perth (Figs. 3.1a & 3.1e). However, SST remained warmer and closer to that of 2015 for the South-West Capes, Albany, Bremer Bay and Esperance.

SWA's shallow-water reef fish assemblages

The shallow-water reef fish assemblages along the SWA coastline were significantly different between years, with each region experiencing varying levels of change (Year x Region, MS = 3901.5, Pseudo-$F_{12, 331} = 1.977$, $p < 0.001$, Table S.3.1). From 2006 to 2015, and 2006 to 2019, all seven regions experienced changes in the fish assemblages present (Fig. 3.2, Table S.3.4), with the warmer, northern and central regions of Geraldton, Jurien Bay, Perth and the South-West Capes subjected to the greatest change (Fig. 3.2, Table S.3.4). In the central and southern regions of Perth, Bremer Bay and Esperance, changes in the shallow-water reef fish assemblages continued between 2015 and 2019, while assemblages in Geraldton, Jurien Bay, South-West Capes and Albany appeared to have stabilised (Fig. 3.2, Table S.3.4).

Thermal affinity, endemism and trophic level

Assemblages along the SWA coast experienced differences in the thermal affinity, endemism and trophic level of shallow-water reef fish that were present (see Section 3.3), with these changes being region-specific as shown in Fig. 3.2 (Tables S.3.5, S.3.6, S.3.7 & S.3.8 for mean±SE). Thermal affinity values were assigned to species based upon occurrence, with warm-water species having a thermal affinity greater than 19℃.

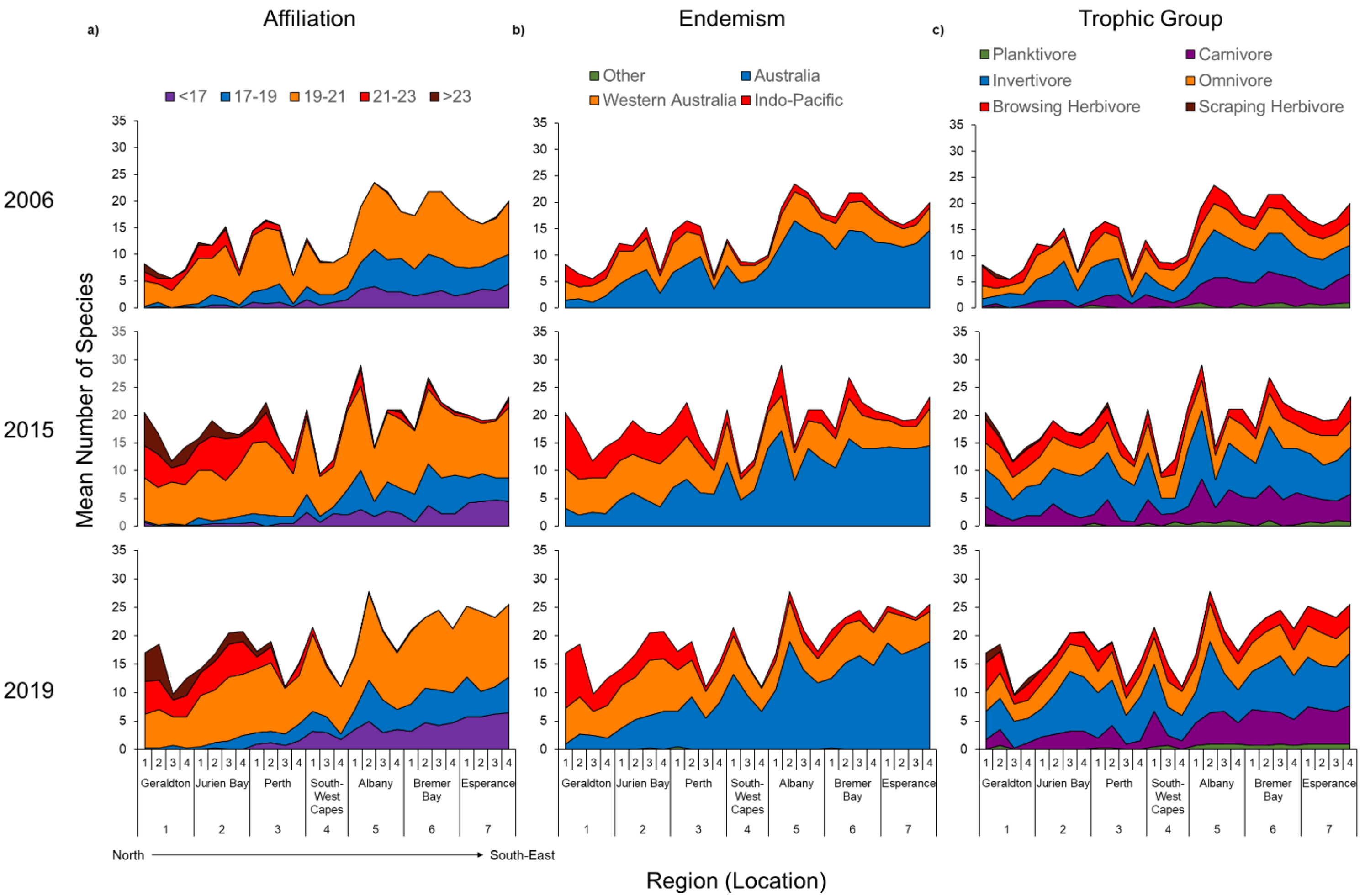

Figure 3.3. The thermal affinity, endemism and trophic group of shallow-water reef fish species observed in SWA: for each of the seven regions (Geraldton, Jurien Bay, Perth, South-West Capes, Albany, Bremer Bay and Esperance) and sampling years (2006, 2015 and 2019). (A) shows the mean number of species with each temperature affiliation: <17°c, 17-19°c, 19-21°c, 21-23°c and >23°c; (B) the endemism level: Indo-Pacific, Australian, Western Australian or Other distribution; and (C) the trophic level: Planktivore, Carnivore, Invertivore, Omnivore, Scraping Herbivore and Browsing Herbivore. Regions one to seven are from north to south-east geographically and correspond to the gradient of water temperature

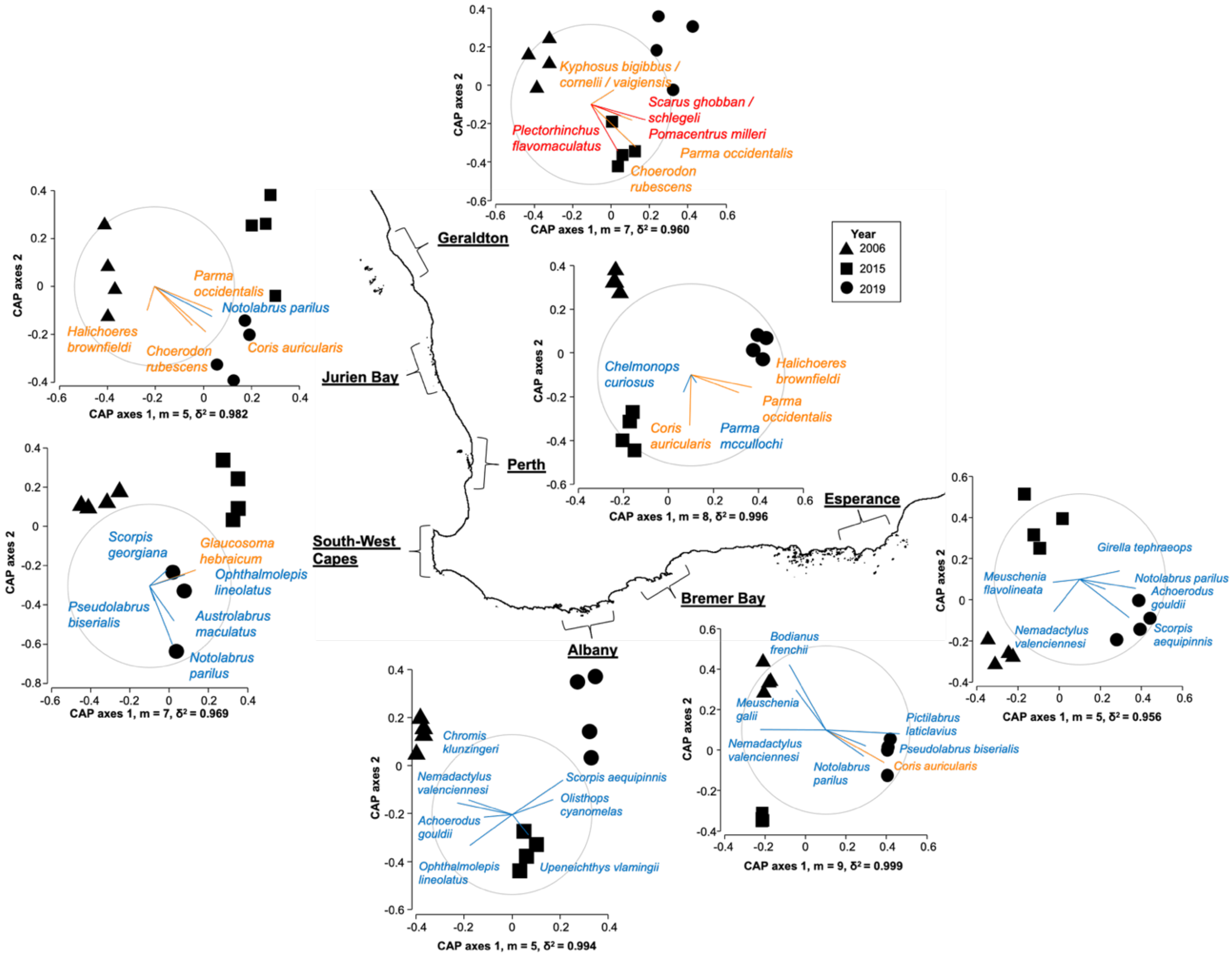

Figure 3.4. Species driving assemblage change through time: Canonical Analysis of Principal Coordinates (CAP) plots of shallow-water reef fish assemblages at each of the seven regions (Geraldton, Jurien Bay, Perth, South-West Capes, Albany, Bremer Bay and Esperance) using each sampling year (2006, 2015 and 2019) as a factor of groups. Each point indicates a location. Characteristic species identified by simper as driving the assemblage change between years are overlaid as vectors

Between 2006 and 2015 the assemblages in the warmest three locations had an increase in the mean number of species with a thermal affiliation above 19°C and these numbers were maintained in 2019 (Fig. 3.3a, Table S.3.5). Within the same period, the mean number of Indo-Pacific species increased for the regions of Geraldton and Jurien Bay, corresponding with this rise in warm-water species (Fig. 3.3b, Table S.3.6).

Geraldton, Jurien Bay and Perth displayed increases in the mean number of browsing herbivorous species between 2006 and 2015, with Geraldton also increasing in the number of omnivorous species (Fig. 3.3c, Table S.3.7). These numbers have remained stable into 2019 (Fig. 3.3c, Table S.3.7). The cooler, southern regions of SWA experienced fewer changes than the warmer locations, however, Esperance had an increase in the mean number of species with a thermal affiliation between 19°C - 21°C since 2006 (Fig. 3.3a, Table S.3.5). Between 2006 and 2015, Esperance also experienced an increase in the number of browsing herbivores. Both Bremer Bay and Esperance regions had an increase in the mean number of species with a thermal affinity < 17°C between 2015 and 2019 (Fig. 3.3a, Table S.3.5) and the number of Australian and Western Australian endemic species within these assemblages also increased between 2006 and 2019 (Fig. 3.3b, Table S.3.6).

Climatic affiliations of species driving the differences in shallow-water reef fish assemblages between years were correlated with the decreasing gradient of SST along the SWA coastline, which is created by the Leeuwin Current (Figs. 3.4 & 3.7). Tropical and subtropical species were the predominant drivers of assemblage change and contributed to an increase in overall species richness in Geraldton and Jurien Bay, with changes in tropical, subtropical and temperate species occurring in Perth. In comparison with warmer regions, changes in the cooler marine assemblages of South-West Capes, Albany, Bremer Bay and Esperance were mainly driven by temperate species. Species with a tropical and subtropical distribution were correlated towards 2015 and 2019 indicating an increased abundance during recent surveys, while several temperate species showed the opposite trend with a decrease in abundance since 2006. For example, warm water species *Choerodon rubescens* (baldchin groper), *Glaucosoma hebraicum* (dhufish) and *Coris auricularis* (western king wrasse) increased in the 2015 and 2019 surveys, while temperate species *Achoerodus gouldii* (blue groper), Nemadactylus valenciennesi (queen snapper) and Bodianus frenchii (foxfish) have decreased since 2006 (Fig. 3.4).

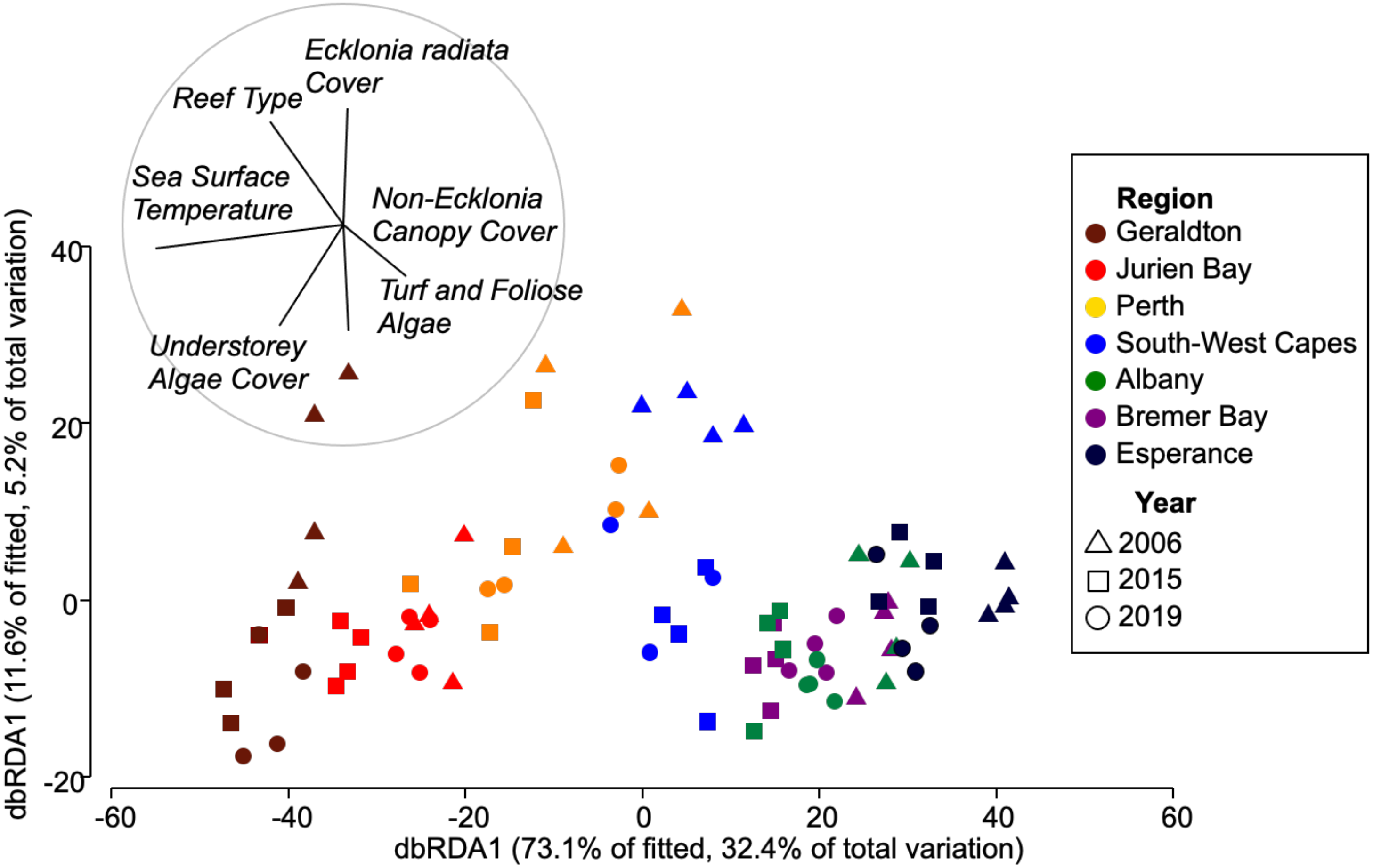

Figure 3.5. Environmental and habitat drivers of assemblages: Distance-based Redundancy Analysis (dbRDA) ordination of first and second fitted axes relating environmental and habitat variables to the densities of shallow-water reef fish across the entire survey area. The vectors show the strength and direction of multiple partial correlations to the first and second RDA axes. The first and second axes explained 73.1% and 11.6% of the variation in the fitted model, respectively

Environmental and habitat variables

Environmental and habitat variables had an influence on the distribution of shallow-water reef fish assemblages (Table S.3.3). Habitat along the SWA coastline significantly differed between years, with changes being region-specific (Year x Region, MS = 9.588, Pseudo-$F_{2, 331}$ = 1.977, $p < 0.001$, Table S.3.2). Along the SWA coastline *Ecklonia radiata* cover, non-*Ecklonia* canopy cover, reef type, understorey algae cover, hard coral cover and SST were selected to explain the variation in shallow-water reef fish assemblages between regions and years ($R^2 = 0.443$, AIC = 600.860, Fig. 3.5, Table S.3.10). Individually, SST was the dominant environmental driver explaining 31.8% of the variation, this was followed by reef type (23.6%) and non-*Ecklonia* canopy cover (11.2%, Table S.3.9). Geraldton had a decrease in the cover of *E. radiata* since 2006, corresponding with increased cover of non-*Ecklonia* canopy, understorey algae and turf and foliose Algae (Fig. 3.6, Table S.3.8). The south-east region of Esperance had an increase in the cover of *E. radiata* between 2006 and 2015, with cover decreasing to similar levels as 2006 in 2019. Perth and the South-West Capes increased in non-*Ecklonia* canopy cover between 2015 and 2019 (Fig. 3.6, Table S.3.8).

Change in fish assemblages over time

The long-term responses of shallow-water reef fish assemblages seen in this study provide an example of how climate change can have a rapid and lasting impact on marine communities. Studies from the Northeast US Shelf have also documented a long-term response of marine species to temperature changes, with ‘cold range edges’ tracking climate change better than their warm edge counterparts over 50 years of warming (Fredston-Heremann et al., 2020). Whilst SST in SWA has been variable with warming events such as the 2011 heatwave followed by periods of decreasing temperatures (Pattiaratchi & Hetzel, 2020), global projections suggest that the continued emission of greenhouse gasses will cause further warming of SST and an increase in extreme weather events (IPCC, 2014; Weatherdon et al., 2016). Ocean temperatures in SWA remained stable from 2006 until 2011 when the region experienced a marine heatwave due to a surge in the Leeuwin Current associated with La-Niña (Feng et al., 2013), with SST then decreasing until 2019. The Leeuwin Current has a major influence on fish assemblages along the SWA coast (Hutchins, 2001) and surges may drive the distribution of tropical and subtropical fauna southwards (Cheung et al., 2012).

This study focussed on the change in shallow-water reef fish assemblages in correlation with SST, based on previous studies documenting temperature as a dominant driver of marine species (Brander et al., 2003; Goldsworthy et al., 2020; Rijnsdorp et al., 2009; Seabra et al., 2015; Fredston-Hermann et al., 2020a). However, alongside SST, other environmental variables such as ocean currents, sediment loading, and nutrient enrichment may additionally drive species movements (Molinos & Donohue, 2010; Molinos et al., 2017). These factors may act synergistically or individually, altering the rate of species responses (Molinos & Donohue, 2010). Previous global studies using climate velocities to track species trajectories documented the prevalence of range expansions over contractions, leading to localised increases in richness and temporal changes in composition (Molinos et al., 2016). These projected changes by Molinos et al., (2016) were reflected locally within SWA, with changes in species richness and composition occurring throughout this study.

Fish assemblages in SWA are changing in association with differing habitat and SST, with changes being region-specific despite similar ocean temperature profiles. On the west coast the magnitude of change was largest between 2006 and 2015, with assemblages appearing to have stabilised in recent years. The west coast of SWA is an intermixing zone with tropical, subtropical and temperate species coexisting along the coastline (Goldsworthy et al., 2020; Hutchins, 2001). Marine species occupy the extent of their thermal ranges and increases in SST are likely to exceed range limits, forcing the contraction of cool-water species and favouring warm-water species (Sunday et al., 2012). Warmer, northern regions experienced an increase in the number of warm-water affiliated species in correlation with the number of browsing herbivorous species, contributing to an increase in overall species richness. These increases were also associated with a higher cover of turf and understorey algae, a pattern which supports the conclusions of previous studies (Smale et al., 2019; Wernberg et al., 2011). Habitat changes have been maintained into 2019 and may continue to prevent a shift back to *E. radiata* dominance. Along the south coast of SWA, particularly in the regions of Bremer Bay and Esperance, changes in the shallow-water reef fish assemblages have continued into 2019 with increases in warm-water affiliated species. This finding is in contrast with many studies completed after the 2011 SWA marine heatwave which

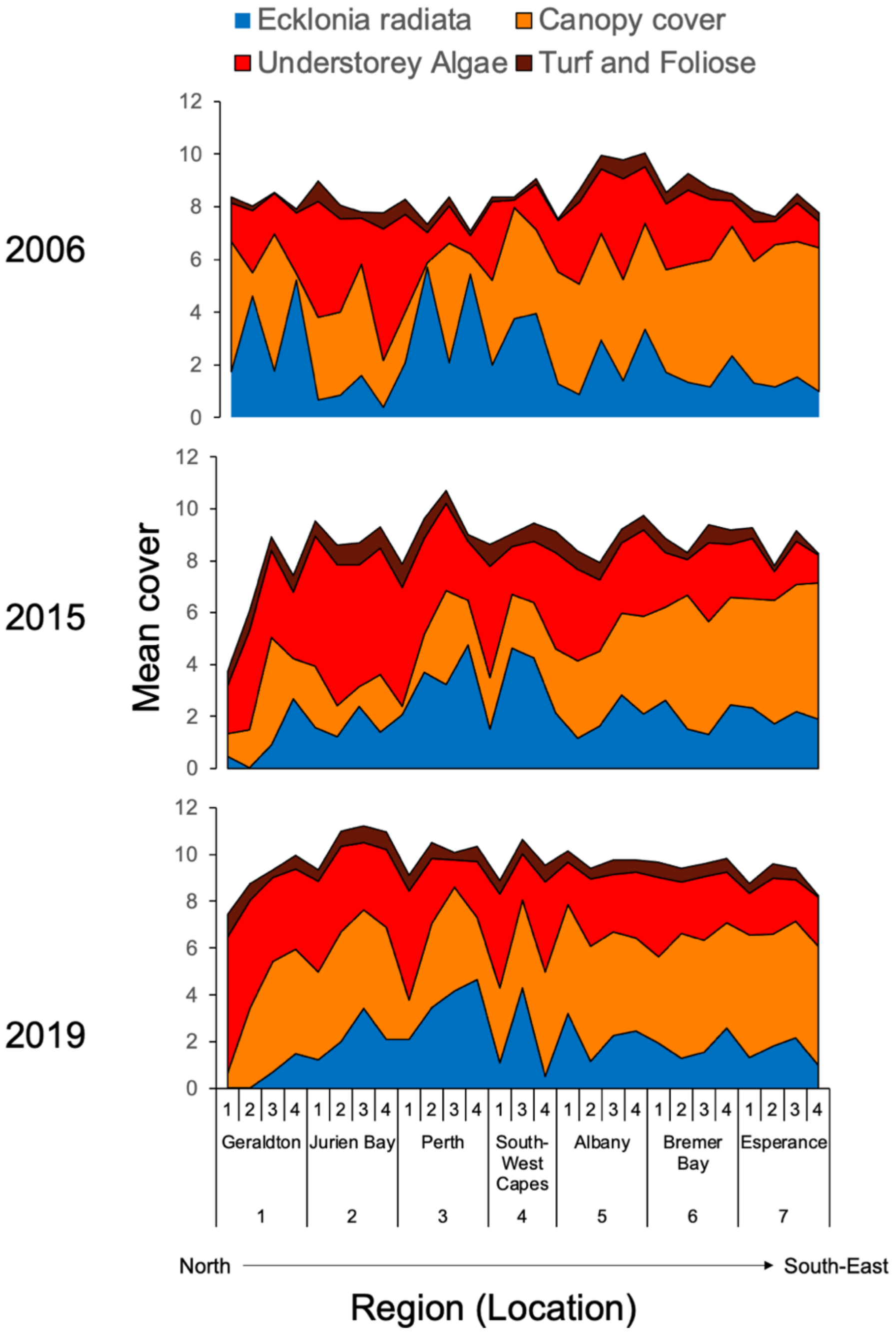

Figure 3.6. Changes in habitat variables through time: for each of the seven regions (Geraldton, Jurien Bay, Perth, South-West Capes, Albany, Bremer Bay and Esperance) and sampling years (2006, 2015 and 2019). Shows the mean category of *Ecklonia radiata*, non-*Ecklonia* canopy, understorey algae and turf and foliose algae cover. Categories correspond to percent cover detailed in methods

documents changes occurring in transitional regions along the west coast, and minor changes along the southern coast (Parker et al., 2019; Smale et al., 2019; Wernberg et al., 2016). These studies have described the south coast of SWA as a stable area subjected to minimal assemblage changes, however, this study indicates that these regions are experiencing continual, gradual shifts. Regions in the south are bordered by the Great Australian Bight, which defines the geographic limit of many short-range endemic species (Cheung et al., 2012). The southern coast of SWA defines part of the 'Great Southern Reef' (GSR), which as a whole provides substantial ecological and socio-economic benefits, despite low awareness and research on the area (Bennett et al., 2016). Therefore, changes in species distributions and associated habitat in this area need to be tracked, especially given the importance and geographic constraints of the region, which inhibit infinite southern shifts (Cheung et al., 2012). The continual assemblage changes documented along the south coast of SWA suggest that management and research should focus on this vulnerable area.

Ecosystem services

Coastal fish assemblages provide important services that affect marine ecosystems and the human populations that are living beside or dependent on them (Barbier, 2017). Healthy fish stocks are important for human food security, livelihoods and culture, as well as commercial and recreational fishing (Brander, 2010; Pecl et al., 2017). Several of the species that characterised assemblage differences between years were important to commercial and recreational fishing in SWA. For example, the abundance of subtropical fish species, *C. rubescens* and *G. hebraicum* were greater during 2015 and 2019, which may correspond with increased recruitment of these species from the 2011 heatwave (Cure et al., 2015). In contrast, the temperate species *N. valenciennesi*, *A. gouldii* and *B. frenchii* decreased in abundance since the 2006 survey, which may be an adverse effect of warming combined with increasing pressure from fisheries (Gaughan & Santoro, 2018). Cumulative pressures from fishing and climate change may not always negatively affect fish species, as climate warming may create new habitat opportunities as species shift ranges south. Therefore, fishing and climate may act synergistically on fish assemblages, as fishing removes species from an area allowing invasive species to inhabit vacant niches (Rijnsdorp et al., 2009).

Conclusion

Tracking fish species over long-term periods can inform conservation and management strategies (Poloczanska et al. 2013; Verges et al., 2014; Wernberg et al., 2016; Fredston-Hermann et al., 2020a). Individual marine species have been shown to respond differently in the face of climate change, and therefore a blanket conservation approach will not be adequate (Fredston-Hermann et al., 2020a). Here, we document differing responses of species to ocean warming, with increases and decreases in abundance across the study area. Different approaches to conservation and management, such as transboundary management, will likely be required for fish species in SWA to ensure the continuation of all ecosystem services provided by these assemblages.

This study identified a change in reef fish assemblages along the southern coast of SWA. Over 14 years of monitoring, fish communities in SWA experienced an assemblage shift. This was characterised by the continued change of fish assemblages along the southern coast and the stabilisation of assemblages along the transitional west coast. Fish communities along the south coast have unique compositions and are characterised by short-range endemic species (Goldsworthy et al., 2020). These species are geographically limited, and as such, they are especially vulnerable to extirpation or extinction. Globally, climatic changes are occurring and further increases in ocean temperatures are predicted. The unique fish communities of SWA will change if steps are not taken across the world to reduce the rate of SST rise.

3.3 Materials and Methods

We targeted shallow water, complex rocky reefs between four and twelve meters deep to sample fish assemblages along 2000 km of the Southwest Australian (SWA) coastline. The hierarchical experimental survey was designed by (Saunders et al., 2014) in 2006, with replication by (Parker et al., 2019; Shalders et al., 2018) in 2015 and this study in 2019. Seven coastline regions were selected that incorporated the subtropical to warm-temperate transition and the heterogeneous habitats of SWA (Fig.3.7). Within each region, four locations were selected and within each location, four reef sites were surveyed. Within each reef site, twelve 25 m by 5 m transects were sampled. Samples were separated by a hierarchical distance scale with regions

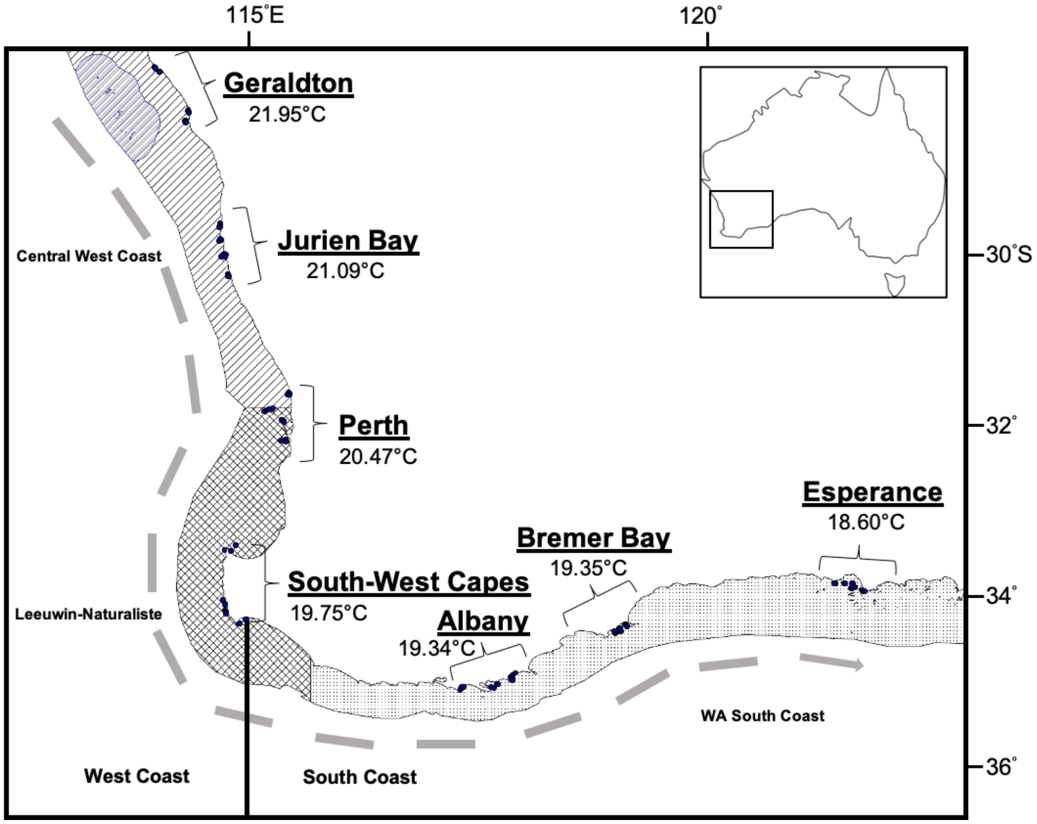

Figure 3.7 Methods: Map of the survey design in Southwest Australia (SWA): with the seven regions; region 1: Geraldton, region 2: Jurien Bay, region 3: Perth, region 4: South-West Capes, region 5: Albany, region 6: Bremer Bay and region 7: Esperance labelled. Within each region the locations of each dive (n = 112) are illustrated. The direction of the Leeuwin Current and the corresponding temperature gradient is shown by the grey arrow along the coast, the three IMCRA mesoscale regions; Central West Coast, Leeuwin Naturaliste and the Western Australian South Coast are illustrated by hatching and shading and the two fisheries management areas of SWA are delineated by the dark line heading south from the South-West Capes.

separated by hundreds to thousands of kilometers and locations within each region by tens of kilometres. Reef sites within each location were separated by hundreds of meters to kilometres and transects within each site by at least ten meters. Due to unexpected bad weather and site inaccessibility, four reef sites in the South-West Capes region were unable to be surveyed in 2019. This amounted to a study that spanned over 15 years with sampling in 2006, 2015 and 2019 and encompassing a coastline comprising 7 degrees of latitude and 10 degrees of longitude. Whilst effort was made to revisit reef sites at similar times during each year, this was not always possible due to weather and logistical constraints. However, analysis of the data (using a Distance-Based Linear model) indicated that time of year was not a significant or important explanatory variable ($p > 0.05$, $R^2 = 0.04$) for the variation in fish assemblages and as species that inhabit shallow reefs are usually site associated (Sale, 1991), seasonal stability within the studied assemblages is likely (Holbrook et al., 1994).

We applied a consistent sampling technique across the entire study period and area (Fig. 3.7). To record and survey the shallow-water reef fish and benthic habitats SCUBA divers maneuvered a Diver Operated Stereo-Video System (stereo-DOVs) along 25 m by 5 m transects. Stereo-DOVs were designed to improve the precision of length and distance estimates, and minimise inter-observer variability (Harvey et al., 2004; Harvey et al., 2010; Harvey & Shortis, 1995; Harvey, et al., 2002). The underwater stereo-video systems used throughout this project were constructed from two video cameras in underwater housings that were fixed 700 mm apart and inwardly converged at 8˚ to maximise the area for measurement (Parker et al., 2019; Saunders et al., 2014; Shalders et al., 2018). Two Sony FDR X3000 Action video cameras were used in 2019, Sony HDR CX700 video cameras were used in 2015 and Sony TRV 900 were used in 2006. The system was calibrated before and after each set of fieldwork, using the CAL software (Seager 2014) in 2015 and 2019, and the Vision Measurement Software Package in 2006 (Robson et al. 2006). Calibration ensured accurate calculation of transect dimensions and length measurements throughout the entire study area (Harvey et al., 2004; Harvey & Shortis, 1998; Shortis & Harvey, 1998).

Video recordings from the stereo-video systems created a permanent record of each transect, which allowed us to analyse fish and benthic habitat post-survey. The video footage was analysed using Event-Measure (stereo) (www.seagis.com.au) in 2015 and

2019, and the Vision Measurement Software Package in 2006 (Robson et al. 2006). An observer would identify, count and measure the lengths of fish seen within the transect. Rules were established within the software to prevent fish that were more than 7 m away from the camera and 2.5 m away from the centre of the transect line (outside the transect) from being counted or measured (Harvey et al., 2004). Fish that were only visible in one camera, due to obstruction of the field of view by algae or substrate, were still counted if we were certain the fish was within transect boundaries.

The same video footage used in the video analysis was also used to quantify the benthic habitat. Video imagery was analysed using a Visual Basic program in Microsoft Excel modified from a design described by Holmes (2005). The procedures described in (Saunders et al., 2014) were followed with five equally spaced frames which were not overlapping and showed an extensive view of the habitat being selected within each 25m transect.

We assigned each frame a Reef Type, either Limestone or Granite, and Reef Cover was approximated and assigned a categorical value from 1 to 6. These categories were according to: (1) 0-25% Reef and 75-100% Sand, (2) 21-50% Reef and 50-75% Sand, (3) 50% Reef and 50% Sand, (4) 50-75% Reef, 25-50% Sand, (5) 75-100% Reef and 0-25% Sand and (6) 100% Reef. Reef Height was also estimated from the field of view and categorised with a value from 1 to 4 corresponding to: (1) Platform Reef, (2) Small (<1m in height boulders or outcrops), (3) Large (1m to 3m in height boulders or outcrops), or (4) Massive (>3m in height outcrops). Reef slope was estimated and assigned a value from 1 to 5 based on (1) Gentle Slope (<30°), (2) Steep Slope (30-70°), (3) Vertical Wall (70-110°), (4) Overhanging Wall (>110°) and (5) Overhead Overhanging Reef or Cave. Benthic habitat was also estimated at each frame for *Ecklonia radiata* canopy, non-*Ecklonia* Canopy Cover, Understorey Algae Cover, Foliose and Turfing algae and Hard Coral Cover, and were given a rank from 0 to 6, with (0) no cover, (1) <1%, (2) 1-10%, (3) 10-25%, (4) 25-50%, (5) 50-75% and (6) >75% cover. Seagrass presence or absence was also recorded for each frame.

We analysed changes in shallow-water reef fish assemblages along the SWA coastline using the PRIMER v7.0 software package (Anderson et al., 2008). Raw assemblage data was summed to site level within each of the three sampling years (n = 112 for 2006 and 2015, n = 108 for 2019) before transformation. Dispersion-weighting followed by a square-root transformation was then applied to transform and down weight overly-dispersed species and those with large abundance fluctuations in the data set. A Bray-Curtis similarity coefficient was then implemented in a resemblance matrix constructed using the transformed site data. Bray-Curtis was used as it does not consider species with joint absences evidence for similarity (Bray & Curtis, 1957; Clarke, 1993). To determine if significant changes in shallow-water reef fish assemblages occurred between years and across regions, we tested the Bray-Curtis resemblance matrix using a three-factor PERMANOVA (Anderson, 2001). This design included Year (fixed factor; 3 levels), crossed with Region (fixed factor; seven levels) and Location (random factor; nested in Region; 28 levels for 2006 and 2015, 27 levels for 2019), with sites being used as replication. To visualise the results of the PERMANOVA test, the distance among centroids for each region within each year were implemented in an Unconstrained Non-Metric Multidimensional Scaling analysis (nMDS) (Clarke & Gorley, 2015). We then overlaid a trajectory through time for each region.

Diversity indices were calculated from raw assemblage data summed to site level within each year using the DIVERSE function in PRIMER. These were the Total Number of Species *(S)* and the Shannon Wiener Diversity Index *(H').* Significant differences ($p < 0.05$) were determined using a univariate Permutational Multivariate Analysis of Variance (PERMANOVA) on the interaction term between Year (fixed factor; 3 levels) and Region (fixed factor; seven levels), based on a Euclidean Distance matrix of the raw assemblage site data. PERMANOVA obtains the p-value from permutations which avoids the assumption of normality (Anderson et al., 2008; Anderson, 2014). Prior to the PERMANOVA analysis, the Euclidean Distance matrix was tested for Homogeneity of Multivariate Dispersions on the factor 'Year' using the PERMDISP function in PRIMER, as PERMANOVA models are sensitive to these dispersions (Anderson, 2014).

The Australian Ocean Data Network (AODN) Open Access to Ocean Data Portal (https://portal.aodn.org.au/, accessed 12 April 2020) was used to determine mean SST at each study location within each sampling year. The AODN uses a single sensor, multi-satellite SSTfnd product which is derived from observations on all available NOAA satellites to produce a 0.02-degree grid. Temperature data was taken every second over each sampling year (2005-06, 2014-15 and 2018-19), for the marine heatwave in 2011, and the 10-year average, and was then averaged to get a single temperature value for each location for the year 2006, 2011 (heatwave) 2015, 2019 and the 10-year average. Bias in the temperature values was accounted for in MATLAB R2019B. Gradient heatmaps were also created in MATLAB using the *contour* function to graph the mean temperature at each location along the SWA coast for each year and the 2011 marine heatwave.

A species list was compiled consisting of all species observed over the three sampling years (Supplementary Information: *Overall Species Table*). The thermal affinity of species was assigned by Stuart-Smith et al. (2015), using data from (Edgar & Stuart-Smith, 2014). Stuart-Smith et al. (2015) assigned each species a thermal affinity value by matching SST data to the location with the highest occurrence of the particular species. We then categorised each thermal affinity value to a temperature bin of either > 17°C, 17 - 19°C, 19 - 21°C, 21 - 23°C and > 23°C based on the specific thermal affinity of the species. Species with a thermal affinity greater than 19℃ were considered 'warm-water', and species with a thermal affinity less than 19℃ were 'cool-water'. Information on trophic groups was gathered from the literature (Supplementary Information: *Overall Species Table*) and each species was categorised as either a Scraping Herbivore, Browsing Herbivore, Omnivore, Invertivore, Planktivore or Carnivore. Endemism data was primarily collected from the Western Australian Museum Records (Australian Museum 2020) with supplementary information from FishBase 2020 (Froese & Pauly, 2019), and species were categorised as either a Western Australian endemic, an Australian endemic, Indo-Pacific species or other (species with global distributions). Species that could not be accurately distinguished to a species level and counted with high certainty were removed from the analysis. These were *Pempheris* spp, *Siphonognathus* spp and *Trachinops* spp. *Kyphosus* species and *Scarus* species could be counted via video but were classified together due to similar morphologies; *Kyphosus cornelli/biggibus/vaigiensis, Kyphosus sydneyanus/gladius* and *Scarus ghobban/schlegeli.*

We analysed the thermal affinity, endemism and trophic groups of species independently for each region and year. The mean number of species (for each region, using sites as replicates), with each temperature bin (< 17°C, 17 - 19°C, 19 - 21°C, 21 - 23°C and > 23°C) were illustrated using stacked area plots with each colour representing a different temperature range. The contribution of Indo-Pacific species, Western Australian and Australian endemics and 'Other' species (species with global distributions), and each trophic group (Omnivore, Invertivore, Herbivore, Planktivore and Carnivore) were also illustrated using stacked area plots. Significant differences were analysed using post-hoc tests on the interaction term between Year and Region. Post-hoc tests were performed using univariate PERMANOVA (Year (fixed factor; 3 levels), crossed with Region (fixed factor; seven levels).

Within each region, characteristic species that were driving the differences in shallow-water reef fish assemblages between years were determined using Similarity Percentages (SIMPER) analysis, with species ranked by their percentage contribution (%contrib). To illustrate how these species were correlated with the abundance data, we conducted a Canonical Analysis of Principal Coordinates (CAP) on the distance among centroids for each location within each region. CAP analysis projected these distances into high dimensional space using ‘Year’ as a factor for groups. CAP analysis is constrained to hypotheses described *a priori* and is used to show maximum differences between levels of a chosen factor (Anderson & Willis, 2003). The resulting CAP plots were then overlaid with species identified from the SIMPER analysis.

To analyse the contribution of habitat (reef cover, reef type, reef height, reef slope, *Ecklonia radiata* cover, non-*Ecklonia* canopy cover, understorey algal cover, turf and foliose algae, hard coral cover and seagrass presence) and SST, we performed a distance-based multivariate linear model (DISTLM) analysis (Anderson, 2004; Anderson et al., 2008). The DISTLM procedure was based on the Bray-Curtis resemblance matrix of the dispersion-weighted shallow-water reef fish assemblage data and selected habitat and temperature variables that best explained the variation in shallow-water reef fish assemblages between years and locations. Before the analysis, the mean for categorical variables was taken for each location within each year and correlations between explanatory variables were viewed in Draftsman Plots, as models based on regression are sensitive to these correlations. All correlations were <0.9, allowing all variables to be available for inclusion in the analysis. Normality was assessed visually via histogram plots, with no variables violating the assumption of normality. We constructed the optimum model using the BEST selection procedure and the AIC selection criterion (Chambers & Hastie, 1992). A Distance-Based Redundancy Analysis (dbRDA) was used to visualise the model, which performs an ordination of the assemblage data that is constrained to the significant habitat and temperature variables produced by the DISTLM analysis. The cover of habitat (*Ecklonia radiata*, non-*Ecklonia* canopy, understorey algal, and turf and foliose algae) for each region and sampling year, were illustrated using stacked area plots. Significant differences were analysed using post-hoc tests on the interaction term between Year and Region. Post-hoc tests were performed using univariate PERMANOVA (Year (fixed factor; 3 levels), crossed with Region (fixed factor; seven levels).

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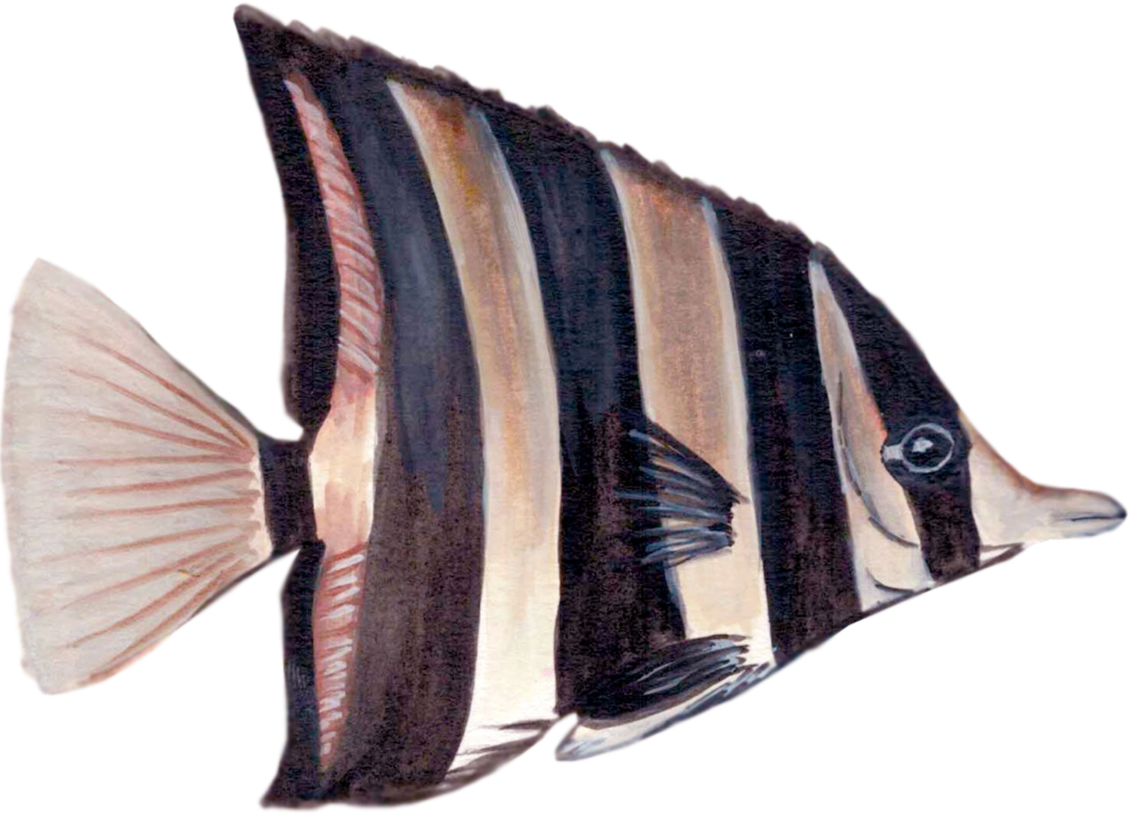
CHAPTER 4

General Discussion



Watercolour of a western talma (*Chelmonops curiosus*) by Savita Goldsworthy

Preface

This general discussion summarises the main results of each data chapter and places the outcomes within the wider context of global research. I also identify what I consider to be the limitations of this research and propose future research questions and directions.

4.1 Key Results

Globally, reef fish species have recreational, commercial and cultural values. These fish assemblages also play important roles in the provision of ecosystem services such as food security and fishing (Brander, 2010), which the human population heavily depend upon, and the regulation of climate through carbon sequestering (Barbier 2017). Reefs in Southwest Australia (SWA) are recognised as global diversity hotspots, with many species being found only in Western Australia (Fox & Beckley, 2005). My research identified that there were four distinct shallow-water reef fish assemblages along the SWA coastline and documented compositional changes in these assemblages in multiple regions over three sampling periods between 2006 and 2019 (Fig. 4.1). Geraldton in the north and Esperance in the south-east were identified as distinct assemblages, with both regions experiencing changes in the composition of the fish assemblages since 2006 (Fig. 4.1). Presently, both of these regions are managed within wider IMCRA and fisheries management bioregions which may not reflect their unique assemblage compositions. Esperance, in particular, is characterised by a high number of short-range endemic species which have a heightened vulnerability to climate change and fishing pressure due to late maturity and long-life spans.

4.1.1 Bioregions

Four bioregions, rather than the current three, would more accurately define the current distribution of fish assemblages along the SWA coastline (Fig. 4.1). In Chapter 2, shallow-water reef fish sampled in 2015 formed four distinct assemblages along the coast, with the boundaries of these assemblages differing from the current IMCRA (Commonwealth of Australia, 2006) and fisheries (Gaughan & Santoro, 2018) management regions (Fig. 4.1). Geraldton and Esperance were identified as having unique fish assemblages; however, they are currently managed within the wider Central

West Coast and Western Australian South Coast IMCRA mesoscale regions. Bioregions in Australia were determined by data that was available in the early 2000s (Fox & Beckley, 2005; Hutchins, 2001; Last et al., 2005). Since then, climatic changes have occurred both in SWA and across the world (Cheung et al., 2012; IPCC, 2014) which may have altered the distribution of marine assemblages. The current boundaries of bioregions and management areas in SWA may not reflect the climatic and oceanographic changes that have occurred over the past two decades.

4.1.2 Assemblage change over time

Shallow-water reef fish assemblages in SWA experienced significant changes over three time points across 14 years (Fig. 4.1). In Chapter 3, fish assemblages varied in association with SST and habitat changes, over a large temporal (14 years) and spatial (~2000 km) scale. The warmer, northern regions of Geraldton, Jurien Bay, Perth and the South-West Capes experienced the highest level of compositional change between 2006 and 2015, with assemblages appearing to stabilise in 2019 (Fig. 4.1). In contrast, assemblages in the cooler, southern regions of Albany, Bremer Bay and Esperance have continued to change up until the last sampling point in 2019 (Fig. 4.1). In particular, there were increases in warm-water affiliated, omnivorous and herbivorous species. This result differs from other studies completed in SWA, which document few or no changes in southern areas (Parker et al., 2019; Shalders et al., 2018; Smale et al., 2019; Wernberg et al., 2016).

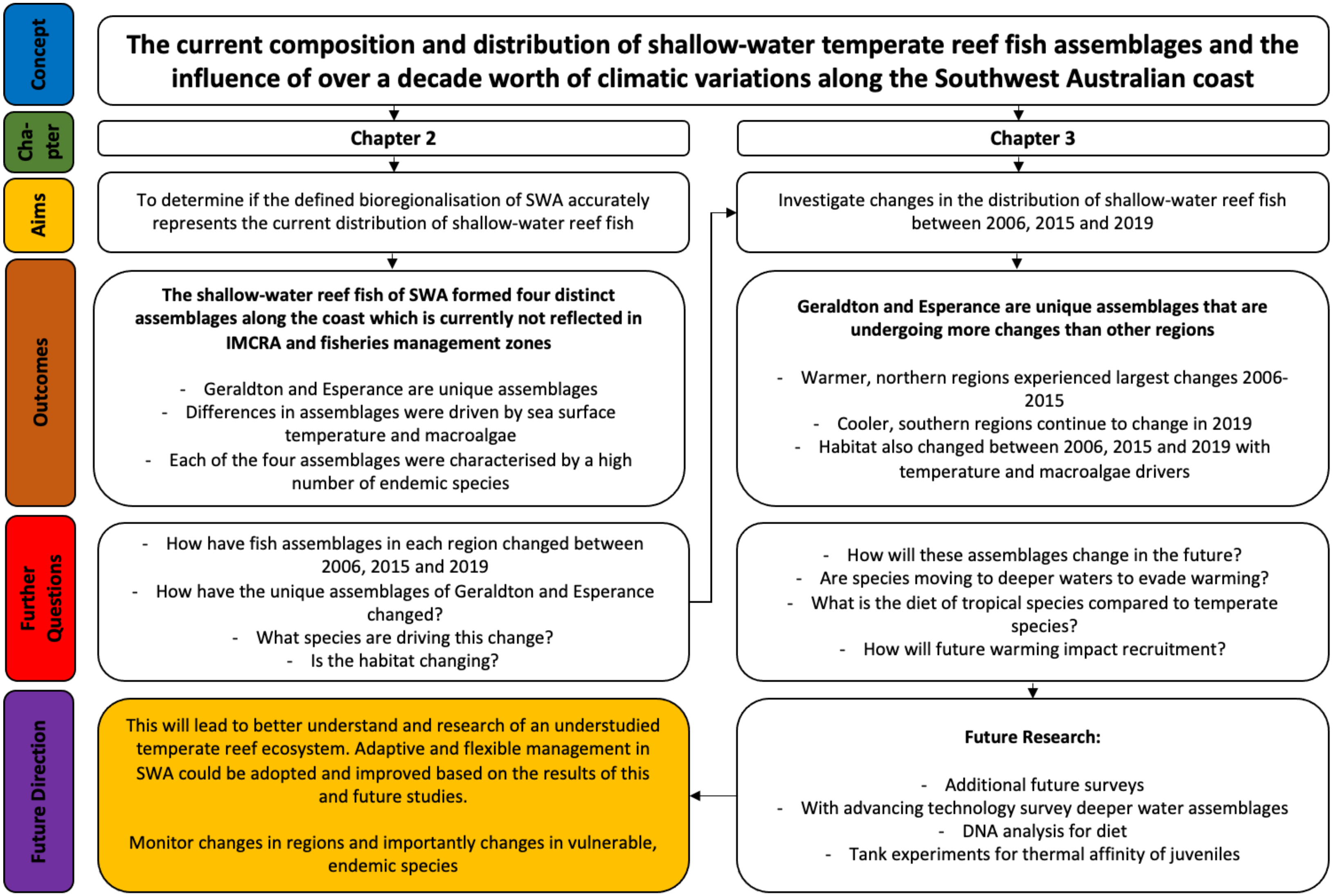
4.1.3 Characteristic species

A high proportion of species that characterised the unique fish assemblages and the compositional changes of these assemblages through time were either short-range endemics, or species that were important to both commercial and recreational fishers in SWA (Fig. 4.1). In Chapter 2 I identified characteristic species of each of the four unique assemblages along the SWA coastline. The distributions of these species changed from a subtropical- to a temperate-affiliation, which followed the gradient of water temperature produced by the Leeuwin Current. Many of these characteristic species were short-range endemics, which have a heightened vulnerability to habitat loss and fishing pressure. For example, *Choerodon rubescens* (baldchin groper), characteristic of the Midwest assemblage, and *Achoerodus gouldii* (western blue groper), characteristic of the Southern assemblages, are vulnerable target species due to their slow growth and longevity (Coulson et al., 2009; Nardi et. al., 2006). Species driving regional assemblage differences over time were identified in Chapter 3, with abundances both increasing and decreasing throughout the study. Many subtropical and tropical species had increased abundances in recent surveys, such as *Choerodon rubescens* (baldchin groper) and *Glaucosoma hebracium* (dhufish). In constrast, the abundances of some temperate species, for example *Nemadactylus valenciennesi* (queen snapper) and *A. gouldii* (western blue groper), have decreased in abundance since 2006.

4.1.4 Environmental and habitat variables

Sea surface temperature (SST) and habitat variables, particularly macroalgae, were important drivers of shallow-water reef fish distributions and the changes in these assemblages through time (Fig. 4.1). Chapter 2 identified that six environmental and habitat variables (SST, *Ecklonia radiata* cover, non-*Ecklonia* canopy cover, understorey algal cover reef type and reef height) explained 25.5% of variation in assemblages, with SST and macroalgae predominantly driving differences between unique bioregions. Similarly, in Chapter 3, *E. radiata* cover, non-*Ekclonia* canopy cover, reef type, understorey algae cover, hard coral cover and SST explained 44.3% of variation in assemblages between the seven regions and over time. Geraldton experienced a decrease in *E. radiata* cover since 2006, with decreases being correlated with an increase in non-*Ecklonia* canopy, understorey, turf and foliose algae. In both Chapter 2 and 3, SST was the dominant environmental driver, individually explaining the highest proportion of variation in assemblages across space and time (Fig. 4.1). Globally, SST is predicted to increase with future greenhouse gas emissions (IPCC, 2014), which will further impact marine assemblages.

My research shows that the conservation and fisheries management regions along the SWA coastline do not accurately reflect more recent data on the distribution of shallow-water reef fish assemblages in SWA (Fig. 4.1). All regions along the coastline experienced assemblage changes, with the south coast continuing to change (Fig. 4.1). The analyses completed in the published Chapter 2 (Section 2.3.5b and 2.4.2, Figure 2.3), to determine the most parsimonious fit of the data to a ‘bioregional model’, were repeated utilising data collected in 2019. The intention of this further analysis was to determine whether the most recent 2019 data supported the bioregional model



The current composition and distribution of shallow-water temperate reef fish assemblages and the influence of over a decade worth of climatic variations along the Southwest Australian coast

Chapter 2

To determine if the defined bioregionalisation of SWA accurately represents the current distribution of shallow-water reef fish

The shallow-water reef fish of SWA formed four distinct assemblages along the coast which is currently not reflected in IMCRA and fisheries management zones

- Geraldton and Esperance are unique assemblages
- Differences in assemblages were driven by sea surface temperature and macroalgae
- Each of the four assemblages were characterised by a high number of endemic species

- How have fish assemblages in each region changed between 2006, 2015 and 2019
- How have the unique assemblages of Geraldton and Esperance changed?
- What species are driving this change?
- Is the habitat changing?

This will lead to better understand and research of an understudied temperate reef ecosystem. Adaptive and flexible management in SWA could be adopted and improved based on the results of this and future studies.

Monitor changes in regions and importantly changes in vulnerable, endemic species

Chapter 3

Investigate changes in the distribution of shallow-water reef fish between 2006, 2015 and 2019

Geraldton and Esperance are unique assemblages that are undergoing more changes than other regions

- Warmer, northern regions experienced largest changes 2006-2015
- Cooler, southern regions continue to change in 2019
- Habitat also changed between 2006, 2015 and 2019 with temperature and macroalgae drivers

- How will these assemblages change in the future?
- Are species moving to deeper waters to evade warming?
- What is the diet of tropical species compared to temperate species?
- How will future warming impact recruitment?

Future Research:

- Additional future surveys
- With advancing technology survey deeper water assemblages
- DNA analysis for diet
- Tank experiments for thermal affinity of juveniles

Figure 4.1. Conceptual diagram outlining the outcomes and future research ideas generated from this thesis

proposed in Chapter 2. This further analysis indicated that the shallow-water reef fish assemblage data were conforming more closely to the proposed ‘four bioregion’ assemblage structure than the ‘three bioregion’ assemblage structure. The leave-one-out allocation success rate for the ‘four bioregion’ structure was >93.75% with the lowest AICc values of 371.12. Although the ‘three bioregion’ structure also had an allocation success >93.75, the AICc value for this structure was 371.52 (Fig. S.4.1), higher than the AICc value for the ‘four bioregion’. This confirmation of change in shallow-water reef fish assemblages highlights the need for long term monitoring and adaptive management that takes into account slow assemblage shifts. I recommend that this more up to date information is incorporated into future management strategies along with future research to incorporate climate effects into conservation approaches.

The marine environment is important to SWA economically, ecologically and socially. Fish assemblages influence the surrounding human population through the provision of food, directly influencing commercial and recreational fishing and have significant cultural values to indigenous people. Many people who live in coastal areas also have livelihoods and businesses associated with the marine environment (e.g., tourism, scuba diving sales and support, and commercial and recreational vessel support (Barbier 2017; Bennet et al., 2016)). Management and conservation in this area needs a flexible approach to target regions and species that are changing to ensure minimal species loss or extinction. Changes in environmental variables and habitats may have cascading implications for associated fish assemblages (Fig. 4.1), and therefore, should be monitored to determine future changes. The data presented in this thesis may be used to update management regions and to focus conservation and research efforts on areas that are continuing to experience change.

4.2 Significance

The data generated throughout this thesis can be used to describe how the current assemblage patterns of shallow-water reef fish in SWA are changing over time. It provides an insight into the impact that changing SST associated with climate change has on shallow-water, rocky reef marine ecosystems in SWA. Environmental and habitat variables, particular SST and macroalgae, were important drivers of unique assemblages and the changes in these through time. Some of the species that characterise the distinct assemblages are vulnerable, short-range endemics that are important to recreational and commercial fishing in SWA. These species need to be managed very carefully.

4.2.1 Geraldton and Esperance

Cooler, southern regions have continued to change into 2019, in contrast to the stabilisation of shallow-water reef fish assemblages along the west coast of SWA. The warmer, northern regions experienced large assemblage changes between 2006 and 2015 which conforms to previous studies in this area that were following the 2011 heatwave (Parker et al., 2019; Shalders et al., 2018; Wernberg et al., 2016). Along the west coast of SWA, Wernberg et al. (2016) documented a 43% loss of kelp forests that was correlated with an increase in turfing seaweeds, and species and functional groups characteristic of subtropical and tropical waters. Other studies found changes in Labridae assemblages (Parker et al., 2019) and increases in the densities of warm water Pomacentridae species in northern, warmer habitats (Shalders et al., 2018). Globally, research from the US has indicated that cold edges of species ranges track changes to climate more closely than warm edges over a long time period (Fredston-Hermann et al., 2020a). This is reflected in the results of this thesis, with the cold edges of tropical species potentially shifting further south into areas previously uninhabitable. Results of my research show that southern regions were continuing to experience changes in the shallow-water reef fish assemblage in 2019, which is in contrast to previous studies that document few or no impacts in the south of SWA (Parker et al., 2019; Shalders et al., 2018) but aligns to research completed in other areas of the world (Fredston-Hermann et al., 2020a). This highlights the need for continued monitoring of the south coast to determine the long-term impacts of these assemblage changes.

Geraldton and Esperance were identified as containing unique assemblages but are currently managed within broader IMCRA and fisheries management regions. As well as containing unique assemblages, these regions are geographically and ecologically important in SWA. Geraldton is an intermixing zone where tropical fauna at their southern range limit and temperate fauna at their northern end coexist (Fox & Beckley, 2005; Hutchins, 2001). Esperance is bordered by the Great Australian Bight and defines the geographic range limit for many short-range endemic species along the coastline (Cheung et al., 2012). The geographic constraints of the southern coast limit species distribution shifts to evade warming SST and they must adapt to new conditions or contract their range (Cheung et al., 2009). Therefore, their abundance and distribution should be monitored regularly to ensure that data can feed into management plans to mitigate species losses or extinctions, especially if these species cannot migrate into suitable habitat in cooler waters. The Esperance region is continuing to experience assemblage changes, particularly with increases in warm-water species.

The west coast of SWA is the current focus of both research and management, while efforts along the southern coast are limited. However, my data suggests that efforts should focus on southern regions as they are continuing to change alongside climatic variations. Research has been limited due to the south coast having highly variable weather conditions and an inaccessible coastline, which limits human access. Despite this lack of research and awareness, the south coast of Australia has been identified as the important ‘Great Southern Reef’ (GSR) (Bennett et al., 2016). This region covers over 8000 km of coastline and is a global diversity hotspot. The GSR provides substantial ecological, social and economic benefits to surrounding ecosystems and the human population, through fishing and tourism (Bennett et al., 2016). My study highlights continuing changes along the Western Australian extent of the GSR. These continuing changes should be considered in adaptive and flexible management with accurate boundaries to help ensure the continuation of human livelihoods and essential ecosystem services provided by the GSR.

4.2.2 Environmental and habitat variables

Across both data chapters SST was the dominant explanatory variable, accounting for the highest proportion of variation in assemblages through space and time. In past decades the marine environment of SWA has experienced rapid and variable climatic changes including changes in salinity, ocean currents and SST (Nagelkerken et al., 2016; Pattiaratchi & Hetzel, 2020), and these are predicted to continue (Cheung et al., 2012; Hobday & Lough, 2011). Marine species conform strictly to thermal tolerances, particularly when compared to terrestrial organisms (Sunday et al., 2012). Changing SST associated with climate change will continue to drive shifts in the abundance, distribution and size (Brander et al., 2003; Rijnsdorp et al., 2009; Seabra et al., 2015; Fredston-Hermann et al., 2020a, 2020b) of species, as temperatures exceed their thermal tolerances. This thesis documented an increase in the number of warm-water affiliated species correlated with changing SST. This supports previous studies in Australia and other areas of the world that demonstrate the tropicalisation (Vergés et al., 2014, 2016), and shifts in species ranges poleward and to deeper water (Dulvy et al., 2008; Perry et al., 2005). Along the southeast coast of Australia, fish assemblages are being subjected to similar environmental and oceanographic processes. Studies in this region have documented the correlation between SST and tropical fishes, with winter warming expected to increase the survival of these recruits by 100% by 2080 (Figueira & Booth, 2010). This data highlights the need for long-term monitoring of fish assemblages within Australia and globally throughout the world. As species ranges shift south with increasing SST, this may have a negative impact on southern, temperate species as they cannot indefinitely evade warm waters due to the orientation of the southern coast (Bennett et al., 2016; Wernberg et al., 2016).

Macroalgae (*E. radiata* and non-*Ecklonia* canopy), alongside SST, were important drivers of fish assemblages across regions and years. The results presented in this thesis correspond to previous studies in SWA which have identified the importance of macroalgae in defining unique regions within a single time frame (Galaiduk et al., 2017; Harvey et al., 2013). In addition, this study suggests that macrolgae may also explain variation in assemblages through time. Studies along the south and east coast of Australia have documented decreases in kelp cover over time which were associated with increases in herbivorous fishes and sea urchins (Valentine & Johnson, 2005; Ling et al., 2018). Geraldton and Esperance experienced a decrease in *E. radiata* cover since 2006 correlated with an increase in other canopy, turf and foliose algae. These results align with studies completed after the 2011 heatwave which reported a 100 km contraction in *E. radiata* and an increase in persistent turfing seaweeds (Bennett et al., 2015; Wernberg et al., 2011, 2016). Wernberg et al. (2016) documented the correlation between turfing and foliose algae, and species characteristic of warmer waters, with herbivorous and omnivorous species potentially preventing the phase shift back to kelp via herbivory. These results suggest that alongside tracking changes in fish distributions, habitat variables should also be monitored as changes may have cascading implications for the coastal reef ecosystem.

This thesis focussed on shifting fish assemblages in relation to habitat variables and SST, based on previous literature that documents the importance of these variables as drivers of species movements (Brander et al., 2003; Galaiduk et al., 2017; Goldsworthy et al., 2020; Harvey et al., 2013). However, in addition to SST, other environmental variables such as ocean currents and sedimentation, may also drive a change in species assemblages (Molinos & Donohue, 2010; Molinos et al., 2017). The velocity of climate change (i.e., the response of species to climatic changes) has been used to project changes in the global patterns of marine species under different IPCC scenarios (Molinos et al., 2016). This research highlighted the prevalence of range expansions over contractions, leading to changes in marine community composition and species range overlap. Within this thesis, changes in community composition were also documented along the SWA coastline, reflecting the results of these global projections. Molinos et al., (2017) documented the variable biogeographical change of species in response to the interaction between local climatic changes and other abiotic and biotic factors. These factors included ocean currents which influenced the range shifts of marine species. Locally in SWA, oceanographic influence from the Leeuwin Current affects the geographical ranges of marine species along the coastline, and changes to this current may have cascading implications to fish assemblages. This thesis, as well as previous research both here in SWA and globally, highlights the importance of monitoring a wide range of environmental and habitat variables, and the cascading implication for fish assemblages.

4.2.3 Conservation and fisheries models

The data and conclusions from this thesis can directly aid conservation and fisheries management strategies in SWA. Both data chapters provide up to date distributional and abundance data of shallow-water reef fish species in SWA with long-term tracking of assemblages. The revised boundaries can assist in updating current management and fisheries bioregions to ensure they adequately protect the fish communities within them. The long-term trends documented in this study can assist in predicting future assemblage shifts, facilitating adaptive management that changes with species distributions. Shifts in fish assemblages are already having an impact on fisheries in other areas of the world, by modifying or reducing catch per effort (Pinsky et al., 2020). As the growing need to increase the protection and management of the marine environment occurs, models, for example Marxan (Ball & Possingham 2000, 2009), were developed to assist in the design and allocation of marine reserve networks and fisheries management regions. These models place management regions to satisfy certain ecological, economic and social criteria (Ball & Possingham, 2000). They can ensure that certain characteristic species and defined habitat types are protected within reserves and can also satisfy areas of heritage and industry. Utilising models to place reserves has been successfully implemented in the rezoning of the Great Barrier Reef (GBR) (Ball et al., 2009; Fernandes et al., 2009). The GBR represents the most successful and complex application of models to assist conservation strategies, deriving bioregions from statistical modelling and analysis of ecological and biophysical data (Day, 2002; GBRMP Authority, 2004). These models rely on accurate, current species and habitat distributional data that has been collected over long time periods. Therefore, the data collected in this thesis could be directly used in models such as Marxan. Together, this could potentially contribute to the zoning of SWA's GSR to ensure bioregions are placed effectively to manage the diversity of habitats and species, and to ensure the continuation of successful, well-managed commercial and recreational fishing.

4.3 Future Directions and Limitations

Globally, the marine environment is under pressure from anthropogenic and climatic changes, with projections indicating that these impacts will continue. As these impacts increase, further changes to the marine environment and associated species assemblages will occur. Research should continue to monitor and track assemblages through time (Fig. 4.1). The patterns described in this thesis should drive future studies and motivate new experiments that utilise novel techniques to increase our knowledge and understanding of the marine environment. The following paragraphs highlight some considerations of this thesis and suggest some logical extensions to this study both through technical and experimental design (Fig. 4.1). This is not an exhaustive list; however, it aims to detail some realistic future research that could be prioritised as the next steps to progress this research theme.

4.3.1 Seasonal variation

A limitation of this thesis was the reliance on divers to complete surveys. This led to surveys being completed across the sampling year to ensure safe fieldwork conditions. Previous studies have documented minimal seasonal variation in reef fish species (Holbrook et al., 1994), as many of these exhibit site specific preferences (Sale, 1991). The methods section in Chapter 3 addressed seasonal variation in relation to this study and found that time of year explained very little variation in shallow-water reef fish assemblages across the larger spatial and temporal scales assessed. However, there is limited data on seasonal variation in fish assemblages locally in SWA. Future studies could potentially address this issue by undertaking an investigation of the variation in reef fish assemblages across seasons to provide accurate, local data here in SWA.

4.3.2 Temporal and spatial resolution of sampling

A consideration in the interpretation of this thesis is the three-point temporal replication. This time series could be made more robust with additional data, which would provide more certainty and clarity in the interpretation of the results. Due to the rapid and diverse assemblage changes seen along the SWA coast, it is recommended that additional datasets are added at 3-5-year intervals. Survey replication will be particularly important following marine heatwaves or weather events such as El Niño or La Niña. Due to funding constraints, it may be logical to undertake intense, frequent surveys at the vulnerable regions identified from this study, for example, Geraldton, Jurien Bay and Esperance. Further replication was outside of the time constraints of a Masters thesis, however the next logical step in this research would be the completion of a 2021 survey. As this thesis was being finalised water temperatures were higher than average and BoM declared that SWA was entering into a La Niña cycle. This increase in water temperatures may contribute to another marine heatwave similar to that experienced in 2011 (Australian Government-Bureau of Meteorology, 2020). Undertaking a 2021 survey will record potential disruptions and further changes in assemblages correlated with this warming. Future replication will allow the tracking of species, particularly those of value to SWA and monitor abundances of species within communities. This will provide answers to questions such as: ‘have the west coast communities continued to stabilise?’ and ‘has the south coast continued to change?’

This study identified the distinctiveness of shallow-water reef fish assemblages along the southern coast, in particular the Esperance region. Future surveys could be completed at a finer, more continuous scale to examine assemblage boundaries along the southern coast, and to analyse the most practical and effective management approach for this area. Undertaking a follow-up analysis, utilising a continuous sampling design and focussing on the Southern Coast and Esperance regions, would determine fine scale shallow-water reef fish assemblage changes in this area. A more continuous survey approach would enable a continuous cluster-type statistical analysis rather than a factorial-type analysis. A cluster analysis on a continuous dataset would define the geographic boundaries of bioregions with a higher certainty.

The aim of Chapter 2 was to assess whether shallow-water reef fish assemblages of SWA align to the current IMCRA bioregions. The shallow-water reef fish assemblages did not align to these regions, and Chapter 2 identified alternative boundaries that may be more suitable. However, it is important to note that IMCRA bioregions consider a larger area than the present study, and holistically considers all marine species and geological data from the continental shelf and slope (Commonwealth of Australia, 2006). As further studies focussing on marine species across both Australia and the world are completed, they can be synthesized with the data collected within this study to fully re-examine the IMCRA bioregions of Australia.

4.3.3 Advancing technology

Technology is constantly advancing, and while this leads to better quality research it also poses a limitation on studies that span large temporal scales. During the time data was collected for this study, new camera technology was developed and adopted. New cameras had a higher picture quality and an increase in the number of pixels on the image sensor. In 2015, Sony HDR CX700 cameras were used in the stereo-DOV system, while the 2019 survey used Sony FDR X3000 Action cameras. These cameras have full high definition and a resolution of 1920 x 1080 pixels. During the 2006 survey, Sony TRV 900 video cameras with a resolution of 720 x 576 pixels were used. The number of pixels and the corresponding increased camera resolution improves the ability to detect, identify and count individual fish in post-survey video analysis. To overcome this, small fish species that occurred in high abundances were removed from the dataset, and species within the same genus and with similar morphologies were grouped together. The details of these species are provided within the Statistical Analysis section in each data chapter. Removal and grouping of these species within the data allowed assemblages to be analysed over time with minimal bias due to camera quality. Species surveyed within this thesis was therefore only a subset of species that could have been sampled using cameras with a higher resolution. These recent surveys in 2015 and 2019 which were completed with a higher camera quality can serve as a baseline for comparison with future datasets using similar technology.

The ability to assess deeper and inaccessible sites could be made possible with the development of new technology, such as Remote-Operated Vehicles (ROVs) (Sward et al., 2019). The use of ROVs reduces the reliance on divers and will allow a database to be built on species assemblages at different depths (Schramm et al., 2020a; Schramm et al., 2020b). Previous studies have demonstrated the movement of species to deeper waters to evade increasing SST (Dulvy et al., 2008; Perry et al., 2005). Monitoring assemblage change across depths has direct implications for management practices in SWA, particularly commercial and recreational fisheries. If species can survive in deeper waters than they may seek refuge at different depths. However, not all species can survive in deeper water. These must therefore shift laterally along the temperature gradient to evade warming SST. While across our survey area the temperature decreases almost linearly from Geraldton to Esperance, geographically the coastline extends south and then eastward. This orientation physically limits the potential for species to continue to shift ranges to evade warming SST (Cheung et al., 2012). Therefore, species risk extinction as they run out of suitable habitat. Using ROVs may also improve the accessibility of the south coast, allowing research to target the southern extent of the GSR more easily in Western Australia.

4.3.4 DNA Analysis

This study documented an increase in warm-water species that are increasingly widespread and competitive throughout SWA. For example, the subtropical *Coris auricularis* is a competitive species that is becoming more abundant and dominant along the coastline. This species has been reported as an omnivore (Lek et al., 2011) and if they are consuming juveniles of other species then this may have cascading impacts on assemblages (Lek et al., 2018; Smith et al., 2016). Species range shifts have the potential to disrupt competition and predator-prey relationships, particularly if juveniles of vulnerable endemic species become a food resource. Competition for resources, such as for food and nesting, may define the distributions of many species, in particular territorial species such as the Pomacentridae (Chase & Myers, 2011; Saunders et al., 2014). Changing SST and habitat may allow competitive species to expand into niches, displacing less competitive species and forcing range contractions. Gut content or stable isotope analyses of rapidly increasing species may provide future insights into how assemblage interactions are changing (Jones et al., 2018). It will determine if warm-water species are consuming cool-water juveniles, out-competing other species for limited resources, and the long-term implications for short-range endemic species. The Labridae and Pomacentridae families were most abundant along the coastline and have shifted southwards in correlation with associated warming (Parker et al., 2019; Shalders et al., 2018). These families are ideal for gut content analysis, and this research may show the extent of competition between species of the same family (Takahashi et al., 2020).

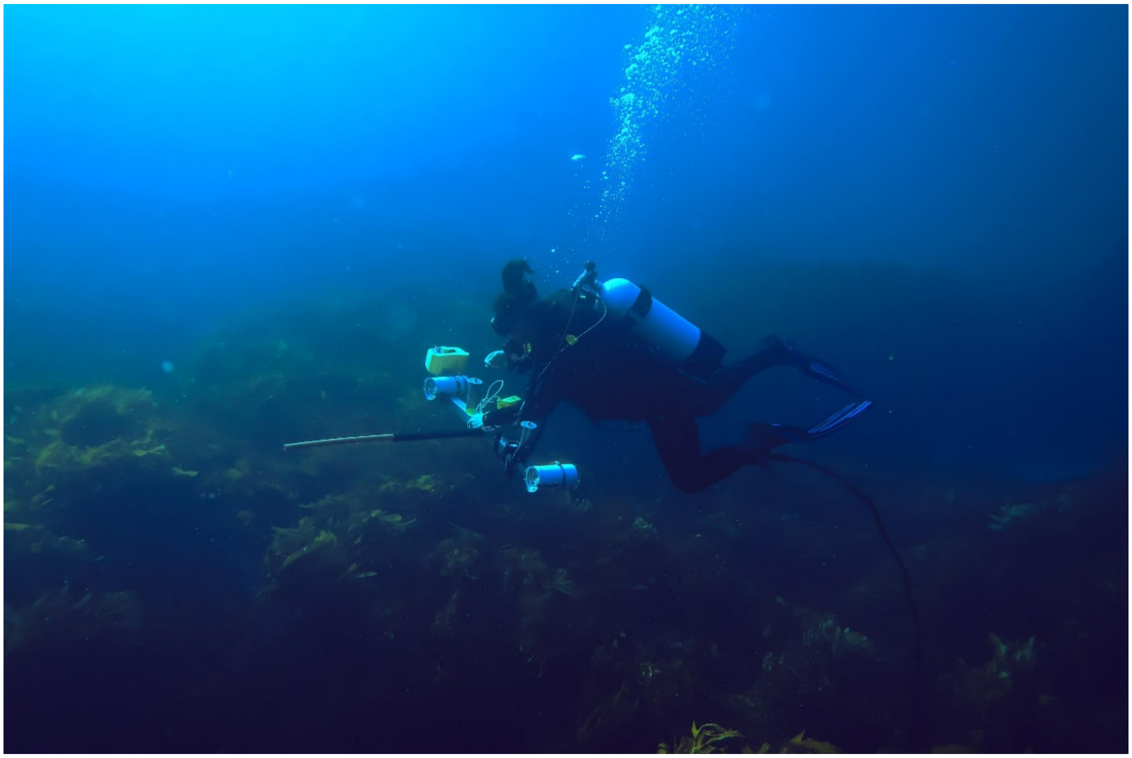
4.3.5 Thermal affinity of juveniles

Tank experiments could be used to determine the thermal affinity of juveniles and the effect of temperature on recruitment success. Increasing SST will have implications for the successful recruitment of certain species. For example, increased recruitment of the subtropical species *Choerodon rubescens* was reported after the 2011 heatwave, which was likely due to warmer waters aiding successful recruitment south of their usual range (Cure et al., 2015). The success of recruits and juveniles (measured by their ability to successfully settle, grow and mature) of different species could be monitored over different water temperatures. This would identify species-specific ideal thermal ranges for recruitment. These ranges could determine future impacts on fish abundance due to increased SST associated with climate change. For example, catch rates for the Western Rock Lobster fishery (one of the world’s largest, successful rock lobster fisheries) are predicted through a combination of indices relating to puerulus settlement and juvenile abundance (Caputi et al., 1995). This allows an understanding of the environmental factors that will affect recruitment, leading to a reactive management strategy that can predict catches 3-4 years in advance (De Lestang et al., 2012). Fisheries and conservation management could utilise the data provided by thermal affinity experiments to take into consideration environmental factors that will affect recruitment success. This could allow overall catch predictions to be more accurate and define limited entry seasons to allow stocks to recover after periods of stress. As well as for fisheries management, the data collected from such studies could aid in conservation by defining limited or no take areas within bioregions, based on the anticipated recruitment success of species. Combined, the utilisation of this data may minimise rapid decreases in species abundances and reduce the risk of extinction and fisheries collapse.

Thesis Conclusion

Southwest Australia is a complex region which is home to a diverse range of fish and habitat. Like many other regions in the world, this area is experiencing climatic and anthropogenic impacts that are affecting the marine environment. Despite these changes, research that documents assemblage change over time is limited in SWA and is focussed along the west coast. My research questions the suitability of the current IMCRA and fisheries management boundaries for shallow water reef fish and highlights vulnerable regions that are experiencing compositional changes. The overarching objective of this thesis was to analyse the current distribution of reef fish assemblages in relation to bioregional management, and to document how these assemblages have changed over time. To complete this objective, I first assessed the current distribution of shallow-water reef fish along the SWA coastline and found that these species form 4 unique assemblages. Geraldton and Esperance were identified as distinct assemblages, despite being currently managed within wider regions. I then documented the compositional changes of assemblages in SWA over time, and found that after initial change, assemblages along the west coast have appeared to stabilise while the south coast are continuing to change. Throughout this thesis I identify driving environmental and habitat variables, and characteristic species of assemblages, many of which are vulnerable, short-range endemic species. These results highlight the need for research and management to refocus along the south coast of SWA, to monitor species and habitats in this changing region. Combined, the outcomes of this thesis can assist managers and researchers to manage the characteristic, important species more accurately and efficiently along the SWA coastline.

While completing this thesis, many avenues for future research have opened. These will continue to improve our understanding and knowledge of fish assemblages in SWA. The work presented here begins to build a robust dataset of the current distribution of shallow-water reef fish in SWA and the changes in these assemblages over time. Southwest Australia forms part of the GSR which contributes substantial ecological and socio-economic value to Australia. However, my research provides evidence that fish assemblages throughout this region are changing. Additional climatic pressure coupled with a rise in greenhouse gasses from anthropogenic impacts will continue to change marine environments across the world. Understanding the direction and magnitude of these changes is essential to ensure the continuation of functioning assemblages and the protection of biodiversity. These assemblages provide services that the human population requires to survive and a degradation to these services will have cascading implications for food security, fishing, tourism and quality of life.



A diver operating a stereo-DOVs system during a transect in Albany (Southwest Australia). Photo: Jack Parker

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Every effort has been made to ensure the rightful owners of copyright material have been fully and appropriately acknowledged. If an acknowledgment has been omitted or is incorrect, I would be pleased to hear from the copyright owner.

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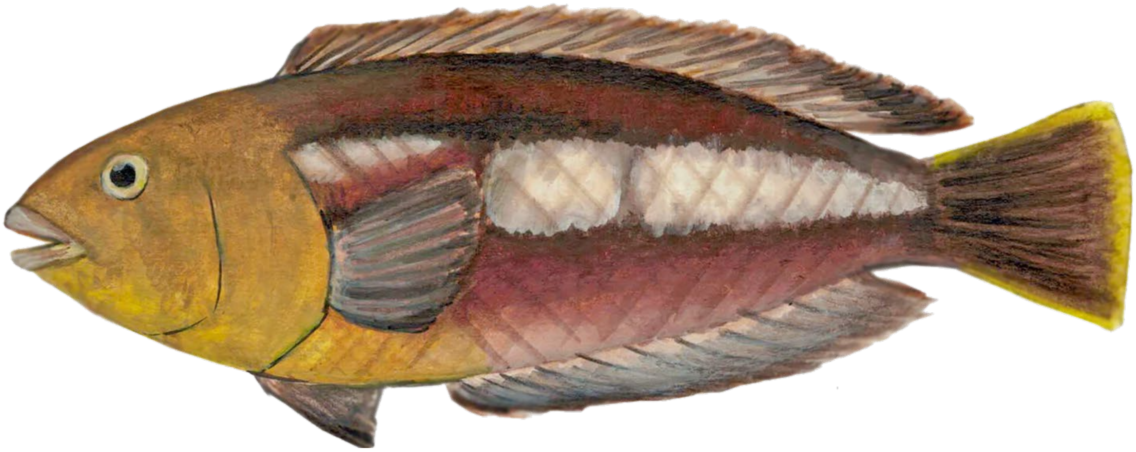
APPENDIX A: COPYRIGHT STATEMENTS



Watercolour of a brownspotted wrasse (*Notolabrus parilus*) by Savita Goldsworthy

Chapter 2:

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To Whom It May Concern: I, Savita Goldsworthy, contributed to the design of the study, undertook fieldwork and collected data, analysed the data and designed the figures and tables, and wrote and edited the final manuscript:

Goldsworthy S.D, Saunders B.J, Parker J.R.C, Harvey E.S (2020). Spatial assemblage structure of shallow-water reef fish in Southwest Australia. Mar Ecol Prog Ser 649:125-140. https://doi.org/10.3354/meps13445

Signed: Savita Goldsworthy

I, as a co-author, endorse that this level of contribution indicated by the candidate above is appropriate:

Ben Saunders

Euan Harvey

Jack Parker

Chapter 3:

In preparation for publication.

To Whom It May Concern: I, Savita Goldsworthy, contributed to the design of the study, undertook fieldwork and collected data, analysed the data and designed the figures and tables, and wrote and edited the final manuscript:

Signed: Savita Goldsworthy

I, as a co-author, endorse that this level of contribution indicated by the candidate above is appropriate:

Ben Saunders

Euan Harvey

Jack Parker

Tanika Shalders

Scott Bennett

APPENDIX B: RESEARCH OUTPUT

Publications

Goldsworthy S.D, Saunders B.J, Parker J.R.C, Harvey E.S (2020) Spatial assemblage structure of shallow-water reef fish in Southwest Australia. Mar Ecol Prog Ser 649:125-140. https://doi.org/10.3354/meps13445

Awards, Presentations and Participation

2020	Secretary for the Curtin Dive Club
2019	Project Management Certificate
2019	AMSA Conference
2018	Australian Government Research Training Program (RTP) Fee Offset

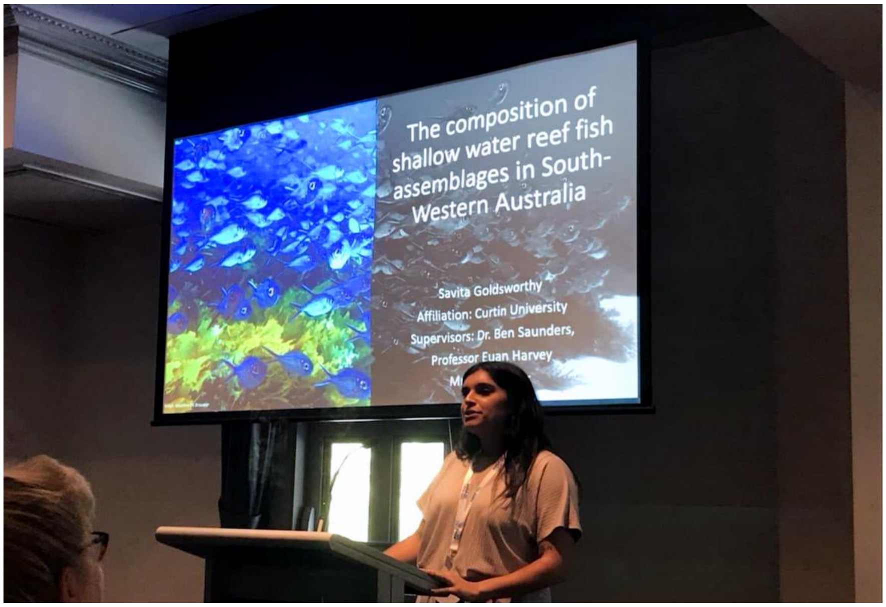


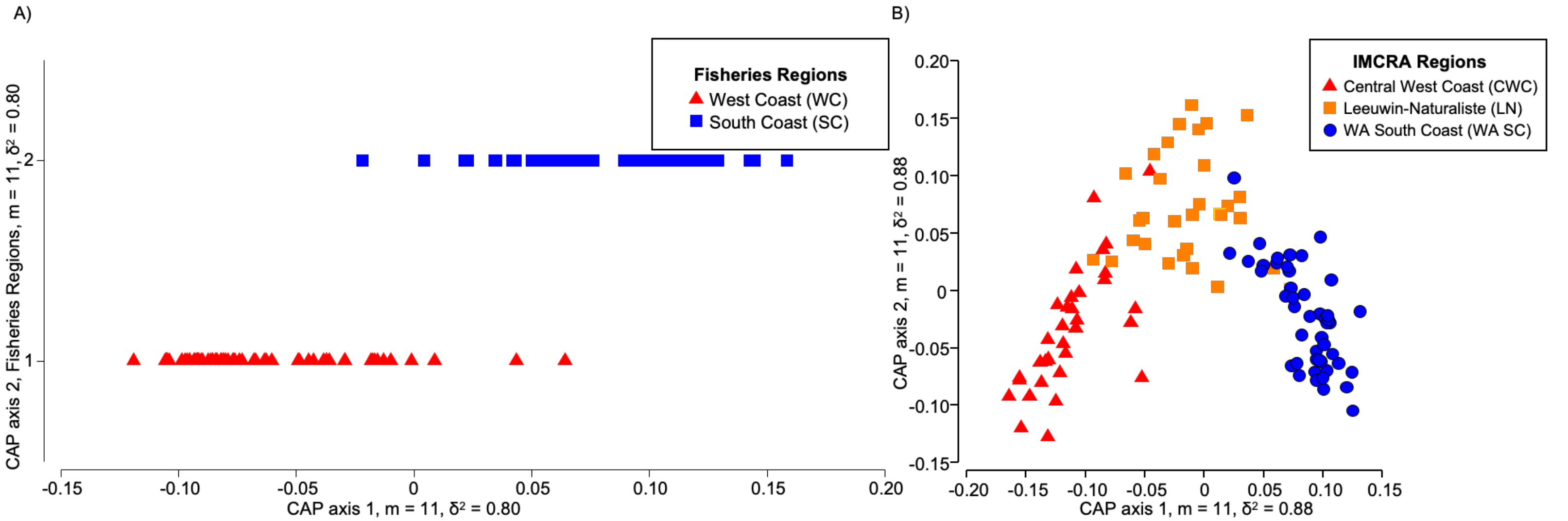
Photo of my research presentation at the 2019 AMSA conference in Fremantle (Western Australia). Photo: Jack Parker

SUPPLEMENTARY INFORMATION

Chapter 2

Table S.2.1. AIC_c values calculated for the seven 'assemblage structures' of SWA

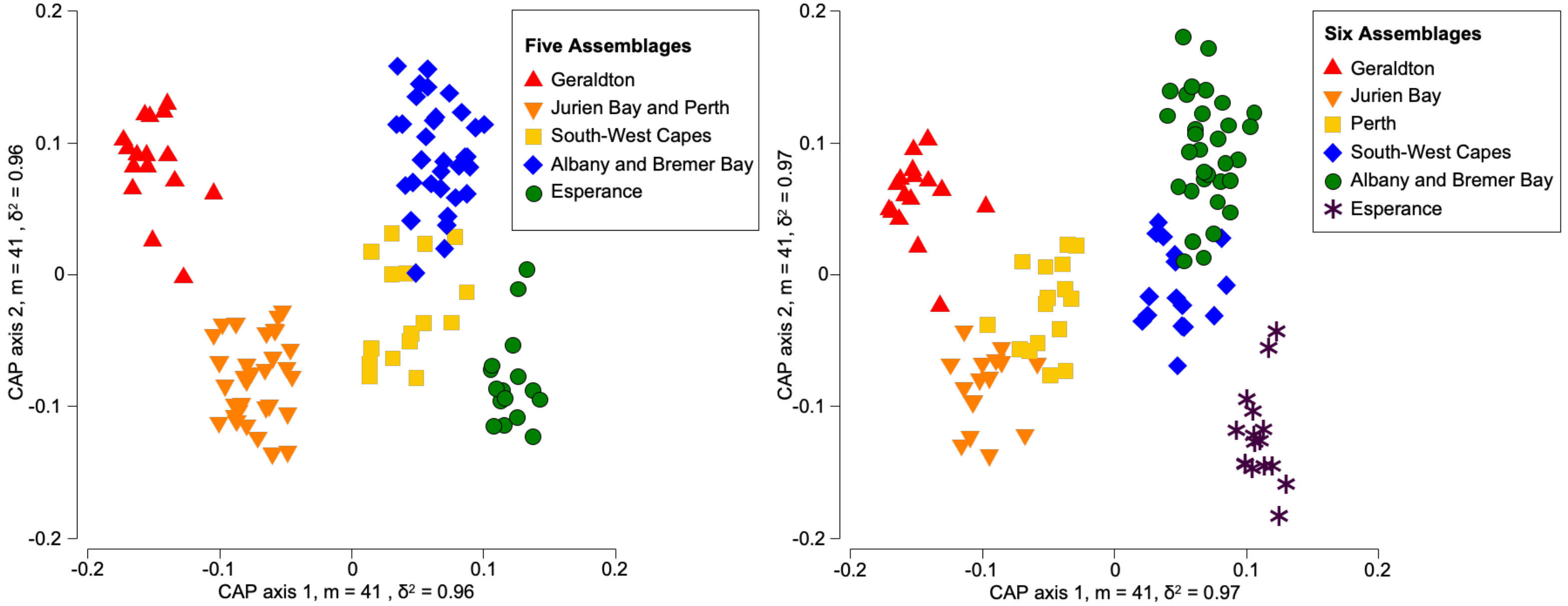
Assemblage Structure	**AIC_c Value**
3 Assemblages	387.879
4 Assemblages	387.955
5 Assemblages	388.116
6 Assemblages	389.109
7 Assemblages	390.458
IMCRA Regions	389.889
Fisheries Regions	391.024



Assemblages	WC	SC	Total	%correct
West Coast	60	4	3	93.75
South Coast	2	46	45	95.83

Assemblages	CWC	LN	WA SC	Total	%correct
Central West Coast	29	4	0	48	87.88
Leeuwin-Naturaliste	3	26	2	16	83.87
WA South Coast	0	4	44	48	91.67

Figure S.2.1. (A) Canonical Analysis of Principal Coordinates (CAP) plot of shallow-water reef fish assemblages using the two fisheries management regions of SWA: West Coast and South Coast (m = 12, n = 112) as a factor of groups. The resulting leave-one-out allocation success of observations is also shown. (B) Canonical Analysis of Principal Coordinates (CAP) plot of shallow-water reef fish assemblages using the three IMCRA mesoscale bioregions of SWA: Central West Coast, Leeuwin Naturaliste and WESTERN AUSTRALIAN South Coast (m = 39, n = 112) as a factor of groups. The resulting leave-one-out allocation success of observations is also shown.



Assemblages	1	2	3	4	5	Total	%correct
Geraldton	14	2	0	0	0	16	87.50
Jurien Bay and Perth	0	31	1	0	0	32	96.88
South-West Capes	0	2	13	1	0	16	81.25
Albany and Bremer Bay	0	1	3	29	0	32	90.63
Esperance	0	0	1	1	14	16	87.50

Assemblages	1	2	3	4	5	6	Total	%correct
Geraldton	15	0	1	0	0	0	16	93.75
Jurien Bay	1	12	4	0	0	0	16	75.00
Perth	0	1	14	1	0	0	16	87.50
South-West Capes	0	0	2	13	1	0	16	81.25
Albany and Bremer Bay	0	0	1	3	28	0	32	87.50
Esperance	0	0	0	1	1	14	16	87.50

Figure S.2.2. (A) Canonical Analysis of Principal Coordinates (CAP) plot of shallow-water reef fish assemblages using the five-assemblage structure of SWA: Geraldton, Jurien Bay and Perth, South-West Capes, Albany and Bremer Bay, and Esperance (m = 12, n = 112) as a factor of groups. The resulting leave-one-out allocation success of observations is also shown. (B) Canonical Analysis of Principal Coordinates (CAP) plot of shallow-water reef fish assemblages using the six-assemblage structure of SW: Geraldton, Jurien Bay, Perth, South-West Capes, Albany and Bremer Bay, and Esperance (m = 36, n = 112) as a factor of groups. The resulting leave-one-out allocation success of observations is also shown.

Table S.2.2. Individual marginal tests for environmental and habitat variables included in the DISTLM analysis (reef cover, reef/outcrop height, reef slope, *Ecklonia radiata* cover, non-*Ecklonia* canopy cover, understorey algae cover, seagrass presence and sea surface temperature)

Environmental Variable	**Sum of Squares (trace)**	**Pseudo-F**	**p**	**Proportion**
Reef Cover	5709.6	1.8082	0.0227	0.016173
Reef / outcrop height	5327.5	1.6854	0.0352	0.01509
Reef Slope	7779.5	2.4785	0.0022	0.022035
Ecklonia Cover	23688	7.9114	0.0001	0.067096
Canopy Cover	20673	6.8418	0.0001	0.058556
Understorey Algae Cover	8507	2.716	0.0011	0.024096
Sea Surface Temperature	53905	19.822	0.0001	0.15269

Table S.2.3. Alternate best models: Alternate best models produced by the DISTLM analysis within two AIC_c of the optimum model

AICc	R^2	Number of variables	Selections
886.7	0.177	2	*Understorey algae cover, SST*
885.67	0.200	3	*Canopy cover, understorey algal cover, SST*
885.04	0.220	4	*Ecklonia cover, canopy cover, Understorey algal cover, SST*
885.05	0.235	5	*Reef slope, Ecklonia cover, canopy cover, Understorey algal cover, SST*
885.38	0.248	6	*Reef cover, reef slope, Ecklonia cover, canopy cover, understorey algal cover, SST*
886.12	0.259	7	*Reef cover, reef and outcrop height reef slope, Ecklonia cover, canopy cover, understorey algal cover, SST*

Table S.3.1. Results of a 3-factor nested Permutational Multivariate Analysis of Variance on dispersion-weighted transformed densities of shallow-water reef fish species across the 7 regions in Southwest Australia (SWA). Year and region are fixed factors; location is nested within region

Source	df	SS	MS	Pseudo-F	p (perm)	Unique perms
Year	2	38663	19331.0	9.796	0.0001	9889
Region	6	2.97E+05	49538.0	12.440	0.0001	9906
Location (Region)	21	83902	3995.3	2.902	0.0001	9640
Year x Region	12	46818	3901.5	1.977	0.0001	9765
Year x Location (Region)	41	80912	1973.5	1.434	0.0001	9488
Residuals	249	3.43E+05	1376.7			
Total	331	8.91E+05				

Table S.3.2. Results of a 3-factor nested Permutational Multivariate Analysis of Variance on normalised environmental and habitat variables across the 7 regions in Southwest Australia (SWA). Year and region are fixed factors; location is nested within region

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Year	2	91.26	45.628	12.654	0.0001	9945
Region	6	250.50	41.750	4.429	0.0001	9914
Location (Region)	21	198.76	9.465	4.569	0.0001	9865
Year x Region	12	115.06	9.588	2.659	0.0004	9913
Year x Location (Region)	41	147.84	3.606	1.741	0.0001	9805
Residuals	249	515.79	2.071			
Total	331	1324.00				

Table S.3.3. Correlations to the first, second and third distance-based redundancy analysis (dbRDA) axes of selected environmental and habitat variables (Multiple Partial Correlations) of Southwest Australia (SWA)

Environmental variable	dbRDA1	dbRDA2	dbRDA3
Reef type	0.329	0.446	0.424
Ecklonia cover	-0.017	0.525	0.428
Canopy cover	-0.285	-0.240	0.057
Understorey algae cover	0.289	-0.452	0.634
Combined turf	-0.022	-0.450	0.321
Sea surface temperature	0.851	-0.105	-0.344

Table S.3.4. Region post-hoc tests: Mean (± SE) abundance and pairwise tests on the interaction between year and region (on dispersion-weighted, square-root transformed densities) for the three sampling years (2006, 2015 and 2019). Regions are Geraldton, Jurien Bay, Perth, South-West Capes, Albany, Bremer Bay, Esperance and significant p-values at α = 0.05 are shown in **bold**

Region	Mean (± SE)			*t* p(perm)		
	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019
1. Geraldton	358.75	672.50	1020.50	1.79	1.96	1.32
	(230.66)	(327.41)	(116.52)	**0.02**	**<0.01**	0.15
2. Jurien Bay	427.50	1753.75	2308.50	2.35	2.71	1.27
	(98.63)	(548.27)	(257.05)	**<0.01**	**<0.01**	0.06
3. Perth	605.00	1304.00	1023.50	1.57	1.48	1.71
	(206.50)	(305.72)	(288.86)	**<0.01**	**<0.01**	**0.02**
4. SW Capes	393.00	848.00	800.00	1.51	1.43	1.37
	(146.40)	(276.13)	(525.13)	**0.04**	**0.03**	0.12
5. Albany	2723.50	1462.75	1605.25	1.45	2.26	1.23
	(1067.65)	(337.51)	(62.60)	**0.03**	**<0.01**	0.20
6. Bremer Bay	1948.75	2188.75	4035.00	1.64	2.69	1.86
	(399.87)	(449.72)	(1694.26)	**0.02**	**<0.01**	**<0.01**
7. Esperance	971.25	2108.50	1885.00	1.65	1.98	1.86
	(253.82)	(563.11)	(185.43)	**<0.01**	**0.01**	**<0.01**

Table S.3.5. Thermal affiliation post-hoc tests: Mean (± SE) number of species and pairwise tests on the interaction between year and region (on dispersion-weighted, square-root transformed densities) for each thermal affiliation (< 17℃, 17 - 19℃, 19 - 21℃, 21 - 23℃ and > 23℃). The three sampling years are 2006, 2015 and 2019 and the regions are Geraldton, Jurien Bay, Perth, South-West Capes, Albany, Bremer Bay, Esperance. Significant p-values at α = 0.05 are shown in **bold**

			<17°C							**17-19°C**		
Region		Mean			*t*			Mean			*t*	
		(± SE)			p(MC)			(± SE)			p(MC)	
	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019
1. Geraldton	0.13	0.31	-	0.88	1.73	1.99	0.31	0.19	1.57	0.77	0.24	0.38
	(0.07)	(0.16)	-	0.45	0.18	0.14	(0.16)	(0.06)	(0.21)	0.50	0.82	0.13
2. Jurien Bay	0.25	0.44	0.06	1.57	1.57	5.20	1.13	0.94	1.03	0.36	0.39	1.38
	(0.14)	(0.06)	(0.06)	0.21	0.22	**0.01**	(0.33)	(0.19)	(0.38)	0.74	0.73	0.43
3. Perth	0.75	0.44	1.13	1.46	1.13	2.67	2.19	1.50	2.04	1.12	0.07	2.25
	(0.18)	(0.16)	(0.16)	0.23	0.34	0.07	(0.64)	(0.18)	(0.13)	0.34	0.95	0.25
4. SW Capes	1.13	1.88	2.67	3.29	2.44	1.25	2.06	2.50	0.39	0.62	0.42	3.06
	(0.24)	(0.39)	(0.46)	**0.05**	0.14	0.34	(0.21)	(0.84)	(0.74)	0.58	0.72	0.83
5. Albany	3.38	2.44	3.75	2.09	1.57	1.93	6.06	4.88	0.07	0.92	1.58	5.52
	(0.24)	(0.28)	(0.43)	0.13	0.21	0.15	(0.41)	(0.88)	(0.94)	0.44	0.21	0.77
6. Bremer Bay	2.63	2.25	4.25	0.68	4.33	5.66	5.94	6.50	2.34	1.71	1.19	5.78
	(0.24)	(0.61)	(0.35)	0.55	**0.02**	**0.01**	(0.48)	(0.54)	(0.10)	0.18	0.32	0.22
7. Esperance	3.50	4.50	6.06	2.83	9.94	9.93	5.06	4.44	1.77	1.13	0.84	4.69
	(0.37)	(0.10)	(0.19)	0.06	**<0.01**	**<0.01**	(0.34)	(0.21)	(0.18)	0.33	0.46	0.61

	19-21°C						**21-23°C**					
Region	Mean (± SE)			*t* p(MC)			Mean (± SE)			*t* p(MC)		
	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019
1. Geraldton	4.25	7.31	2.83	5.96	2.32	5.81	1.50	4.50	4.44	2.92	3.67	0.24
	(0.53)	(0.21)	(0.07)	**0.01**	0.10	0.37	(0.31)	(0.84)	(0.64)	0.06	**0.03**	0.83
2. Jurien Bay	7.69	8.44	1.77	0.51	2.28	10.06	2.25	5.88	5.13	7.49	4.22	1.39
	(0.99)	(0.50)	(0.17)	0.64	0.11	0.55	(0.43)	(0.63)	(0.41)	**0.01**	**0.03**	0.26
3. Perth	9.31	11.25	1.60	6.99	0.58	9.94	0.81	3.19	1.75	4.21	1.57	2.60
	(1.39)	(1.24)	(0.21)	**0.01**	0.61	0.99	(0.28)	(0.70)	(0.53)	**0.02**	0.21	0.08
4. SW Capes	6.69	10.69	0.74	2.40	3.61	10.55	0.19	0.88	0.50	3.22	1.89	1.25
	(0.61)	(1.99)	(0.54)	0.09	0.07	1.24	(0.12)	(0.16)	(0.27)	**0.05**	0.20	0.34
5. Albany	11.06	12.44	0.31	0.77	0.73	12.47	0.06	1.25	0.20	1.83	3.00	1.61
	(0.90)	(1.17)	(0.77)	0.49	0.52	1.08	(0.06)	(0.62)	(0.05)	0.17	0.06	0.21
6. Bremer Bay	11.38	12.19	0.87	1.58	2.13	12.66	-	0.69	-	2.48	1.00	1.99
	(0.53)	(0.64)	(0.45)	0.20	0.12	0.57	-	(0.28)	-	0.09	0.39	0.14
7. Esperance	8.75	10.69	2.11	4.69	5.69	12.37	0.06	0.63	0.45	2.18	1.00	2.89
	(0.53)	(0.78)	(0.12)	**0.02**	**0.01**	0.73	(0.06)	(0.22)	(0.45)	0.12	0.39	0.07

	>23°C					
Region	Mean (± SE)			*t* p(MC)		
	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019
1. Geraldton	0.69	3.50	3.81	4.23	3.55	0.41
	(0.34)	(0.98)	(1.15)	**0.02**	**0.04**	0.71
2. Jurien Bay	0.25	1.38	1.44	2.06	3.61	0.10
	(0.14)	(0.48)	(0.28)	0.14	**0.04**	0.92
3. Perth	0.06	0.63	0.56	1.57	2.19	0.26
	(0.06)	(0.41)	(0.26)	0.22	0.12	0.81
4. SW Capes	-	0.06	-	1.00	-	1.00
	-	(0.06)	-	0.39	-	0.42
5. Albany	-	0.31	-	1.67	-	1.67
	-	(0.19)	-	0.19	-	0.20
6. Bremer Bay	-	0.19	-	1.57	-	1.57
	-	(0.12)	-	0.22	-	0.21
7. Esperance	-	0.13	0.22	1.00	-	1.00
	-	(0.13)	(0.22)	0.40	-	0.38

Table S.3.6. Endemism post-hoc tests: Mean (± SE) number of species and pairwise tests on the interaction between year and region (on dispersion-weighted, square-root transformed densities) for each endemism level (Indo-Pacific, Australian and Western Australian). The three sampling years are 2006, 2015 and 2019 and the regions are Geraldton, Jurien Bay, Perth, South-West Capes, Albany, Bremer Bay, Esperance. Significant p-values at α = 0.05 are shown in **bold**

	Indo-Pacific						**Australia**					
Region	Mean (± SE)			*t* p(MC)			Mean (± SE)			*t* p(MC)		
	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019
1. Geraldton	2.19	6.69	6.69	4.06	3.59	-	1.63	2.50	2.06	1.99	0.91	0.68
	(0.44)	(1.54)	(1.67)	**0.03**	**0.04**	-	(0.26)	(0.27)	(0.39)	0.14	0.43	0.55
2. Jurien Bay	1.38	5.06	4.13	6.45	5.88	2.42	5.13	4.75	5.38	0.52	0.20	0.64
	(0.24)	(0.41)	(0.41)	**0.01**	**0.01**	0.10	(0.97)	(0.51)	(0.63)	0.64	0.86	0.58
3. Perth	1.69	3.81	2.13	2.77	0.87	3.66	7.06	6.81	7.31	0.20	0.13	0.67
	(0.33)	(1.01)	(0.66)	0.07	0.46	**0.03**	(1.34)	(0.62)	(0.87)	0.86	0.90	0.55
4. SW Capes	0.56	1.31	0.67	2.22	0.40	-	6.44	9.19	9.83	2.00	1.46	0.26
	(0.06)	(0.31)	0.42	0.12	0.73	-	(0.84)	(2.15)	1.88	0.14	0.28	0.83
5. Albany	1.19	2.75	1.50	1.58	1.32	1.17	14.31	12.88	13.81	0.53	0.48	0.26
	(0.12)	(0.97)	0.18	0.22	0.28	0.33	(0.89)	(1.88)	1.87	0.63	0.67	0.81
6. Bremer Bay	1.38	2.31	1.44	2.61	0.23	1.50	13.19	13.56	14.69	0.73	3.79	1.73
	(0.16)	(0.50)	0.28	0.08	0.83	0.23	(0.89)	(1.10)	0.89	0.51	**0.03**	0.18
7. Esperance	0.88	1.31	0.88	2.05	0.00	2.33	12.69	14.19	18.06	2.48	11.63	9.35
	(0.16)	(0.24)	0.16	0.13	1.00	0.10	(0.71)	(0.12)	0.51	0.08	**<0.01**	**<0.01**

	Western Australia					
Region	Mean (± SE)			*t* p(MC)		
	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019
1. Geraldton	3.06	6.63	5.69	12.85	3.95	2.27
	(0.28)	(0.22)	(0.50)	**<0.01**	**0.03**	0.11
2. Jurien Bay	5.06	7.25	8.50	2.63	3.45	2.61
	(0.69)	(0.18)	(0.59)	0.08	**0.04**	0.08
3. Perth	4.38	6.38	6.06	4.38	2.03	0.36
	(0.99)	(0.75)	(0.53)	**0.02**	0.14	0.75
4. SW Capes	3.06	5.50	5.33	2.72	28.00	0.79
	(0.57)	(0.82)	0.79	0.07	**<0.01**	0.51
5. Albany	5.06	5.69	5.38	0.66	0.49	0.32
	(0.62)	(0.40)	0.65	0.56	0.65	0.77
6. Bremer Bay	5.38	5.94	6.31	1.14	2.85	1.04
	(0.16)	(0.47)	0.21	0.34	0.07	0.37
7. Esperance	3.81	4.88	5.63	2.20	3.67	0.86
	(0.19)	(0.65)	0.39	0.12	**0.03**	0.46

Table S.3.7. Trophic group post-hoc tests: Mean (± SE) number of species and pairwise tests on the interaction between year and region (on dispersion-weighted, square-root transformed densities) for each trophic group (planktivore, carnivore, invertivore, omnivore and herbivore). The three sampling years are 2006, 2015 and 2019 and the regions are Geraldton, Jurien Bay, Perth, South-West Capes, Albany, Bremer Bay, Esperance. Significant p-values at α = 0.05 are shown in **bold**

Region	**Planktivore**						**Carnivore**					
	Mean (± SE)			*t* p(MC)			Mean (± SE)			*t* p(MC)		
	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019
1. Geraldton	0.06	0.06	0.19	-	1.00	0.58	0.31	2.00	1.50	3.76	2.71	1.07
	(0.06)	(0.06)	(0.19)	0.39	0.60	-	(0.12)	(0.47)	(0.52)	**0.03**	0.08	0.36
2. Jurien Bay	-	-	-	-	-	-	1.13	2.38	2.88	2.81	3.93	0.78
	-	-	-	-	-	0.39	(0.30)	(0.56)	(0.24)	0.07	**0.03**	0.49
3. Perth	0.19	0.13	0.13	1.00	1.00	Negative	1.50	2.00	2.06	0.57	0.76	0.20
	(0.12)	(0.13)	(0.07)	0.38	-	0.52	(0.44)	(0.93)	(0.66)	0.61	0.49	0.86
4. SW Capes	0.19	0.38	0.42	0.73	0.65	1.00	1.63	2.75	3.17	3.12	1.31	0.15
	(0.12)	(0.16)	(0.22)	0.58	0.42	0.57	(0.31)	(0.62)	(1.54)	0.05	0.33	0.89
5. Albany	0.50	0.69	0.94	0.63	1.58	1.73	4.75	5.19	4.75	0.30	-	0.32
	(0.23)	(0.12)	(0.06)	0.22	0.19	0.42	(0.53)	(1.03)	(0.51)	0.78	-	0.78
6. Bremer Bay	0.56	0.31	0.81	0.93	1.73	1.85	5.38	5.44	5.56	0.29	0.32	0.23
	(0.19)	(0.24)	(0.06)	0.18	0.17	1.00	(0.36)	(0.34)	(0.39)	0.78	0.77	0.83
7. Esperance	0.75	0.75	1.00	0.00	2.45	2.45	4.13	4.31	6.25	0.34	4.21	16.19
	(0.10)	(0.10)	(0.00)	0.09	0.10	0.14	(0.55)	(0.31)	(0.23)	0.76	**0.03**	**<0.01**

Region	Invertivore						Omnivore					
		Mean			*t*			Mean			*t*	
		(±SE)			p(MC)			(± SE)			p(MC)	
	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019
1. Geraldton	1.94	5.50	4.88	3.73	6.08	1.07	2.00	4.25	3.56	4.81	3.10	2.67
	(0.30)	(0.66)	(0.26)	**0.03**	**0.01**	0.36	(0.29)	(0.31)	(0.33)	**0.02**	0.06	0.08
2. Jurien Bay	4.94	6.75	8.06	1.84	2.56	1.53	4.44	5.19	4.81	3.00	0.81	1.73
	(0.95)	(0.40)	(1.23)	0.17	0.08	0.22	(0.33)	(0.12)	(0.16)	0.06	0.48	0.19
3. Perth	5.38	7.81	7.19	2.50	1.03	0.76	4.19	4.44	3.88	1.41	1.00	1.90
	(1.38)	(0.47)	(0.73)	0.09	0.38	0.50	(0.47)	(0.44)	(0.41)	0.26	0.39	0.15
4. SW Capes	3.31	6.19	5.92	1.90	2.36	0.55	3.69	4.69	4.50	1.96	1.61	1.15
	(0.48)	(1.96)	(1.18)	0.15	0.14	0.64	(0.43)	(0.41)	(0.14)	0.15	0.26	0.37
5. Albany	7.69	8.38	7.63	0.35	0.06	0.25	4.69	5.00	5.25	0.66	1.36	0.34
	(0.56)	(1.49)	(1.65)	0.76	0.96	0.82	(0.28)	(0.23)	(0.53)	0.56	0.27	0.77
6. Bremer Bay	6.81	8.56	8.19	2.36	3.67	0.51	4.63	5.06	5.19	1.33	2.03	0.77
	(0.50)	(0.95)	(0.68)	0.10	**0.03**	0.64	(0.22)	(0.41)	(0.28)	0.27	0.13	0.49
7. Esperance	5.56	7.44	8.38	3.57	6.81	4.39	4.00	4.56	5.25	1.45	4.63	1.84
	(0.06)	(0.47)	(0.38)	**0.04**	**0.01**	**0.02**	(0.18)	(0.31)	(0.23)	0.25	**0.02**	0.16

Region	Browsing Herbivore						Scraping Herbivore					
	Mean (± SE)			t p(MC)			Mean (± SE)			t p(MC)		
	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019
1. Geraldton	2.31	3.31	3.25	4.90	2.72	0.13	0.25	0.69	1.06	2.05	2.93	3.00
	(0.52)	(0.33)	(0.74)	**0.02**	0.08	0.91	(0.18)	(0.21)	(0.31)	0.13	0.06	0.06
2. Jurien Bay	1.06	2.63	2.19	3.17	2.43	1.40	-	0.13	0.13	1.73	1.73	-
	(0.49)	(0.22)	(0.19)	**0.05**	0.09	0.25	-	(0.07)	(0.07)	0.18	0.18	-
3. Perth	1.88	2.44	2.31	4.70	1.00	0.23	-	0.19	0.06	1.00	1.00	1.00
	(0.41)	(0.49)	(0.43)	**0.02**	0.39	0.83	-	(0.19)	(0.06)	0.39	0.39	0.39
4. SW Capes	1.25	1.94	1.83	1.62	0.97	1.15	-	0.06	-	1.00	-	1.00
	(0.10)	(0.43)	(0.65)	0.20	0.43	0.36	-	(0.06)	-	0.40	-	0.42
5. Albany	2.94	2.06	2.13	1.38	2.10	0.15	-	-	-	-	-	-
	(0.33)	(0.40)	(0.07)	0.26	0.13	0.89	-	-	-	-	-	-
6. Bremer Bay	2.56	2.44	2.75	0.77	0.68	0.87	-	-	-	-	-	-
	(0.12)	(0.24)	(0.34)	0.49	0.55	0.45	-	-	-	-	-	-
7. Esperance	2.94	3.31	3.69	5.20	2.78	1.13	-	-	-	-	-	-
	(0.28)	(0.33)	(0.06)	**0.01**	0.07	0.34	-	-	-	-	-	-

Table S.3.8. **Habitat post-hoc tests:** Mean (± SE) number of species and pairwise tests on the interaction between year and region (on dispersion-weighted, square-root transformed densities) for each habitat variable (*Ecklonia radiata* cover, non-*Ecklonia* canopy cover, understorey algae cover and turf and foliose algae cover). The three sampling years are 2006, 2015 and 2019 and the regions are Geraldton, Jurien Bay, Perth, South-West Capes, Albany, Bremer Bay, Esperance. Significant p-values at α = 0.05 are shown in **bold**

Region	***Ecklonia radiata* Cover**						**Non-*Ecklonia* Canopy Cover**					
	Mean (± SE)			*t* p(perm)			Mean (± SE)			*t* p(perm)		
	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019
1. Geraldton	3.33	1.01	0.33	2.79	3.34	1.72	2.82	2.00	3.02	0.69	0.26	1.85
	(0.92)	(0.58)	(0.18)	0.08	**0.04**	0.18	(1.31)	(0.73)	(0.86)	0.55	0.95	0.16
2. Jurien Bay	0.87	1.64	2.20	5.58	4.43	1.79	3.07	1.64	4.26	1.71	2.00	5.47
	(0.26)	(0.26)	(0.45)	**0.02**	**0.02**	0.16	(0.50)	(0.40)	(0.19)	0.18	0.12	**0.02**
3. Perth	3.82	3.43	3.33	0.60	0.25	0.64	1.85	1.78	3.19	0.09	1.43	4.48
	(1.01)	(0.56)	(0.44)	0.60	0.81	0.54	(0.96)	(0.68)	(0.57)	0.90	0.23	**0.04**
4. SW Capes	2.74	3.12	1.97	1.20	1.08	1.31	3.73	2.18	3.80	6.27	1.38	7.02
	(0.66)	(0.77)	(0.83)	0.37	0.40	0.33	(0.30)	(0.11)	(0.26)	**0.01**	0.31	**<0.01**
5. Albany	2.14	1.92	2.27	0.32	0.14	0.57	4.02	3.20	4.50	3.64	2.53	3.33
	(0.60)	(0.35)	(0.42)	0.77	0.90	0.59	(0.07)	(0.19)	(0.20)	**0.04**	0.10	0.07
6. Bremer Bay	1.64	1.96	1.84	1.72	2.17	0.58	4.54	4.32	4.58	0.69	0.15	3.45
	(0.26)	(0.33)	(0.28)	0.18	0.14	0.60	(0.23)	(0.32)	(0.34)	0.54	0.92	**0.05**
7. Esperance	1.26	2.03	1.57	7.05	1.72	1.58	5.15	4.78	5.02	3.77	0.48	0.86
	(0.11)	(0.14)	(0.26)	**0.01**	0.19	0.22	(0.19)	(0.22)	(0.10)	**0.04**	0.63	0.46

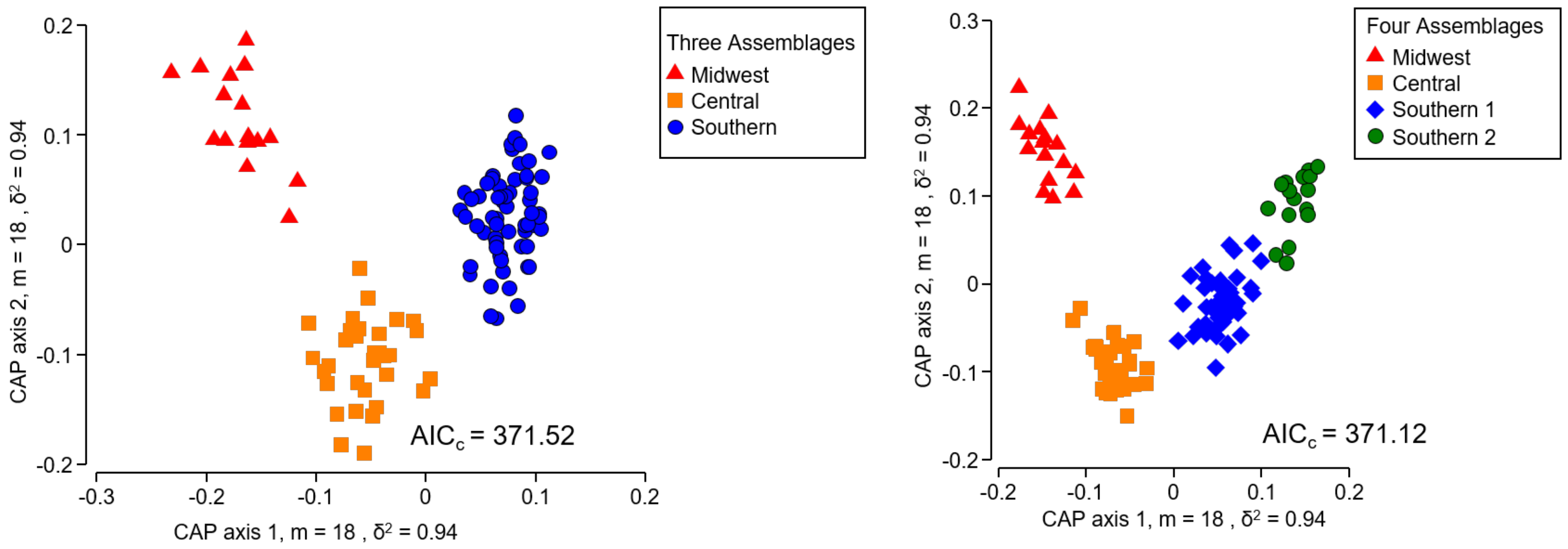
	Understorey Algae Cover						Turf and Foliose Algae					
Region		Mean			*t*			Mean			*t*	
		(± SE)			p(perm)			(± SE)			p(perm)	
	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019	2006	2015	2019	2006 - 2015	2006 - 2019	2015 - 2019
1. Geraldton	1.92	2.90	4.59	2.53	3.57	1.73	0.15	0.62	0.67	8.11	5.04	0.23
	(0.24)	(0.43)	(0.46)	0.10	**0.05**	0.19	(0.04)	(0.05)	(0.14)	**0.01**	**<0.01**	0.84
2. Jurien Bay	3.67	5.01	3.46	1.95	0.39	10.22	0.53	0.74	0.61	1.35	0.74	7.54
	(0.71)	(0.15)	(0.22)	0.09	0.73	**<0.01**	(0.11)	(0.06)	(0.04)	0.28	0.54	**0.01**
3. Perth	1.74	3.48	2.84	4.89	2.21	1.36	0.35	0.61	0.57	3.35	2.10	0.16
	(0.67)	(0.47)	(0.71)	**0.03**	0.12	0.25	(0.08)	(0.14)	(0.08)	0.06	0.11	0.85
4. SW Capes	1.74	3.04	3.28	5.44	2.24	0.98	0.13	0.71	0.64	6.95	5.87	2.60
	(0.55)	(0.57)	(0.46)	**0.02**	0.15	0.43	(0.04)	(0.08)	(0.03)	**0.01**	0.06	0.16
5. Albany	2.89	3.07	2.48	0.37	0.75	1.44	0.56	0.62	0.52	0.68	1.21	1.21
	(0.37)	(0.21)	(0.25)	0.71	0.51	0.25	(0.05)	(0.04)	(0.04)	0.56	0.32	0.30
6. Bremer Bay	2.14	2.14	2.62	0.01	1.20	1.33	0.43	0.51	0.59	0.53	1.95	0.84
	(0.40)	(0.34)	(0.28)	0.97	0.34	0.25	(0.08)	(0.09)	(0.02)	0.61	0.15	0.55
7. Esperance	1.20	1.54	2.02	2.00	2.71	1.12	0.33	0.28	0.40	0.68	0.49	1.33
	(0.15)	(0.30)	(0.15)	0.11	0.09	0.34	(0.05)	(0.09)	(0.12)	0.57	0.65	0.29

Table S.3.9. Marginal tests: Individual marginal tests for environmental and habitat variables included in the DISTLM analysis (reef cover, reef type, *Ecklonia radiata* cover, non-*Ecklonia* canopy cover, understorey algae cover, turf and foliose algae cover, hard coral cover, seagrass presence and sea surface temperature)

Environmental Variable	Sum of Squares (trace)	Pseudo-F	p	Proportion
Reef Cover	2479.6	1.162	0.2618	0.014
Reef Type	41304.0	24.967	0.0001	0.236
Ecklonia radiata Cover	5434.4	2.591	0.0176	0.031
Non-*Ecklonia radiata* (Canopy) Cover	19561.0	10.173	0.0001	0.112
Understorey Algae Cover	19377.0	10.066	0.0001	0.111
Hard Coral Cover	4248.8	2.012	0.0503	0.024
Seagrass Presence	11154.0	5.504	0.0003	0.064
Sea Surface Temperature	55715.0	37.736	0.0001	0.318

Table S.3.10. Alternate best models: Alternate best models produced by the DISTLM analysis within two AIC_c of the optimum model

AICc	R^2	Number of variables	Selections
600.99	0.455	7	Reef Cover, Reef Type, *Ecklonia* Cover, Canopy Cover, Understorey Algae Cover, Hard Coral Cover, SST
601.20	0.467	8	Reef Cover, Reef Type, *Ecklonia* Cover, Canopy Cover, Understorey Algae Cover, Hard Coral Cover, Seagrass Presence, SST
601.21	0.454	7	Reef Type, *Ecklonia* Cover, Canopy Cover, Understorey Algae Cover, Hard Coral Cover, Seagrass Presence, SST
601.50	0.425	5	Reef Type, *Ecklonia* Cover, Canopy Cover, Understorey Algae Cover, SST
601.65	0.424	5	Reef Type, *Ecklonia* Cover, Understorey Algae Cover, Hard Coral Cover, SST



Assemblages	1	2	3	Total	%correct
Midwest	15	1	0	16	93.75
Central	0	32	0	32	100
Southern	0	0	60	60	100

Assemblages	1	2	3	4	Total	%correct
Midwest	15	1	0	0	16	93.75
Central	0	32	0	0	32	100
Southern 1	0	1	42	1	44	95.455
Southern 2	0	0	0	16	16	100

Figure S.4.3. (A) Canonical Analysis of Principal Coordinates (CAP) plot of shallow-water reef fish assemblages using data collected in 2019 constrained by the ‘four bioregion’ assemblage structure: Midwest (Geraldton), Central (Jurien Bay and Perth), Southwest 1 (South-West Capes, Albany and Bremer Bay) and Southwest 2 (Esperance) (m = 37, n = 108) as a factor of groups. The resulting leave-one-out allocation success of observations is also shown. (B) Canonical Analysis of Principal Coordinates (CAP) plot of shallow-water reef fish assemblages using the ‘three bioregion’ assemblage structure: Midwest (Geraldton), Central (Jurien Bay and Perth) and Southwest (South-West Capes, Albany, Bremer Bay and Esperance) (m = 18, n = 108) as a factor of groups. The resulting leave-one-out allocation success of observations is also shown.

Overall Species Table

Table S. 1 Family, Genus, Species and Common Name of all 147 species of shallow-water reef fish identified in this study. The thermal affinity, level of endemism, trophic group, the abundance of each species over the entire survey area and frequency (percentage of sites (n = 112) at which the species was observed) are also recorded for each species

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
Acanthuridae	*Acanthurus grammoptilus*	Inshore Surgeonfish	8	5	26.64	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2014	Indo-Pacific	Bray, 2019	Browsing Herbivore	Richardson 1843
Aplodactylidae	*Aplodactylus westralis*	Western Seacarp	76	66	19.32	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2015	Western Australia	Fairclough et al. 2011	Browsing Herbivore	Shepherd et al. 2005
Apogonidae	*Ostorhinchus rueppellii*	Western Gobbleguts	10	3	21.05	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2016	Indo-Pacific	Froese and Pauly, 2019 Paxton et al. 1989	Invertivore	Poh et al. 2018
	Ostorhinchus victoriae	Western Striped Cardinalfish	13	9	20.77	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2017	Western Australia	Bray, 2019	Invertivore	Paxton et al. 1989
Aulopidae	*Latropiscis purpurissatus*	Sergeant Baker	21	21	19.41	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2018	Australia	Bray and Gormon, 2018	Carnivore	Paxton & Niem 1999
Berycidae	*Centroberyx gerrardi*	Bright Redfish	1	1	17.60	Stuart-Smith et al. 2015 Edgar and	Australia	Bray, 2017	Carnivore	May & Maxwell 1986

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2019				
	Centroberyx lineatus	Swallowtail	13125	87	18.51	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2020	Indo-Pacific	Froese and Pauly, 2019 May and Maxwell, 1986	Carnivore	May & Maxwell 1986
Blenniidae	*Blenniidae sp*	Blenny	102	42	-	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2021	Indo-Pacific	Froese and Pauly, 2019 Nelson, 1994	Browsing Herbivore	Nelson 1994
Carangidae	*Seriola dumerili*	Amberjack	7	4	17.68	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2022	Other	Froese and Pauly, 2019 Paxton et al. 1989	Carnivore	Paxton et al. 1989
	Seriola hippos	Samsonfish	27	14	20.70	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2023	Indo-Pacific	Froese and Pauly, 2019 Paxton et al. 1989	Carnivore	Fairclough et al. 2011
	Seriola lalandi	Yellowtail Kingfish	3	2	21.28	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2024	Other	Froese and Pauly, 2019 Paxton et al. 1989	Carnivore	Paxton et al. 1989
Chaetodontidae	*Chaetodon assarius*	Western Butterflyfish	70	42	21.63	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2025	Western Australia	Fairclough et al. 2011	Omnivore	Fairclough et al. 2011
	Chelmonops curiosus	Western Talma	425	305	19.39	Stuart-Smith et al. 2015 Edgar and	Australia	Bray and Gormon, 2018	Invertivore	Fairclough et al. 2011

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2026				
	Heniochus acuminatus	Longfin Bannerfish	7	7	25.41	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2027	Indo-Pacific	Froese and Pauly, 2019 Steene, 1978	Invertivore	Steene 1978
Cheilodactylidae	*Dactylophora nigricans*	Dusky Morwong	99	86	17.43	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2028	Australia	Froese and Pauly, 2019 May and Maxwell, 1986	Invertivore	May & Maxwell 1986
	Nemadactylus valenciennesi	Blue Morwong	279	209	17.86	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2029	Australia	Bray, 2019	Carnivore	Bell 1979
Dasyatidae	*Bathytoshia brevicaudata*	Smooth Stingray	3	3	17.89	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2030	Indo-Pacific	Froese and Pauly, 2019 Last et al. 2016	Invertivore	Last et al. 2016
	Bathytoshia lata	Black Stingray	1	1	20.20	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2031	Indo-Pacific	Froese and Pauly, 2019 Compagno, 1999	Carnivore	Last et al. 2016 Michael 1993
Dinolestes	*Dinolestes lewini*	Longfin Pike	662	143	16.85	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2032	Australia	Froese and Pauly, 2019 Nelson, 1984	Carnivore	Nelson 1984
Diodontidae	*Diodon nicthemerus*	Globefish	2	2	15.15	Stuart-Smith et al. 2015 Edgar and	Australia	Bray, 2019	Carnivore	Bray 2020

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2033				
Enoplosidae	*Enoplosus armatus*	Old Wife	1232	206	18.29	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2034	Australia	Bray, 2018	Invertivore	Fairclough et al. 2011
Gerreidae	*Parequula Melbournensis*	Silverbelly	36	18	17.16	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2035	Australia	Bray, 2018	Invertivore	Iwatsuki et al. 2012
Glaucosomatidae	*Glaucosoma hebraicum*	Western Australian Dhufish	102	60	20.96	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2036	Western Australia	Fairclough et al. 2011	Carnivore	Fairclough et al. 2011
Haemulidae	*Plectorhinchus flavomaculatus*	Goldspotted Sweetlips	222	165	21.81	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2037	Indo-Pacific	Bray, 2018	Invertivore	Fairclough et al. 2011
	Diagramma pictum	Painted Sweetlips	7	6	26.19	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2038	Indo-Pacific	Froese and Pauly, 2019 Randall et al. 1990	Invertivore	Randall et al. 1990
	Plectorhinchus caeruleonothus	Blue Bastard	4	4	25.00	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2039	Australia	Bray, 2017	Invertivore	Fairclough et al. 2011
Heterodontidae	*Heterodontus portusjacksoni*	Port Jackson Shark	3	3	18.61	Stuart-Smith et al. 2015 Edgar and	Australia	Froese and Pauly, 2019	Carnivore	Fairclough et al. 2011

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2040		Compagno, 1984		
Kyphosidae	*Girella tephraeops*	Western Rock Blackfish	174	92	19.31	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2041	Western Australia	Fairclough et al. 2011	Browsing Herbivore	Gomon et al. 1994
	Girella zebra	Zebrafish	2361	485	16.41	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2042	Australia	Bray, 2018	Browsing Herbivore	Scott et al. 1974
	Kyphosus bigibbus / cornelii / vaigiensis	Western Buffalo Bream	3733	464	22.01	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2043	Western Australia	Fairclough et al. 2011	Browsing Herbivore	Masuda et al. 1993
	Kyphosus sydneyanus / gladius	Silver Drummer	4695	638	19.15	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2044	Indo-Pacific	Froese and Pauly, 2019 Knudsen and Clements, 2013	Browsing Herbivore	Knudsen & Clements 2013
Labridae	*Achoerodus gouldii*	Western Blue Groper	639	343	17.68	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2045	Australia	Bray, 2018	Invertivore	Sheperd 2007
	Anampses geographicus	Scribbled Wrasse	419	83	21.82	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2046	Indo-Pacific	Froese and Pauly, 2019 Westneat, 2001	Invertivore	Fish Base 2018

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
	Anampses melanurus	Blacktail Wrasse	3	2	26.70	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2047	Indo-Pacific	Froese and Pauly, 2019 Myers, 1991	Invertivore	Hodge et al. 2012
	Austrolabrus maculatus	Blackspotted Wrasse	808	411	19.78	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2048	Australia	Bray, 2018	Invertivore	Fairclough et al. 2011
	Bodianus frenchii	Western Foxfish	244	187	20.68	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2049	Australia	Gomon and Bray, 2019	Invertivore	Platell et al. 2010
	Scarus frenatus	Sixband Parrotfish	2	2	24.76	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2050	Indo-Pacific	Bray, 2018	Scraping Herbivore	Fish Base 2018
	Choerodon rubescens	Baldchin Groper	226	159	21.17	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2051	Western Australia	Fairclough et al. 2011	Invertivore	Cure 2016 Lek 2004
	Coris auricularis	Western King Wrasse	19227	1643	20.79	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2052	Western Australia	Fairclough et al. 2011	Omnivore	Lek et al. 2011
	Dotalabrus alleni	Little Rainbow Wrasse	264	149	20.39	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2053	Western Australia	Fairclough et al. 2011	Carnivore	Bray 2017

Family	Genus Species	Common Name	Abund- ance	Frequ- ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
	Dotalabrus aurantiacus	Castelnau's Wrasse	51	38	15.47	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2054	Australia	Bray, 2018	Carnivore	Western Australian Museum 2020
	Eupetrichthys angustipes	Snakeskin Wrasse	14	11	19.25	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2055	Australia	Bray, 2018	Carnivore	Bray 2018
	Halichoeres brownfieldi	Brownfield's Wrasse	808	309	20.85	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2056	Western Australia	Fairclough et al. 2011	Invertivore	Fairclough et al. 2011
	Labroides dimidiatus	Common Cleanerfish	18	13	23.80	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2057	Indo-Pacific	Froese and Pauly, 2019 Randall et al. 1990	Invertivore	Grutter 1997
	Notolabrus parilus	Brownspotted Wrasse	4138	1784	20.25	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2058	Australia	Bray, 2020	Omnivore	Lek et al. 2011
	Ophthalmolepis lineolatus	Southern Maori Wrasse	2732	1009	19.34	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2059	Australia	Bray, 2019	Omnivore	Lek et al.2011
	Pictilabrus laticlavius	Senator Wrasse	205	155	16.74	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2060	Australia	Bray, 2018	Invertivore	Fairclough et al. 2011

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
	Pseudojuloides elongatus	Long Green Wrasse	2	2	19.92	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2061	Indo-Pacific	Bray, 2018	Invertivore	Bray 2020
	Pseudolabrus biserialis	Redband Wrasse	3809	1123	20.59	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2062	Western Australia	Fairclough et al. 2011	Invertivore	Fairclough et al. 2011
	Pseudolabrus rubicundus	Rosy Wrasse	1	1	15.47	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2063	Australia	Bray, 2018	Carnivore	Bray 2018
	Scarus rivulatus	Surf Parrotfish	2	2	25.65	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2064	Indo-Pacific	Froese and Pauly, 2019 Randall and Choat, 1980	Scraping Herbivore	Randall & Choat 1980
	Stethojulis bandanensis	Redspot Wrasse	3	3	23.85	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2065	Indo-Pacific	Bray, 2018	Invertivore	Randall 2000
	Stethojulis interrupta	Brokenline Wrasse	1	1	20.88	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2066	Indo-Pacific	Froese and Pauly, 2019 Randall, 2000	Invertivore	Bray 2018
	Stethojulis strigiventer	Silverstreak Wrasse	3	2	23.59	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2067	Indo-Pacific	Froese and Pauly, 2019 Randall, 2000	Invertivore	Randall 2000

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
	Suezichthys cyanolaemus	Bluethroat Rainbow Wrasse	9	8	21.00	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2068	Western Australia	Fairclough et al. 2011	Omnivore	Bray 2020
	Thalassoma lunare	Moon Wrasse	65	45	22.79	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2069	Indo-Pacific	Bray, 2018	Carnivore	Holmes et al. 2012 Connell 2000
	Thalassoma lutescens	Green Moon Wrasse	283	89	23.03	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2070	Indo-Pacific	Bray, 2018	Carnivore	Fish Base 2018 Bray 2017
	Thalassoma septemfasciatum	Sevenband Wrasse	120	81	21.04	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2071	Western Australia	Bray, 2018	Invertivore	Fairclough et al. 2011
Latidae	*Psammoperca waigiensis*	Waigieu Seaperch	39	28	24.85	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2072	Indo-Pacific	Froese and Pauly, 2019 Randall et al. 1990	Carnivore	Fairclough et al. 2011
Latridae	*Goniistius gibbosus*	Magpie Morwong	73	59	20.37	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2073	Western Australia	Fairclough et al. 2011	Invertivore	Gomon et al. 1994
	Pseudogoniistius nigripes	Magpie Perch	41	39	16.12	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2074	Australia	Bray, 2019	Invertivore	Bray 2019

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
	Goniistius rubrolabiatus	Redlip Morwong	221	190	20.61	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2075	Western Australia	Bray , 2019	Invertivore	Eschmeyer 1999
Lethrinidae	*Lethrinus laticaudis*	Grass Emperor	1	1	28.01	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2076	Indo-Pacific	Froese and Pauly, 2019 Carpenter and Allen, 1989	Generalist Carnivores	Carpenter and Allen 1989; Nguyen and Nguyen 2006
Lutjanidae	*Lutjanus bohar*	Red Bass	1	1	26.07	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2077	Indo-Pacific	Froese and Pauly, 2019 Allen, 1985	Carnivore	Western Australian Museum 2020
	Lutjanus carponotatus	Stripey Snapper	2	2	26.87	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2078	Indo-Pacific	Bray, 2017	Generalist Carnivores	Allen and Erdmann 2012
Monacanthidae	*Acanthaluteres brownii*	Spinytail Leatherjacket	65	19	17.82	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2079	Australia	Bray, 2018	Invertivore	Fairclough et al. 2011
	Acanthaluteres vittiger	Toothbrush Leatherjacket	3	3	15.39	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2080	Australia	Bray, 2018	Browsing Herbivore	May & Maxwell 1986
	Eubalichthys caeruleoguttatus	Bluespotted Leatherjacket	3	1	22.11	Stuart-Smith et al. 2015 Edgar and	Australia	Bray, 2018	Omnivore	Malcolm et al. 2007

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2081				
	Eubalichthys cyanoura	Bluetail Leatherjacket	9	5	20.25	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2082	Australia	Bray, 2017	Omnivore	Malcolm et al. 2007
	Eubalichthys gunnii	Gunn' s Leatherjacket	1	1	15.48	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2083	Australia	Bray, 2018	Omnivore	Malcolm et al. 2007
	Eubalichthys mosaicus	Mosaic Leatherjacket	3	3	18.92	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2084	Australia	Bray, 2018	Omnivore	Malcolm et al. 2007
	Meuschenia flavolineata	Yellowstriped Leatherjacket	737	392	17.91	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2085	Australia	Bray, 2018	Carnivore	Bray 2020
	Meuschenia freycineti	Sixspine Leatherjacket	36	25	16.96	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2086	Australia	Bray, 2017	Omnivore	Fairclough et al. 2011
	Meuschenia galii	Bluelined Leatherjacket	226	175	19.02	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2087	Australia	Bray, 2018	Carnivore	Fairclough et al. 2011
	Meuschenia hippocrepis	Horseshoe Leatherjacket	109	73	17.14	Stuart-Smith et al. 2015 Edgar and	Australia	Bray, 2018	Carnivore	Fairclough et al. 2011

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2088				
	Meuschenia venusta	Stars and Stripes Leatherjacket	11	4	18.49	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2089	Australia	Bray, 2019	Omnivore	Malcolm et al. 2007
	Scobinichthys granulatus	Rough Leatherjacket	13	11	18.79	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2090	Australia	Bray, 2018	Omnivore	Fairclough et al. 2011
Mullidae	*Upeneichthys vlamingii*	Bluespotted Goatfish	318	186	16.65	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2091	Australia	Bray, 2018	Invertivore	Fairclough et al. 2011
	Parupeneus chrysopleuron	Rosy Goatfish	4	4	21.03	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2092	Indo-Pacific	Froese and Pauly, 2019 Randall, 2004	Invertivore	Fairclough et al. 2011
	Parupeneus spilurus	Blacksaddle Goatfish	123	58	20.25	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2093	Indo-Pacific	Froese and Pauly, 2019 Randall et al. 1990	Invertivore	Kuiter 1993
Muraenidae	*Gymnothorax woodwardi*	Woodward's Moray	1	1	18.00	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2094	Western Australia	Fairclough et al. 2011	Carnivore	Fairclough et al. 2011
Myliobatiformes	*Myliobatis tenuicaudatus*	Southern Eagle Ray	1	1	20.90	Stuart-Smith et al. 2015 Edgar and	Indo-Pacific	Bray, 2018	Invertivore	Francis 1993

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2095				
Nemipteridae	*Pentapodus vitta*	Western Butterfish	67	39	21.66	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2096	Western Australia	Fairclough et al. 2011	Invertivore	Lieske and Myers 1994
Neosebastidae	*Neosebastes pandus*	Bighead Gurnard Perch	2	2	20.23	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2097	Australia	Froese and Pauly, 2019 Motomura, 2003	Invertivore	Greenwell et al 2018
Odacidae	*Haletta semifasciata*	Blue Weed-whiting	2	2	15.60	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2098	Australia	Bray, 2018	Omnivore	Bray 2020
	Heteroscarus acroptilus	Rainbow Cale	44	37	18.11	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2099	Australia	Bray, 2017	Omnivore	Gomon & Paxton 1985
	Olisthops cyanomelas	Herring Cale	1808	828	17.56	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2100	Australia	Froese and Pauly, 2019 Gomon and Paxton, 1985	Invertivore	Fairclough et al. 2011
Orectolobidae	*Orectolobus maculatus*	Spotted Wobbegong	1	1	20.39	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2101	Australia	Bray, 2018	Carnivore	Western Australian Museum 2020
Ostraciidae	*Anoplocapros amygdaloides*	Blue Boxfish	7	7	20.61	Stuart-Smith et al. 2015 Edgar and	Australia	Bray, 2018	Carnivore	Fairclough et al. 2011

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2102				
	Anoplocapros lenticularis	Whitebarred Boxfish	14	12	19.96	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2103	Australia	Bray, 2019	Carnivore	Bray 2020
	Aracana aurita	Shaw's Cowfish	6	6	14.46	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2104	Australia	Bray, 2018	Carnivore	Bray 2018
	Aracana ornata	Ornate Cowfish	2	2	15.61	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2105	Australia	Bray, 2017	Carnivore	Bray 2017
Parascyllidae	*Parascyllium variolatum*	Carpetshark	1	1	17.15	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2106	Australia	Bray, 2018	Carnivore	Bray 2018
Pentacerotidae	*Paristiopterus gallipavo*	Yellowspotted Boarfish	3	2	19.65	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2107	Australia	Bray, 2019	Carnivore	Bray 2020
	Pentaceropsis recurvirostris	Longsnout Boarfish	9	9	15.38	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2108	Australia	Bray, 2018	Omnivore	Robins et al. 1991
Pinguipedidae	*Parapercis haackei*	Wavy Grubfish	2	2	20.20	Stuart-Smith et al. 2015 Edgar and	Australia	Bray, 2018	Invertivore	Fairclough et al. 2011

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2109				
Plesiopidae	*Paraplesiops meleagris*	Southern Blue Devil	27	23	18.91	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2110	Australia	Bray, 2018	Carnivore	Western Australian Museum 2020
Plotosidae	*Cnidoglanis macrocephalus*	Estuary Cobbler	1	1	19.33	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2111	Australia	Gomon and Bray, 2018	Omnivore	Gomon & Bray 2018
Pomacanthidae	*Pomacanthus semicirculatus*	Blue Angelfish	3	3	25.01	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2112	Indo-Pacific	Froese and Pauly, 2019 Myers, 1991	Omnivore	Bray 2020
Pomacentridae	*Abudefduf bengalensis*	Bengal Sergeant	372	80	25.98	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2113	Indo-Pacific	Bray, 2018	Omnivore	Western Australian Museum 2020
	Abudefduf septemfasciatus	Banded Sergeant	3	2	26.71	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2114	Indo-Pacific	Bray, 2018	Omnivore	Western Australian Museum 2020
	Abudefduf sexfasciatus	Scissortail Sergeant	41	6	24.26	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2115	Indo-Pacific	Bray, 2018	Browsing Herbivore	Western Australian Museum 2020
	Abudefduf vaigiensis	Indo-Pacific Sergeant	3	2	24.50	Stuart-Smith et al. 2015 Edgar and	Indo-Pacific	Bray, 2018	Omnivore	Allen 1991

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2116				
	Chromis westaustralis	West Australian Puller	180	16	21.02	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2117	Western Australia	Fairclough et al. 2011	Omnivore	Fairclough et al. 2011
	Chromis klunzingeri	Blackhead Puller	38761	738	19.69	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2118	Western Australia	Fairclough et al. 2011	Omnivore	Fairclough et al. 2011
	Dischistodus prosopotaenia	Honeyhead Damsel	2	1	26.28	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2119	Indo-Pacific	Froese and Pauly, 2019 Allen, 1991	Omnivore	Allen 1991
	Pomacentrus coelestis	Blue Damsel	3	3	22.07	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2120	Indo-Pacific	Froese and Pauly, 2019 Allen, 1991	Invertivore	Allen 1991
	Neopomace-ntrus aktites	Western Australian Demoiselle	50	7	26.30	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2121	Western Australia	Bray, 2018	Planktivore	Bray 2018
	Neopomacen-trus azysron	Yellowtail Damoiselle	4	1	26.59	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2122	Indo-Pacific	Froese and Pauly, 2019 Allen, 1991	Planktivore	Allen 1991
	Parma bicolor	Bicolor Scalyfin	6	5	20.76	Stuart-Smith et al. 2015 Edgar and	Australia	Froese and Pauly, 2019 Allen, 1991	Omnivore	Allen 1991

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2123				
	Parma mccullochi	McCulloch's Scalyfin	4807	1738	20.73	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2124	Western Australia	Fairclough et al. 2011	Omnivore	Fairclough et al. 2011
	Pomacentrus milleri	Miller's Damsel	2904	400	22.62	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2125	Indo-Pacific	Froese and Pauly, 2019 Allen, 1991	Omnivore	Fairclough et al. 2011
	Parma occidentalis	Western Scalyfin	1348	572	20.90	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2126	Western Australia	Fairclough et al. 2011	Browsing Herbivore	Allen 1991
	Parma victoriae	Scalyfin	451	285	16.57	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2127	Australia	Bray, 2018	Browsing Herbivore	Bray 2019
	Stegastes obreptus	Western Gregory	43	24	23.10	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2128	Indo-Pacific	Bray, 2019	Browsing Herbivore	Bray 2019
Pseudochromidae	*Labracinus lineatus*	Lined Dottyback	47	42	21.51	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2129	Western Australia	Fairclough et al. 2011	Carnivore	Fairclough et al. 2011
Scaridae	*Chlorurus sordidus*	Greenfin Parrotfish	9	7	24.90	Stuart-Smith et al. 2015 Edgar and	Indo-Pacific	Bray, 2017	Scraping Herbivore	Fish Base 2018

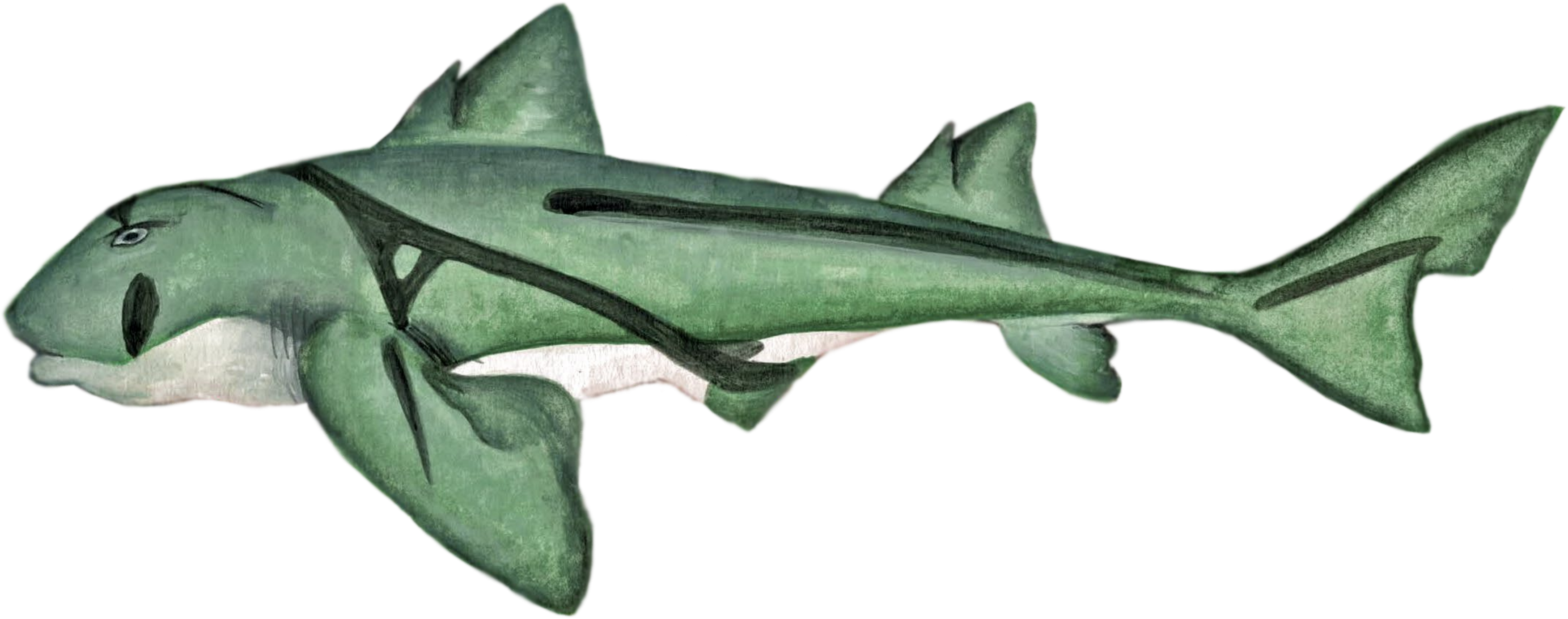
Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2130				
	Scarus ghobban / schlegeli	Bluebarred Parrotfish	232	113	24.48	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2131	Indo-Pacific	Froese and Pauly, 2019 Parenti and Randall, 2000	Scraping Herbivore	Bennett et al. 2015b
Scorpididae	*Microcanthus strigatus*	Stripey	9	3	20.28	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2132	Indo-Pacific	Bray, 2017	Invertivore	Western Australian Museum 2020
	Neatypus obliquus	Footballer Sweep	1074	161	20.37	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2133	Australia	Bray, 2018	Invertivore	Fairclough et al. 2011
	Scorpis aequipinnis	Sea Sweep	1124	418	16.62	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2134	Australia	Bray, 2018	Planktivore	Western Australian Museum 2020
	Scorpis georgiana	Banded Sweep	610	381	20.71	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2135	Australia	Bray, 2017	Invertivore	May & Maxwell 1986
	Tilodon sexfasciatus	Moonlighter	200	118	17.54	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2136	Australia	Bray, 2018	Carnivore	Bray 2018
Serranidae	*Acanthistius serratus*	Western Wirrah	6	5	20.30	Stuart-Smith et al. 2015 Edgar and	Australia	Bray, 2018	Carnivore	Fairclough et al. 2011

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2137				
	Caesioperca rasor	Barber Perch	55	6	15.16	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2138	Australia	Froese and Pauly, 2019 May and Maxwell, 1986	Carnivore	Bray 2020
	Callanthias australis	Splendid Perch	7	4	18.21	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2139	Indo-Pacific	Froese and Pauly, 2019 Anderson, 1999	Invertivore	Anderson 1999
	Epinephelides armatus	Breaksea Cod	500	215	20.76	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2140	Australia	Fairclough et al. 2011	Carnivore	Fairclough et al. 2011
	Epinephelus rivulatus	Chinaman Rockcod	13	13	24.23	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2141	Australia	Fairclough et al. 2011	Carnivore	Craig et al. 2011 Sommer et al. 1996
	Hypoplectrodes nigroruber	Banded Seaperch	4	4	18.80	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2142	Australia	Bray, 2018	Carnivore	Fairclough et al. 2011
	Othos dentex	Harlequin Fish	24	24	18.38	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2143	Australia	Bray, 2018	Carnivore	Fairclough et al. 2011
	Plectropomus leopardus	Common Coral Trout	15	11	25.80	Stuart-Smith et al. 2015 Edgar and	Indo-Pacific	Froese and Pauly, 2019 Heemstra	Carnivore	Heemstra & Randall 1993

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2144		and Randall, 1993		
Siganidae	*Siganus fuscescens*	Black Rabbitfish	2210	52	23.53	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2145	Indo-Pacific	Bray, 2018	Browsing Herbivore	Lieske and Myers 1994 Yamada et al. 1995
Sillaginidae	*Sillago schomburgkii*	Yellowfin Whiting	1	1	19.15	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2146	Australia	Froese and Pauly, 2019 McKay, 1992	Invertivore	McKay 1992
Sparidae	*Chrysophrys auratus*	Snapper	25	10	19.76	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2147	Indo-Pacific	Froese and Pauly, 2019 Paulin, 1990	Invertivore	Paulin 1990
	Rhabdosargus sarba	Tarwhine	335	25	20.15	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2148	Indo-Pacific	Froese and Pauly, 2019 Bauchot and Smith, 1984	Omnivore	Fairclough et al. 2011
Sphyraenidae	*Sphyraena obtusata*	Striped Barracuda	115	46	22.87	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2149	Indo-Pacific	Bray, 2018	Carnivore	May and Maxwell 1986 Senou 2001
	Sphyraena novaehollandiae	Snook	8	3	17.06	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2150	Indo-Pacific	Froese and Pauly, 2019, Myer, 1991	Carnivore	Myers 1991
Terapontidae	*Helotes octolineatus*	Western Striped Grunter	66	1	19.81	Stuart-Smith et al. 2015 Edgar and	Australia	Froese and Pauly, 2019	Omnivore	Fairclough et al. 2011

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2151		Paxton et al. 1989		
	Pelsartia humeralis	Sea Trumpeter	1	1	20.92	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2152	Australia	Bray, 2018	Omnivore	Fairclough et al. 2011
	Arothron hispidus	Stars and Stripes Puffer	1	1	22.71	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2153	Indo-Pacific	Froese and Pauly, 2019 Myers, 1991	Invertivore	Myers 1991
	Arothron reticularis	Reticulate Toadfish	1	1	27.35	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2154	Indo-Pacific	Froese and Pauly, 2019 Masuda et al. 1984	Invertivore	Myers 1991
	Omegophora cyanopunctata	Bluespotted Toadfish	29	28	18.78	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2155	Australia	Bray, 2018	Carnivore	Bray 2020
	Torquigener pleurogramma	Weeping Toadfish	31	7	20.31	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2156	Australia	Bray, 2017	Carnivore	Fairclough et al. 2011
Triglidae	*Chelidonichthys kumu*	Red Gurnard	2	2	19.30	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2157	Indo-Pacific	Froese and Pauly, 2019 Heemstra, 1986	Invertivore	Heemstra 1986
Urolophidae	*Trygonoptera ovalis*	Striped Stingaree	3	3	20.50	Stuart-Smith et al. 2015 Edgar and	Western Australia	Fairclough et al. 2011	Carnivore	Fairclough et al. 2011

Family	Genus Species	Common Name	Abund-ance	Frequ-ency	Thermal Affinity	Supporting reference	Endemism	Supporting reference	Trophic Group	Supporting reference
						Stuart-Smith, 2158				
	Trygonoptera personata	Masked Stingaree	3	3	20.40	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2159	Western Australia	Bray, 2018	Invertivore	Last & Stevens 1994
	Urolophus circularis	Circular Stingaree	1	1	20.00	Stuart-Smith et al. 2015 Edgar and Stuart-Smith, 2160	Western Australia	Fairclough et al. 2011	Invertivore	Bray 2018



Watercolour of a port Jackson shark (*Heterodontus portusjacksoni*) by Savita Goldsworthy