Faculty of Science and Engineering

School of Molecular and Life Sciences

# The Composition of Continental Shelf and Slope Demersal Fish: The Effects of Depth and Latitude

Claire Margaret Wellington

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## Declaration

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

The research presented and reported in this thesis was conducted in compliance with the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes (7th edition, 2004). The proposed research study received animal ethics approval from the University of Western Australia Animal Ethics Committee, Approval reference RA/3/100/1107 and RA/3/100/1051.

Date: 11th November 2019

# Abstract

In Western Australia (WA), deepwater fishes are targeted by commercial and recreational fishers. Deepwater fisheries (~170-700 m) represent a large proportion of the market value of WA fisheries, consequently, impacts to these assemblages will have far-reaching economic and potentially long-lasting ecological effects. There is little information on the status, habitat use, and depth preferences of deepwater species or their connectivity to inshore habitats. Sustainable management requires an understanding of the dynamics of deepwater fisheries and the factors underpinning their structure and distribution.

Because assessments of deepwater ecosystems are logistically challenging, time-consuming and expensive (the requirement for boats big enough to deploy and retrieve sampling equipment to depth), they tend to be data deficient. Many deepwater fishes have an inherent vulnerability to exploitation and environmental shifts due to a combination of life history characteristics and ecology (slow-growing, long life spans, late maturation and physiological constraints). Valuable data is gathered from extractive fishing catch and effort statistics. However, these sources can vary in data quality, target species and spatial scales making broader extrapolations and comparisons regarding ecosystem function problematic. Furthermore, few data sets incorporate environmental parameters such as habitat classification from *in situ* observations.

The marine environment of Western Australia encompasses a wide latitudinal range from tropical to temperate climates, including regions of unique biogeography and are known for high levels of endemism. These marine bioregions encompass features such as offshore islands, reefs, submarine canyons and their proximity to the continental shelf and the length of the continental shelf in a general north/south orientation of the coastline makes Western Australia a good site for investigating factors influencing the structure of deepwater fish assemblages.

This thesis assesses the distribution of deepwater fish assemblages in Western Australia encompassing continental shelf and upper slope depths over a 16° latitudinal range using Baited Remote Underwater Stereo-Video Systems (stereo-BRUVs) as a sampling tool. In doing so, I investigate the factors influencing the distribution, abundance, biomass and length characteristics of deepwater demersal fish to elucidate whether existing ecological paradigms apply to deepwater fish assemblages in Western Australia.

Depth is considered one of the primary drivers influencing the distribution of marine species. In Chapter 2 I examined the influence of depth from an offshore island to the upper slope of the continental shelf which had been incised by a submarine canyon. This sampling encompassed depths from 0-570 m. At this single location, benthic biota, depth and seabed relief explained the greatest proportion of the assemblage variation, with distributions identifying three distinct groups based on depth; corresponding with the continental shelf (5–199 m), margin (200-300 m) and upper slope (300-570 m). At the intersection of the continental margin (200-400 m), large-bodied meso-predators dominated the biomass and assemblage composition in correlation to sessile invertebrates and sponge dominated habitats. This pattern was also evident at six sites across 16° of latitude (Chapter 3) where a minority of larger-bodied species dominated depth ranges at approximately 300 m. Additional environmental parameters from the BRAN ocean model enhanced the explanatory power of covariates (Chapter 3). The fish assemblages were separated into north, mid and south along the western Australian coastline indicating the significant influence of latitude on distributions. Assemblage composition was strongly influenced by latitude and depth with deepwater assemblages becoming more similar with increasing depth. A combination of nine environmental and physical covariates best explained the assemblage distributions across all six surveys. At smaller spatial scales, benthic biota and seabed relief were more important.

The data presented here has contributed to the ecological framework regarding fish distributions globally and is informative for ecosystem related fisheries management spanning the continental shelf and upper slope in Western Australia.

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The shallow water stereo-BRUVs data, used in Chapter 2, from around Rottnest Island was collected through funding provided by an Australian and Western Australian Government Natural Heritage Trust Strategic Project, ‘Securing Western Australia’s Marine Futures’. I’m grateful to South Coast Natural Resource Management Inc. for access to the data and the staff of the Marine Futures team who collected the data. Some of the deepwater samples were collected with financial support from Fisheries Research and Development Corporation (Project 2009/024). Logistic and financial support for this work was provided by the Department of Fisheries, Government of Western Australia; now the Department of Primary Industries and Regional Development (DPIRD), the University of Western Australia, Curtin University and the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

## Statement of Contributors

### *Published chapters*

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**Author contributions:** EH, CW, SN and AW designed the study. CMW conducted the fieldwork, and collected the data, executed the data analyses, wrote and edited the manuscript. TL contributed to the data analysis. All co-authors reviewed and commented on the manuscript.

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**Author contributions:** CW and CMW designed the manuscript. CMW conducted the fieldwork and collected the data, executed the data analyses, and wrote the manuscript. WW provided identification advice. All co-authors edited, reviewed and commented on the manuscript.

### *Chapter in submission*

**Chapter 3:** Wellington, C. M., Harvey, E. S., Wakefield, C. B., Abdo, D., and Newman, S. J. Latitude, depth and environmental variables shape deepwater fish assemblages along the broad and continuous coastline on the west coast of Australia. **Submitted to the *Journal of Experimental Marine Biology and Ecology*.**

**Author contributions:** CMW, EH, CW, and SN designed the study. CMW conducted the fieldwork and collected the data, executed the data analyses and wrote the manuscript. DA contributed the ocean modelling data. Curtin Marine Ecology Lab assisted with video processing. All co-authors reviewed and commented on the manuscript.

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# Chapter 1 Introduction

## *Background and Rationale*

Deepwater (> 170 m) environments represent the largest ecosystem on earth with a vast array of marine organisms, habitats and geological features (Koslow et al., 2000; Koslow, 2007; Danovaro et al., 2010). Deepwater ecosystems around the continental margin (170-300 m) and upper continental slope (300-700 m) are targeted by many commercial and recreational fishers. It is also a zone subject to a number of pressures through fisheries resource extraction, habitat disturbance, industrial development such as oil and gas, pollution and climatic shifts (Levin and Dayton, 2009; Danovaro et al., 2010; Vieira et al., 2015). As these impacts proliferate through the ocean ecosystem, the consequences can include loss of resources (depleted stock levels), loss of biodiversity, and shifts in food webs and habitats (Ramirez-Llodra et al., 2011). The loss of fisheries resources, in particular, has negative economic implications, as well as impacts to the broader marine environment where ecosystem function supports fisheries recovery.

There has been significant progress in research into deepwater habitats in recent decades, facilitated by developments in technology across many industries, but there is still much we do not understand (Levin and Sibuet, 2012; Da Ros et al., 2019). There remain questions about the drivers affecting deepwater fish assemblage diversity and abundance, their interactions with and the influence of environmental factors within these habitats. Ecological theories, in particular, remain comparatively scant and untested with some theories having been adapted from terrestrial or shallow water habitats (Levin and Sibuet, 2012) leaving the ecological significance of deepwater habitats often underestimated. Consequently, there is a need to understand the mechanisms controlling deep sea biodiversity and how future impacts and changes (for example habitat disturbance, marine plastics, pollution and climate change) may alter these ecosystems (Haedrich, 1996; Levin and Dayton, 2009; Ramirez-Llodra et al., 2011).

There is a critical need to understand deepwater fish distributions in an ecosystem-based context as a greater ecological understanding of the principles that govern species and ecosystems in deepwater can yield new insights in the mechanisms that control diversity, distribution and resilience on the continental shelf, margin and upper slope. Recognising how fish assemblage characteristics are influenced in deeper water and linking these understandings to existing knowledge of the shallow water environment will provide an interrelated understanding of how to manage areas of shared resources and use.

This deepwater ecosystem and the fishes that inhabit them are intrinsically linked to oceanic ecosystems globally. Yet, they are fragile with sparse and heterogeneous habitats subject to the same environmental pressures that we see in shallow water environments (Pauly et al., 2005; Compton et al., 2013; Kuhnz et al., 2014). Many deepwater species of fish are inherently vulnerable to fishing exploitation due to their slow growth rates, late maturity and long life spans (Haedrich, 1996; Koslow et al., 2000; Gordon, 2001).

Deepwater sampling is considered time-consuming and expensive due to vessel and equipment requirements as well as logistical complexities in accessing the environment. Scientific studies have used a variety of methods for sampling deepwater fish, the most common of which is trawling, traps and long lines, supplemented with acoustic sampling (Shortis et al., 2008). Valuable data is sourced this way and forms the basis of stock assessment statistics and fisheries resource data (Newman et al., 2015). However, data from extractive techniques such as traps, trawls or lines frequently only collect information on abundance, lengths and weight of target species. By-catch is not consistently recorded, and *in-situ* data such as habitat and other environmental parameters are rarely linked. As with all methods, selectivity exists with each of these approaches; net, hook or trap sizes and other gear choices influence the catch rate and species diversity, as does location and depth range. Such variation can make comparisons between datasets problematic. Traditional methods of sampling, such as demersal trawling, are often indiscriminate and are destructive of the benthos highlighting a need for the development of fishery-independent non-destructive sampling methods (Hutchings, 2000; Amoroso et al., 2018).

There have been great strides in recent decades in the use of underwater cameras, video systems and baited camera systems, facilitated by developments in technology and industry, which have expanded the field of *in-situ* observations and data collection for the assessment of fish assemblages (Priede and Merrett, 1996; Cundy et al., 2017). From the use of remotely operated vehicles (ROVs), autonomous vehicles and landers which can be deployed for months at a time, systems have developed to cater to a wide range of scientific applications (Bailey et al., 2007).

Underwater video techniques are broadening our understanding and knowledge base of fish behaviour, assemblage structure, habitat preferences, and provide an accurate tool for analysis in a non-destructive way (Harvey et al., 2013). Baited remote underwater stereo video systems (stereo-BRUVs) are a fisheries independent sampling tool that can provide a permanent record of a fish assemblage in time with associated habitat. Although any technique utilising bait can have bias, stereo-BRUVs are highly effective at drawing in scavenging fish and subsequent predators while not diminishing the presence of omnivorous and herbivorous species (Harvey et al., 2007).

Baited underwater cameras provide a relatively consistent methodology (Langlois et al., 2018). Calibration gives a high degree of accuracy, trained assessors relieve observer related biases, and stratified designs across a range of habitats mean there is a relatively high degree of representative sampling and comparable results. Abundance estimates can be derived a number of ways, depending on the objectives of the sampling program, locations, depths and treatments. Priede and Merrett (1996) developed the $n_{peak}$ model to estimate absolute density taking into account fish swimming speeds, bait plume and current velocities. Further work by Bailey and Priede (2002) expanded theoretical estimates that took into account variations in foraging behaviours for abyssal scavengers. However, applications of these models in shallow waters produced inverse results where arrival times, species diversity and abundances are much higher. Standard operating procedures across shallow water and shelf depths have therefore adopted MaxN (maximum number of a fish species in the field of view at one time) to derive relative abundance estimates (Harvey et al., 2013).

The stereo-BRUVs cost per unit is relatively cheap, making the method replicable with sets of stereo-BRUVs being deployed at one time. However, to date, a great deal of the underwater visual assessments undertaken have been limited to shallow water deployments.

Generalised trends in deepwater fish assemblage characteristics indicate abundance, biomass and diversity decrease with increasing depth (Stefanescu et al., 1994; Haedrich, 1996). As depth increases, ecological factors such as resource availability, and environmental conditions such as temperature, light and pressure change, altering biological and physiological habitats (Massuti et al., 2004; Farré et al., 2016). A clear distinction in fish assemblage structure exists at 200 metres depth, representing the limit of photosynthesis across much of the ocean and the divide between continental shelf and slope (Bergstad, 1990; Haedrich, 1996). Often, it is the local geographical and biological factors, influenced by the surrounding environment, that have been found to have a dominant influence on assemblage structure, abundance and biomass (Haedrich and Merrett, 1990; Gordon, 2001; Moranta et al., 2004). It, therefore, becomes necessary to study particular geographic locations, in order to comprehend and assess the assemblages within.

There has been relatively little research on deepwater fish assemblages on the west Australian coast (Williams et al., 2001; Last et al., 2011). Governance of fishery related resources in Western Australia is approached through a bioregional boundary structure using an Ecosystem-Based Fishery Management (EBFM) framework (Fletcher and Santoro, 2014). While there has been an emerging deepwater fishery since the 1980s (Wakefield, 2010; Wakefield et al., 2010) there has been only modest commercial interest in the deepwater demersal fish fauna (Jernakoff, 1988; Fletcher and Santoro, 2014).

The Western Australian coastline encompasses a large latitudinal range, covering tropical to temperate biomes, including bathymetry and topographical features such as offshore islands, reefs, submarine canyons, and an accessible continental slope. Distinct assemblage patterns exist for deepwater fish on the west Australian coast delineated by depth and geographic biomes displaying high species diversity and endemism (Fox and Beckley, 2005; Last et al., 2011). The diversity of features makes the west Australian marine environment ideal for investigation into the primary drivers of deepwater fish assemblages.

## *Study Area and Research Design*

The large Western Australian coast (ca 20,000 km) includes a wide latitudinal range (> 20°S) with marine climatic environments spanning tropical regimes in the north to temperate regimes in the south (Hutchins, 1994). The poleward flowing Leeuwin current brings warm, nutrient poor tropical water south along the western coast, and east along the southern coast. Surveys were designed to target geographic features along the continental shelf and upper slope of the west Australian coastline encompassing significant geomorphic features such as submarine canyons, offshore shoals and islands.

Stereo-BRUVs can be used remotely to sample deep habitats, for long periods and in a cost-effective manner (Langlois et al., 2010). These systems, which can be deployed remotely, were found to be a successful and economical way to sample fish assemblages (Cappo et al., 2006). Each survey was designed to collect approximately 20 deployments using stereo-BRUVs adapted for deepwater areas (robust frame, additional weight and illumination) across each 100 m depth range (100-199, 200-299, 300-399, 400-499, 500-599) (Fig. 1.1).

Within each depth range, a diversity of benthic geomorphology and rugosity was sought to sample varying factors of habitat, benthic biota and seabed relief. Specifically, these locations included the Rowley Shoals, Montebello Islands, Ningaloo Reef, Abrolhos Islands, Perth Canyon and the South West Capes (Fig. 1.2).

**Figure 1.1 Photograph illustrating the basic design of the stereo baited remote underwater video system (stereo-BRUVs) adapted for deepwater deployments.**

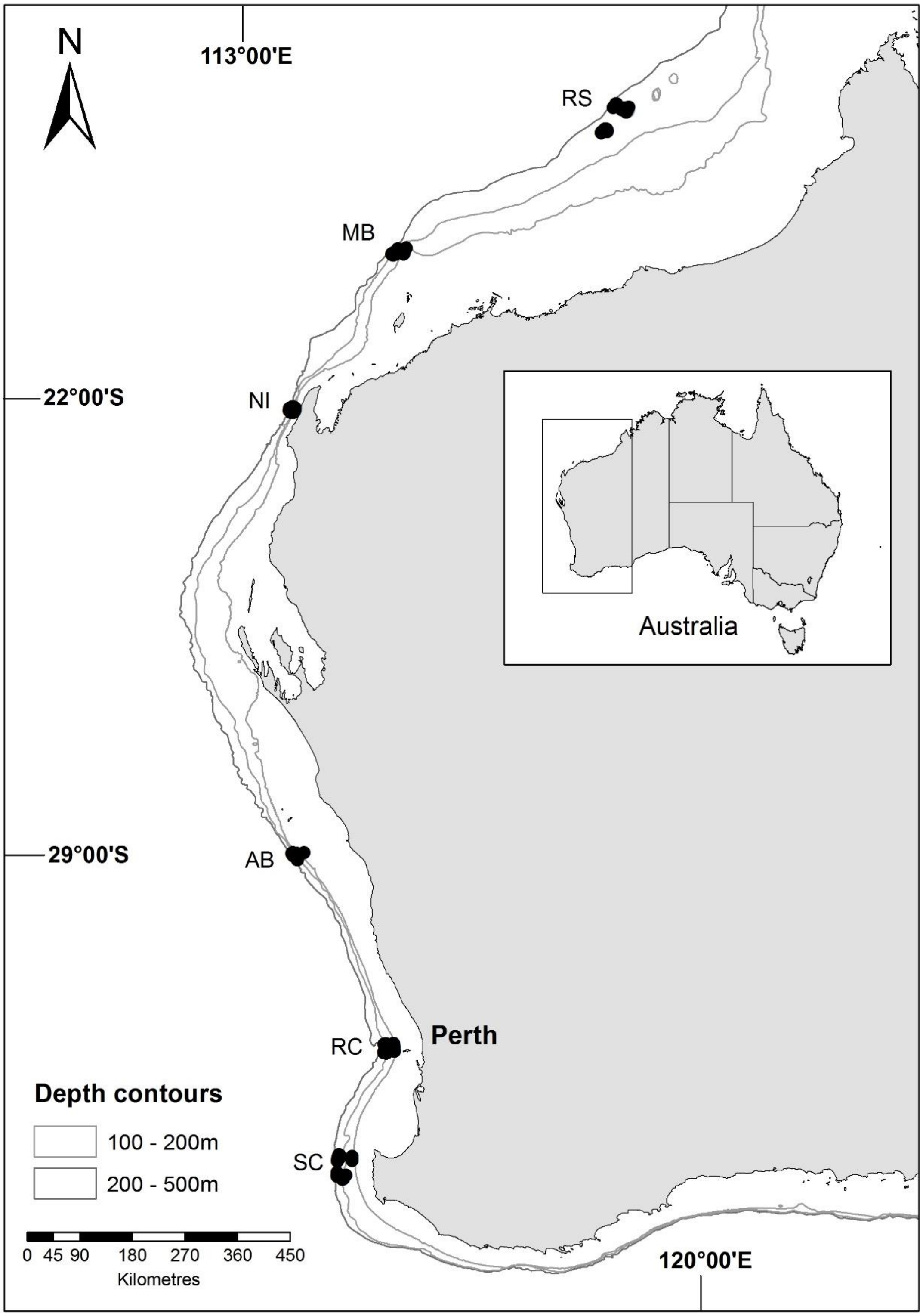

**Figure 1.2 Map of sampling locations on the West Australian coast. RS = Rowley Shoals, MB = Montebello Islands, NI = Ningaloo Reef, AB = Abrolhos Islands, RC = Perth Canyon, SC = South West Capes.**

## *Aims and Objectives*

The purpose of this thesis is to investigate the effects of latitude and depth on the composition of deepwater continental slope fishes along the coast of Western Australia (Fig. 1.3). I aim to address two specific questions about changes in assemblage composition over depth and latitudinal gradients. 1) How do fish assemblage compositions, i.e. species richness, abundance and biomass change with increasing depth? 2) How do assemblage patterns change with latitudinal variations, and what factors are influencing this variation?

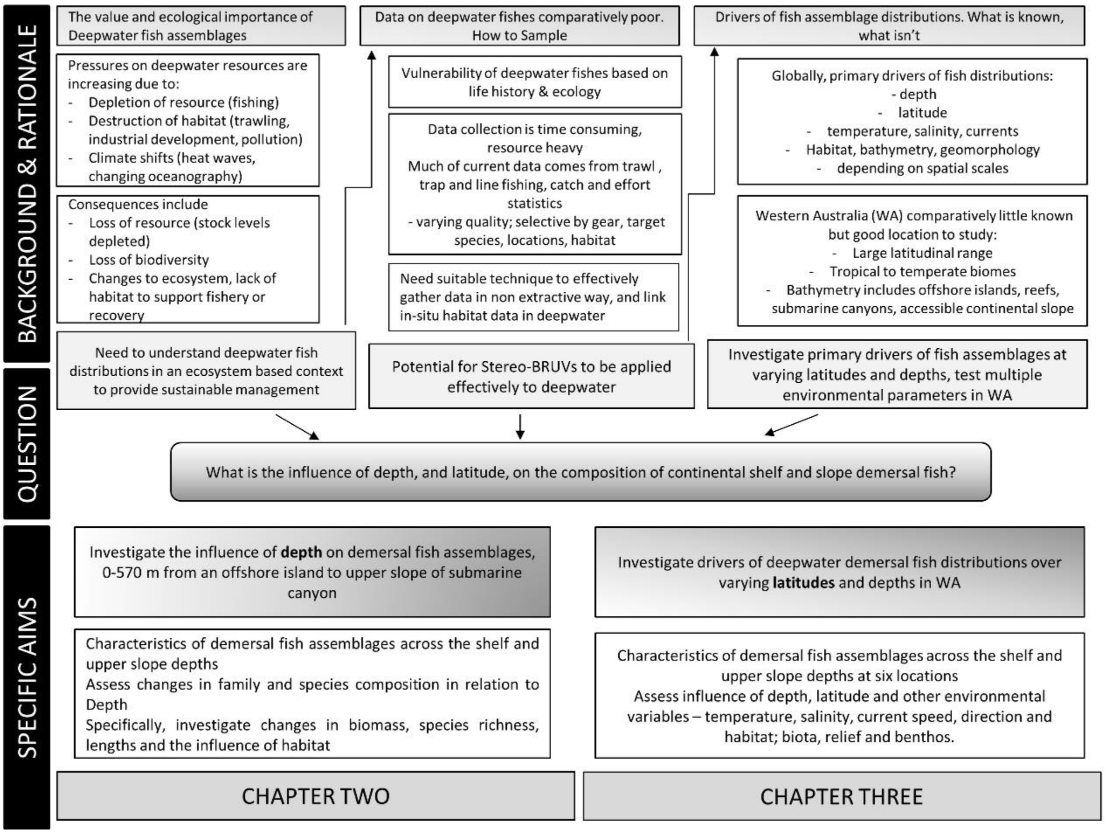

**Figure 1.3 Thesis flow diagram outlining the background and rationale, aims and thesis structure.**

This information will provide much-needed knowledge about the ecology of the deepwater distribution and habitat use of demersal fishes along the west Australian coastline. There are increasing challenges in regards to the sustainable management of aquatic resources through such issues as expanding populations, fishing technology, changing climatic and oceanographic conditions, and increasing industrial and coastal development. An integrated approach to fisheries management can provide a robust process to inform regulation frameworks. The data herein will be used to enhance future management and conservation of deepwater fisheries and build a body of knowledge about the west Australian coast and its unique confluence of environmental variables. The use of stereo-BRUVs overcomes many of the limitations set by other traditional methods, such as the selectivity inherent in extractive processes, the difficulty in sampling steep and uneven terrain and the limitations of depth. This method of sampling allows for accurate measurements and identification of fish, as well as a fishery-independent, permanent record of fish assemblages and their behaviour.

In chapter two I investigate how the characteristics of demersal fish assemblages (i.e. teleosts and chondrichthyans) varied across the continental shelf and slope at a temperate latitude on the lower west coast of Australia and identify the influence of benthic habitat and other environmental variables on assemblage structure. Specifically, to assess how the species assemblage and richness, biomass, and mean length varied with depth. Based on established ecological theories I expected to find distinct changes in fish assemblages between the continental shelf and upper slope habitats, such that species richness and biomass would decrease with increasing depth, whereas average fish length would increase with depth. This chapter has been published in Continental Shelf Research in 2018 (Wellington et al., 2018).

In chapter three, I assess how the demersal fish assemblages on the Western Australian continental shelf and upper slope vary with regard to latitude and depth from tropical to temperate environments. In this chapter, I consider the effect of ocean variables such as temperature, salinity and currents, as well as benthic habitat factors on demersal fish assemblage structure across depth and latitude. Based on existing evidence, I expected to see latitudinal trends to be evident between tropical and temperate regimes, in keeping with bioregional information from Western Australia (Last et al., 2011) with species richness predicted to decrease with depth and with latitude. Overall, the data presented here will be informative for ecosystem related fisheries management spanning the continental shelf and upper slope in Western Australia, as well as contribute to the ecological frameworks regarding fish distributions globally. This chapter has been submitted to the Journal of Experimental Marine Biology and Ecology for publication.

# Chapter 2 Peak in biomass driven by larger-bodied meso-predators in demersal fish communities between shelf and slope habitats at the head of a submarine canyon in the south-eastern Indian Ocean

## *Abstract*

This study investigated variations in the composition and biomass of demersal fish assemblages over a 570-metre depth gradient on the temperate, lower west coast of Australia (32˚ S) in the south-eastern Indian Ocean. Fish assemblages were sampled using Baited Remote Underwater Stereo Video systems (stereo-BRUVs, n = 284 deployments) from shallow waters around a mid-shelf island (Rottnest Island) to the continental slope within a submarine canyon (Perth Canyon). A total of 9,013 individual fishes (i.e. ΣMaxN) belonging to 179 species and 75 families were identified. Multivariate statistical analyses revealed three distinct fish assemblages associated with the continental shelf (5–199 m), margin (200-300 m) and upper slope (300-570 m). A distance-based linear model revealed that among environmental covariates, benthic biota (sessile invertebrates and macroalgae) accounted for the highest proportion of variation in fish assemblage composition (16.9%) followed by depth (12.5%) and seabed relief (10.5%). Generalised additive models indicated higher biomass of fish associated with habitats characterised by benthic biota. Species richness decreased with increasing depth across the continental shelf but remained constant with increasing depth on the continental slope. Average fish length was not correlated with depth but was greatest at 200–400 m depth. The continental margin and upper slope habitats revealed a distinct change in assemblage composition as well as a peak in biomass of species that was dominated by larger-bodied meso-predators at the continental margin. The trends exhibited in fish assemblage characteristics across this broad depth range can inform ecosystem-based management for deepwater fisheries resources.

Keywords: Stereo-BRUVs; baited cameras; deepwater; continental margin; benthic biota; fish assemblage.

## *Introduction*

Variations in fish assemblages can be influenced by a number of factors, including (but not limited to) depth, environmental conditions, and local geomorphology (Koslow et al., 2000; Newman and Williams, 2001; Johnson et al., 2013). These general patterns and theories explain much of the diversity, abundance and biomass of fish assemblages in many regions of the ocean globally, but relatively little is known about the assemblage structure of deepwater demersal fishes in the temperate region of the west coast of Australia (Williams et al.; Williams et al., 2001). In a fisheries context, deepwater has broadly been defined as the continental shelf (~170 m), continental margin (170-300 m) and upper continental slope (300-700 m) which collectively is a depth zone occupied by the majority of commercial fisheries globally (Newman et al., 2016). Research in deepwater environments is typically expensive and problematic, with data traditionally sourced from extractive methods (e.g. trawls, traps and longlines; (Levin and Dayton, 2009; Fabri et al., 2014). Baited Remote Underwater Stereo Video systems (stereo-BRUVs) offer a cost-effective means of gathering fish abundance indices, biomass and benthic habitat data providing valuable information on the status of fish species, including those vulnerable to fishing exploitation or cryptic species rarely captured through traditional methods (McLean et al., 2016; Warnock et al., 2016).

Depth is considered one of the strongest predictors of biodiversity in the deep sea (Haedrich, 1996; Bergstad et al., 2008; Gaertner et al., 2013). Trends in fish species richness in these deepwater habitats have been shown to generally decrease with increasing depth (Stefanescu et al., 1994; D'Onghia et al., 2004; Tolimieri, 2007). Relative biomass is thought to decrease with depth due to reductions in light, temperature, primary productivity and food (Haedrich, 1996; Carney, 2005; Bergstad et al., 2008). However, local epipelagic primary productivity can influence both species richness and biomass trends, with areas of low primary productivity exhibiting increased diversity and biomass at the continental margin before decreasing again with depth (Williams et al., 2001; Rennie et al., 2009a; Tolimieri and Anderson, 2010; Gaertner et al., 2013). Significant geomorphology such as submarine canyons can also facilitate a range of oceanic processes enhancing the transfer of energy and productivity in a localised region (Rennie et al., 2006; Danovaro et al., 2010). Canyons are unique geological features and have been reported to be areas of high local diversity for both fish and benthic habitat (Williams et al., 2010; Davies et al., 2014; De Leo et al., 2014).

Many deepwater species are mid-level predators, feeding on smaller prey such as fishes and invertebrates. As meso-predators, they form an integral part of trophic flows and can have important consequences in trophic cascades (Sieben et al., 2011). These larger-bodied fish species are also important to recreational and commercial fisheries. Heincke’s law generally interpreted as the ‘bigger-deeper’ trend, postulates that larger species are generally found in deeper water environments. Heincke’s law has been the subject of much debate, depending on the species studied and the region/context examined (Macpherson and

Duarte, 1991; Merrett and Haedrich, 1997). Deepwater fish species typically have a higher inherent vulnerability to fishing exploitation than shallower water species due to potentially lower production potential inferred from life history characteristics (e.g. slower rates of growth, later maturation and longer life spans; Haedrich, 1996; Cheung et al., 2007; Wakefield et al., 2013a; Newman et al., 2016). These life history characteristics, coupled with a trend towards increased biomass in deepwater environments, highlight the potential vulnerability of deepwater species and the need for sustainable management.

Sound governance, management and stock assessments require knowledge of species' life-history characteristics and an understanding of the environmental and ecological characteristics within which those species exist (Newman et al., 2017). Often the relevant biological and ecological information is limited or unknown. Fisheries management in deepwater areas can be further complicated if there are overlapping management jurisdictions governing the exploitation of shared stocks. For example, in Western Australia State and Commonwealth managed fisheries have the capacity to harvest the same fishery resources in depths greater than 200 m (Brayford and Lyon, 1995). It is therefore important to have a thorough understanding of the trends and factors influencing fish assemblage characteristics in deeper water environments, and how they relate to those in shallower water in order to comprehensively manage shared resources in this zone.

The objective of this study was to investigate how the characteristics of demersal fish assemblages (i.e. teleosts and chondrichthyans) varied across the continental shelf and slope at a temperate latitude on the lower west coast of Australia and identify the influence of benthic habitat and other environmental variables on assemblage structure. Specifically, we aimed to assess how the species assemblage and richness, biomass, and mean length varied with depth. Based on established ecological theories we expected to find distinct changes in fish assemblages between the continental shelf and upper slope habitats, such that species richness and biomass would decrease with increasing depth, whereas average fish length would increase with depth. The trends exhibited in fish assemblage characteristics across this broad depth range and diverse habitats will be useful for informing ecosystem-based management for deepwater fisheries resources.

## *Material and methods*

### ***Study site and sampling regime***

Sampling sites extended from the mid-shelf shallow waters (5 m) of Rottnest Island, across the continental shelf to the upper continental slope of the submerged Perth Canyon (to 570 m depth, ~32°S, Fig. 2.1). Rottnest Island is located ~18 km off the coast of Perth, Western Australia, and is the only mid-shelf island on the lower west coast of Australia. The marine fauna and flora around Rottnest Island comprises a combination of subtropical and temperate marine species, many of which are endemic (Hutchins, 1994; Harry, 2001). The Perth Canyon, which is located 27 km west of Rottnest Island, constitutes a geological relict of the Swan River incised into the edge of the continental slope (Rennie et al., 2006). The shallowest point of this canyon occurs at the continental margin at ~200 m depth, with relatively steep slopes to ~1000 m deep.

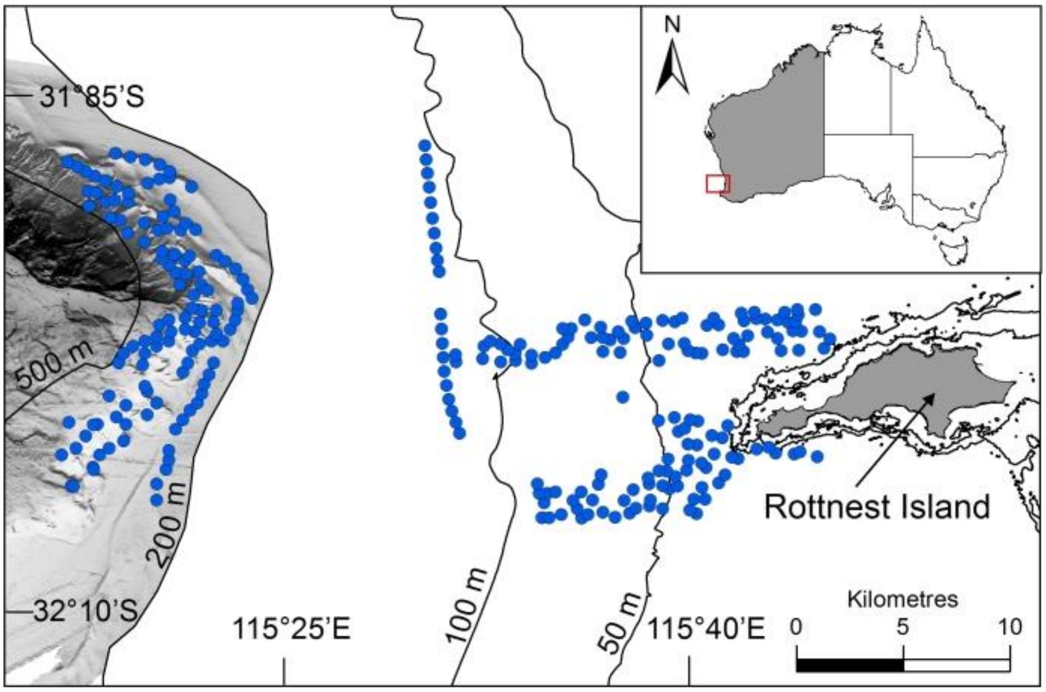

**Figure 2.1 Sampling locations of stereo-BRUVs (blue circles) from shallow waters of Rottnest Island to the continental slope of the Perth Canyon on the lower west coast of Western Australia. The position and geographic features of the Perth Canyon are shown using overlayed bathymetry (> 200 m, provided by the CSIRO).**

Stereo-BRUVs were used to record the composition, relative abundance and size of fishes and characteristics of the habitats they occupied (i.e. substrate type, seabed relief, and dominant benthic biota). Sampling was completed during four research surveys in September 2007 and March, April, and November 2010. A total of 284 stereo-BRUVs were deployed during daylight (0800-1700 h) in sets of up to ten. Sampling was stratified into ten depth categories consisting of five categories in consecutive 20 m depth increments from 0-100 m and five categories in consecutive 100 m depth increments from 100-599 m. At depths of 100 m or more, between 10 and 20 replicate samples were collected in each depth category. In depths greater than 200 m, the location of each stereo-BRUVs deployment was determined from a GPS overlay of the vessel position onto swath maps that displayed detailed bathymetry and backscatter (i.e. relative density of substrate, Fig. 2.1). This allowed soft, intermediate and hard substrate types to be sampled within each depth category. Habitats were further classified from recorded footage during video analysis.

The stereo-BRUVs used two high-definition cameras (Sony® CX7 or CX12 models) inside waterproof camera housings. The configurations of the cameras were the same as that described in Watson et al. (2005) and Zintzen et al. (2012). In depths greater than 100 m, blue LED lights (CREE Inc. 420 nm Royal Navy) were used for illumination as they are considered to be below the visual sensitivity of most fish (Lythgoe et al., 1994; Douglas et al., 1998). While red illumination (> 600nm) is thought to result in less disturbance to fishes (Raymond and Widder, 2007; Fitzpatrick et al., 2013), blue illumination was used in this instance as longer wavelengths do not attenuate in water as quickly, increasing the field of view for image analysis (Harvey et al., 2012). Lights were positioned on the top of the metal frame between the two cameras with a bait bag extended 1.2 m from the frame within the cameras field of view.  For each deployment, the bait bag was filled with 800 to 1000 g of Australian pilchards (*Sardinops sagax*), that were crushed to maximise the bait plume and facilitate comparisons with other stereo-BRUV studies (Westerberg and Westerberg, 2011; Dorman et al., 2012). Stereo-BRUVs were deployed at a minimum distance of 500 m from each other to reduce the potential for overlap of bait plumes and the likelihood of fish moving between baited videos during the same sampling period (Cappo et al., 2003; Langlois et al., 2011).

### *Image analyses*

Stereo-BRUVs were calibrated before and after field trips using CAL software (www.seagis.com.au) to facilitate accurate length measurements during video analysis following the procedures outlined by Harvey and Shortis (1998). EventMeasure Stereo software (see http://www.seagis.com.au/event.html) was used to record the relative abundance of fish and to measure fish lengths from the video imagery. The relative abundance of fish was determined as the maximum number of any one species recorded within the field of view at any one time (i.e. MaxN). This relative abundance measure is considered a conservative estimate that avoids recounting an individual fish that may re-enter the field of view several times during a single deployment (Cappo et al., 2004; Harvey et al., 2007). For deployments < 100 m the first 60 minutes of video imagery was analysed from each deployment, commencing once the stereo-BRUV system had settled on the seafloor (Watson et al., 2005; Langlois et al., 2010). Deepwater deployments (> 100 m) were analysed for 90 minutes in order to allow slower-moving deepwater species time to move towards the bait (McLean et al., 2015; Zintzen et al., 2017). Fish species were identified to the lowest possible taxa using available literature and in consultation with ichthyologists and fisheries scientists in Australia (Gomon et al., 2008; Last and Stevens, 2009; Froese and Pauly, 2019). The lengths of individual fish were converted to weight using relationships obtained from local fisheries unpublished data or from Fishbase (Froese and Pauly, 2019). Where species-specific relationships were not available, the relationship of a similar congener was used. Biomass estimates were calculated from the MaxN of each species in each deployment.

Images from each video deployment were used to categorise benthic habitat based on biota, substrate type and seabed relief. Biota was categorised into kelp, other macroalgae, or sessile invertebrates (which included a complex of sponges, corals, bryozoans, hydroids and ascidians). Substrate was classified as either sand or reef. Seabed relief was classified into high, moderate, low and flat profiles, with flat relief representing an absence of any gradient or underlying reef structure. Only the dominant habitat category was scored for each stereo-BRUVs deployment.

### *Statistical analyses*

Checking data and formatting EventMeasure outputs was under-taken using the R language for statistical computing (R Core Team, 2017) using scripts adapted from Langlois et al. (2015) with the dplyr (Wickham and Francois, 2016) and tidyr (Wickham, 2017) data handling packages.

The depth range of each fish family was plotted using the minimum and maximum depths at which they were observed from the videos. The mean number of species and average length of individual fishes was calculated for each depth category (± 1 SE).

The distribution of total biomass and correlation with likely environmental variables was investigated using generalised additive models (GAMs; Hastie and Tibshirani, 1990). GAMs use a sum of smooth functions to model covariate effects, as opposed to a linear (or some other parametric) form, allowing for more flexible functional dependence of the response variable on the covariates. This makes GAMs useful for capturing the shape of a relationship without making prior assumptions about its parametric form. A full subsets approach was used to fit all combinations of predictor variables up to a maximum of three, preventing overfitting whilst ensuring models remained ecologically interpretable (Fisher et al., 2018). Biomass data was assessed using a Tweedie distribution within a GAM (Wood, 2017). Model sizes were limited to only three terms (size = 3), and k was limited to 5 (degrees of freedom). All analyses and plots were performed using the R language for statistical computing (R Core Team, 2017) with the statistics package mgcv (Wood, 2011), plotting package ggplot2 (Wickham, 2009).

Multivariate statistical analyses exploring differences in the abundance and biomass data were undertaken using PRIMER (version 6.1.13) (Clarke and Warwick, 2001) with the PERMANOVA + add on (version 1.0.3) (Anderson et al., 2008). A similarity matrix using the Modified Gower (log10) distance measure was chosen for both abundance and biomass data sets based on an optimal stress performance derived from Shepard diagrams. Shepard diagrams display the departure of pairwise distances from the best-fitting inclining linear regression from non-metric multi-dimensional scaling (nMDS). Modified Gower (log10) transformation minimises the effect of highly abundant species and schools of fish overwhelming the data set and differentiates between multiple zero entries making it suitable for use with community data as it emphasises species composition and relative abundances (Anderson et al., 2011).

An unconstrained distance-based principal coordinate analysis (PCO) examined trends in the relative abundance and biomass of fish assemblages (at the family and species level, separately) with depth and substrate type. Depths were categorised into ten strata consisting of five consecutive 20 m increments from 0-99 m (i.e. 0-20, 21-40, 41-60, 61-80, 81-99 m) and five consecutive 100 m increments from 100-599 m (i.e. 100-199, 200-299, 300-399, 400-499, 500-599 m). Substrate type was classified into either sand or reef.

A distance-based linear model (DistLM) and associated distance-based redundancy analysis (dbRDA) plot measured and visualised the relationship between the fish assemblage structure and physical and biological environmental variables. Variables were pooled into their major categories (i.e. depth, biota and seabed relief) to identify them in order of their significance on the fish assemblages. DistLM is designed to determine how much of the variability is attributable to predictor indicators (Anderson et al., 2008). The BEST selection procedure was used to examine the value of the selection criterion for all possible combinations of predictor variables (Clarke and Warwick, 2001). The best overall model was found using the Akaike Information Criterion (AIC) in order to reveal the paramount combination of significant variables influencing the fish assemblage composition (Akaike, 1973; Anderson et al., 2008).

Canonical analyses of principal coordinates (CAP) ordinations further investigated trends in both the relative abundance of fish assemblages and biomass with relation to depth. This is a constrained ordination that allows *a priori* habitat classifications to be maintained in order to identify the variable with the strongest correlation. Spearman correlations of ≥ 0.6 were used to graphically present potential correlations between the data and variables relative to the canonical axes.

## *Results*

### ***Distribution of abundances and lengths of fish with relation to depth***

A total of 9,013 individual fish (ΣMaxN) were identified from 179 species and 75 families. The majority of families (45%) were recorded exclusively in continental shelf waters (i.e. < 200 m, Fig. 2.2). Eleven families were distributed in waters from the continental shelf to margin, nine families from the continental shelf to upper slope, and 21 families exclusively inhabited the upper slope (i.e. 300–600 m, Fig. 2.2). The largest depth ranges were recorded for the Urolophidae (8–440 m), Scyliorhinidae (28–440 m) and Sebastidae (108–523 m) with these three families distributed from continental shelf to slope habitats. A full species list is included in the Supplementary Material (Table S 2.1).

The highest numbers of species were recorded in the 0–20 m depth range with an average of 16.0 species (± 1.2 SE) per stereo-BRUV (Fig. 2.3a). Species richness decreased with increasing depth across the continental shelf to 5.7 species (± 0.42 SE) per stereo-BRUV in the 100-199 m depth range. In waters deeper than 200 m, species richness was relatively consistent between 4.6 (± 0.3 SE) and 5.4 (± 0.6 SE) species per stereo-BRUV (Fig.2.3a). In contrast, the average length of all fish observed was positively correlated with depth from 0 to 300 m, where it peaked at an average of 479 mm, before decreasing with increasing depth (Fig. 2.3b).

The most abundant species recorded (ΣMaxN by species) were *Neatypus obliquus* (ΣMaxN = 1476) and *Coris auricularis* (ΣMaxN = 1176). The habitats occupied by these species were constrained to the continental shelf, whereas those of the third most abundant, *Pseudocaranx* spp. (ΣMaxN = 1087), extended across the shelf to the continental margin. *Chrysophrys auratus* (ΣMaxN = 320) was the most ubiquitous species and was encountered on 120 stereo-BRUVs (i.e. 42% of deployments) between depths of 13–316 m.

### ***Trends in biomass and significance of habitat variables***

The most parsimonious model for trends in total biomass included correlations with depth, seabed relief and benthos, which collectively explained 47% of the variance (Table 2.1). The second top model contained all four variables indicating that substrate type was also important across all possible models. The GAM revealed there was a strong non-linear relationship of biomass with depth indicating a significant peak in total biomass at the continental margin in 190–240 m depth (Fig. 2.4a).

Total biomass increased with depth to ~240 m, then decreased precipitously with increasing depth on the upper slope from 300–570 m. Overall, total biomass was generally negatively correlated with depth, positively correlated with increasing seabed relief and generally lower in sand dominated habitats (Fig. 2.4a-c).

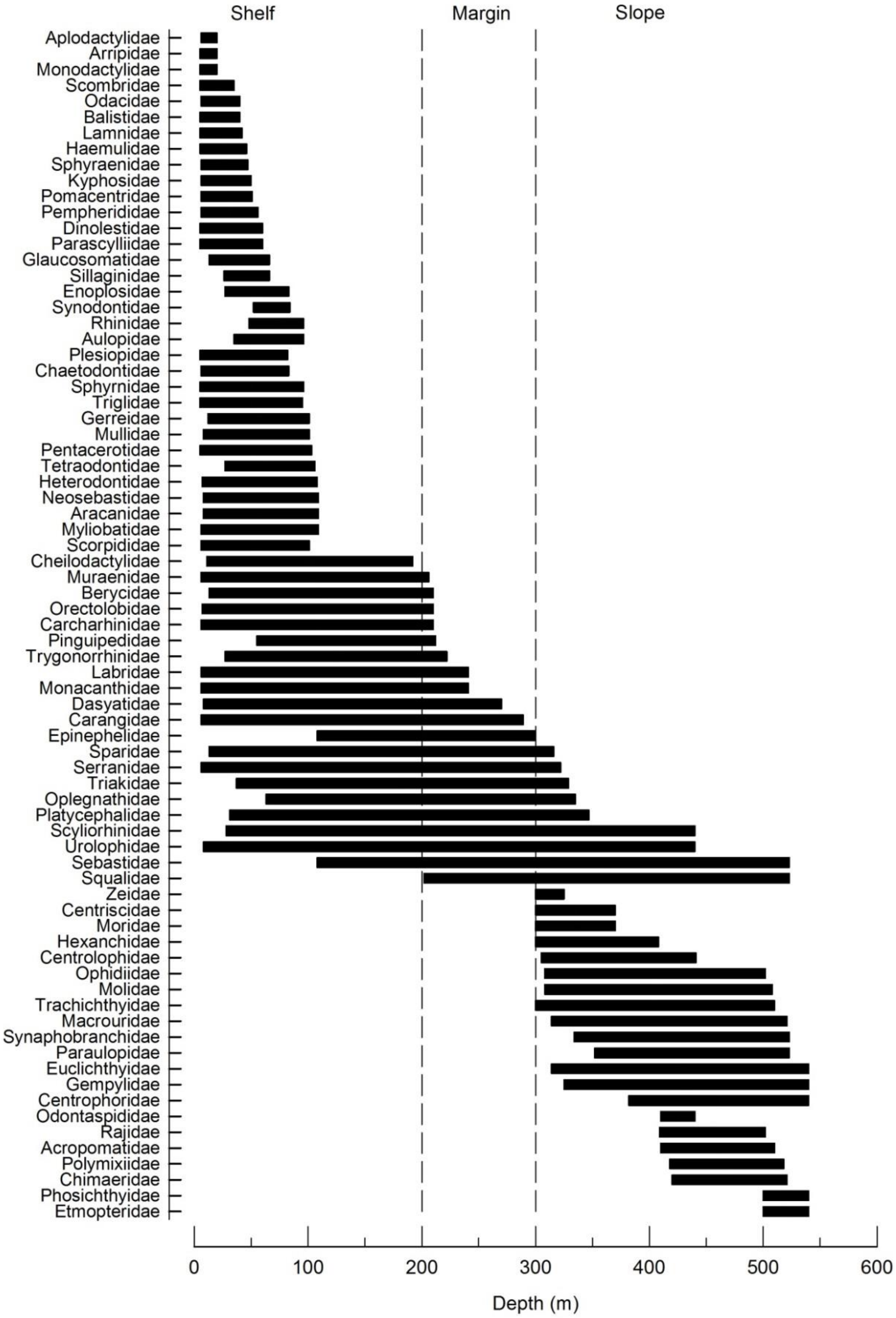

**Figure 2.2 Depth ranges of each fish family recorded from stereo-BRUVs from shallow waters of Rottnest Island (~5 m) to the continental slope of the Perth Canyon (~600 m). Dashed lines represent depth ranges for continental shelf, continental margin and continental slope habitats derived from multivariate distinction of species compositions.**

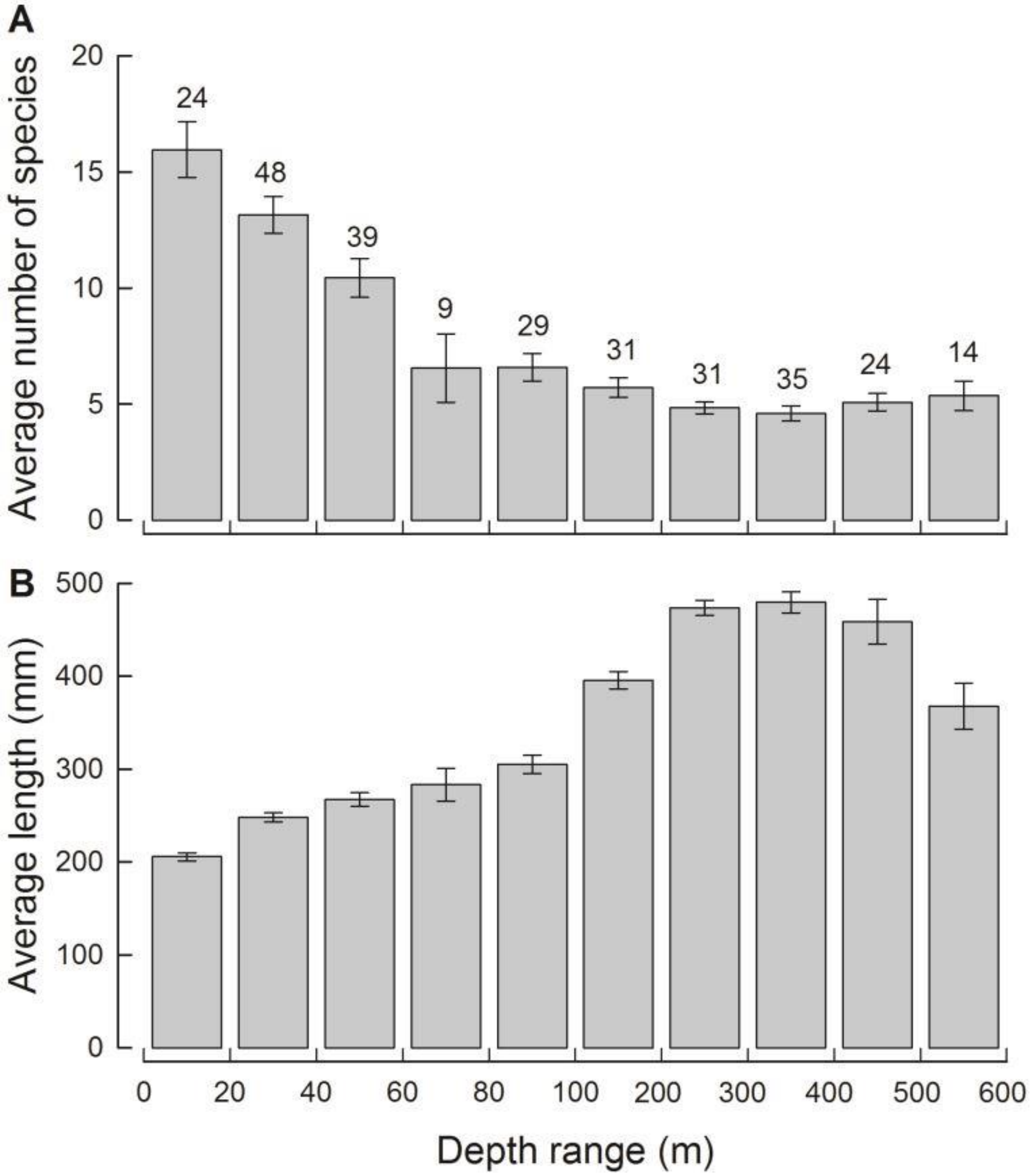

**Figure 2.3 a. Average number of fish species per stereo-BRUVs (± 1 SE) in consecutive depth gradients from 0 to 599 m. b. Average length (mm) of fish measured from stereo-BRUVs imagery across each depth gradient.**

**Table 2.1 Top generalised additive models (GAMs) for predicting the total biomass from full subset analyses. Difference between lowest reported corrected Akaike Information Criterion (ΔAICc) and Bayesian Information Criterion (ΔBIC), both AICc and BIC weights (ωAICc and ωBIC), variance explained ($R^2$), and effective degrees of freedom (EDF) are reported for model comparison. Model selection was based on the most parsimonious model (fewest variables) within two units of the lowest AICc.**

| | **Best models** | **ΔAICc** | **ΔBIC** | **ωAICc** | **ωBIC** | **R2** | **EDF** |
|---|---|---|---|---|---|---|---|
| Total biomass | Depth + Relief + Benthos | 0 | 0.996 | 0.562 | 0.26 | 0.472 | 19.41 |
| | Depth + Relief + Substrate Type | 0.563 | 1.564 | 0.04 | 0.029 | 0.333 | 20.07 |

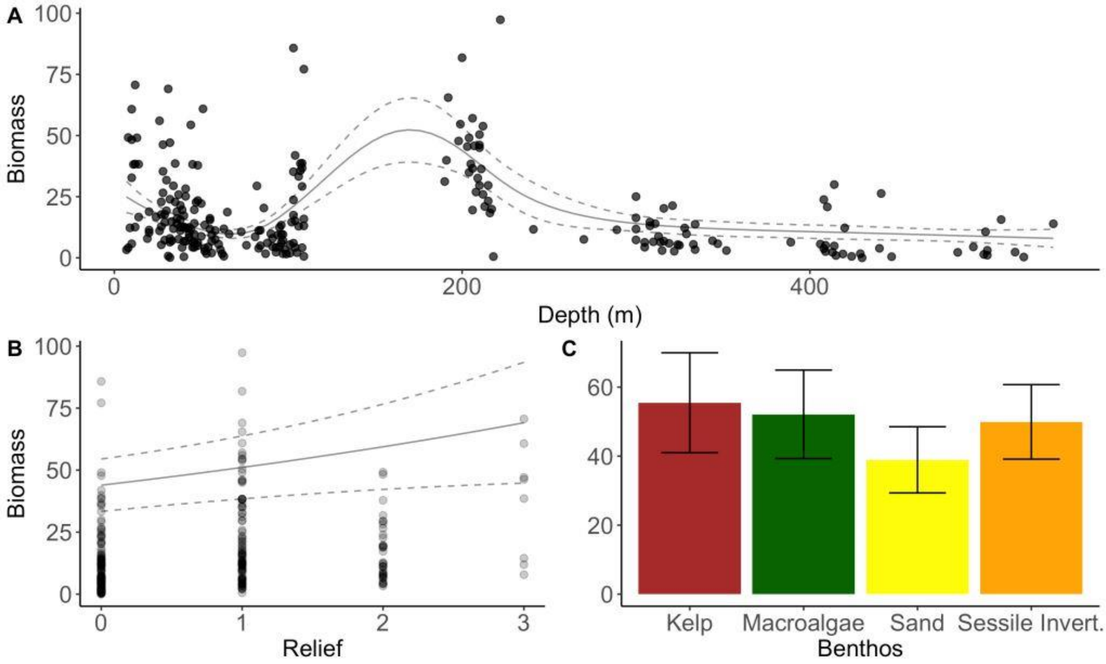

**Figure 2.4 a. Plots of the most parsimonious model found to predict the total biomass from all possible combinations of variables GAM analyses over depth (0–600 m) (see Table 2.1) b. Model of total biomass by seabed relief profiles 0 = flat 1= low 2= moderate 3= high seabed relief c. Model of total biomass by biota categories (Sessile Invert. – sessile invertebrates). Solid lines are fitted GAM curves, with dashed lines indicating standard error confidence bands.**

### *Multivariate significance of habitat variables for abundance and biomass among fish assemblages*

At the family level, the first two PCO axes explained 38% of the variation in fish assemblages, with the distribution of data points within the ordination showing a strong correlation between fish assemblages and depth (Fig. 2.5a). The relative abundances of the families Scorpididae and Labridae were strongly correlated with shallower continental shelf waters (Spearman correlation ≥ 0.6, Fig. 2.5b). In contrast, the relative abundances of Oplegnathidae, associated with both reef and sand substrate, and Squalidae with a preference towards sand habitat, were both strongly correlated with deeper continental margin and upper slope waters (Fig. 2.5b).

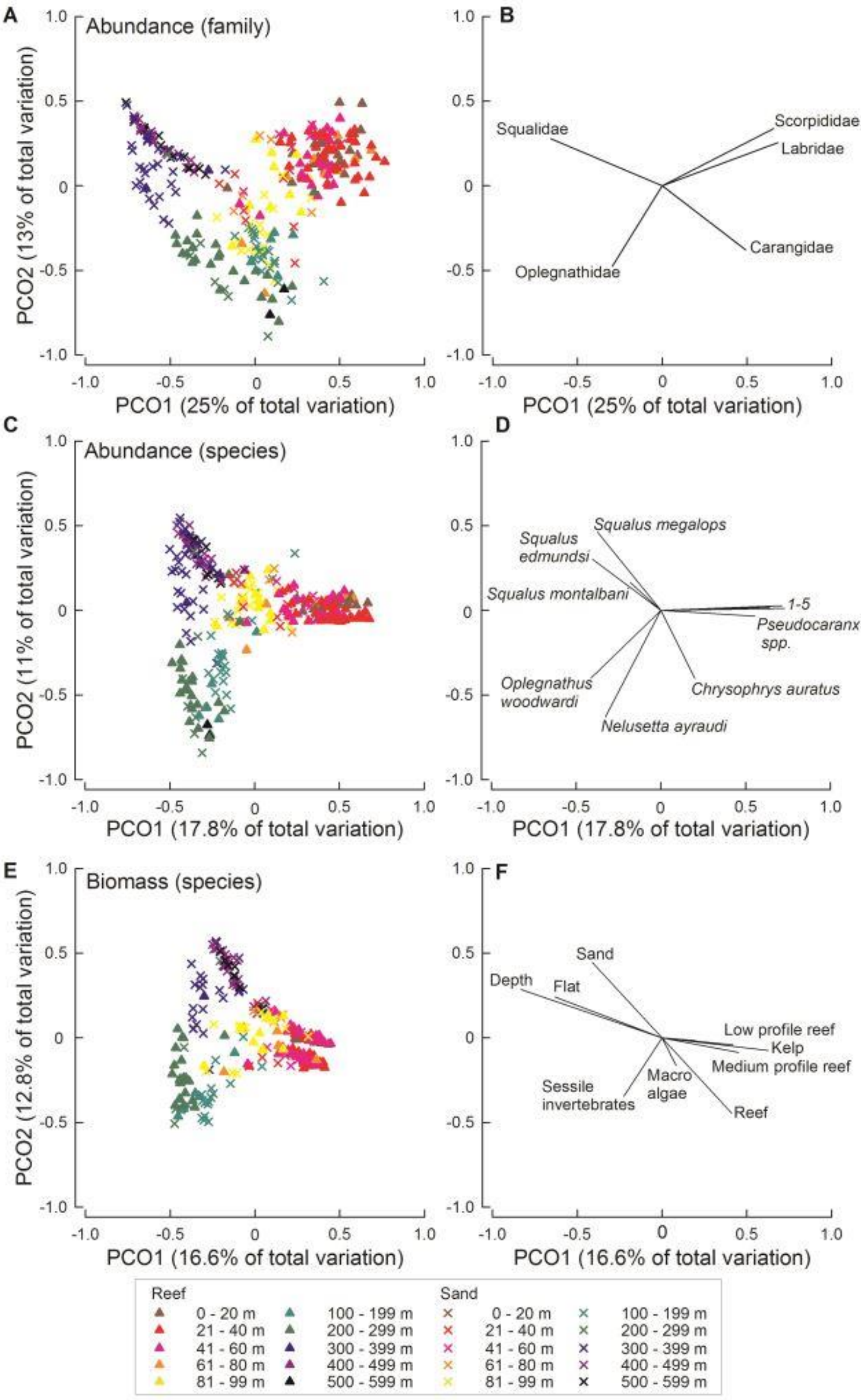

**Figure 2.5 a. Principal coordinates analysis (PCO) of fish assemblage data using depth range and substrate type with b. Corresponding strength and direction of spearman correlation ≥ 0.6 of family taxa shown as line vectors. c. Principal coordinates analysis (PCO) ordination of fish abundance data using depth range and substrate type with d. Corresponding strength and direction of spearman correlation ≥ 0.6 of fish species shown as line vectors. Fish species 1-5 are *Opthalmolepis lineolatus*$^{1}$, *Pseudolabrus biserialis*$^{2}$, *Notolabrus parilus*$^{3}$, *Coris auricularis*$^{4}$, *Neatypus obliquus*$^{5}$ e. Principal coordinates analysis (PCO) of biomass data using depth range and substrate type with f. corresponding strength and direction of spearman correlation ≥ 0.6 of habitat variables shown as line vectors. In all figures, the analysis was based on Modified Gower (log10) dissimilarities. Key is the same for all figures.**

At the species level, 28.9% of the variation in the relative abundance among fish assemblages was explained by the first two PCO axes (PCO1 17.8%, PCO2 11%) (Fig.2.5c). There were six species with relative abundances strongly correlated with predominantly shallow reef habitats on the continental shelf that were distinguished by the first PCO axis (Fig. 2.5d). These species included *Opthalmolepis lineolatus*, *Pseudolabrus biserialis*, *Notolabrus parilus*, *Coris auricularis*, *Neatypus obliquus* and *Pseudocaranx spp*.. Again, there was a pronounced shift in the orientation of data points within the ordination between deployments on the continental shelf and those from the continental margin and slope. Chrysophrys auratus was highly correlated directly between the shallow water shelf deployments and continental margin depths. In depths > 200 m on the continental margin and upper slope, the relative abundances of two teleosts, *Oplegnathus woodwardi* and *Nelusetta ayraud*, were strongly associated with reef and sand in continental margin habitats whilst the abundance of three squalid shark species (i.e. *Squalus edmundsi, S. megalops* and *S. montalbani*) were strongly correlated with sand in upper slope habitats (Fig. 2.5d).

Biomass of fish species among assemblages explained 29.4% of the variation within the first two PCO axes (PCO1 = 16.6% and PCO2 = 12.8% Fig. 2.5e). The shift in the orientation of data points within the ordination was once again pronounced between continental shelf habitats and those from the continental margin and upper slope habitats. Assemblages of fish species based on total biomass in shallower continental shelf locations (i.e. < 100 m) had a stronger correlation with kelp, reef, and low to medium seabed relief habitats as distinguished by the first PCO axis (Fig.2.5f). Whereas assemblages of fish species based on total biomass in deeper waters were associated with benthic sessile invertebrates at the continental margin (100-199 m depth) and sand habitats with flat seabed relief dominating the upper slope (200–570 m depth).

DistLM identified all three environmental indicators (biota, depth, seabed relief) as significant in relation to abundance indices ($p < 0.001$, Table 2.2). An overall best solution model revealed that biota, depth and seabed relief together explained the greatest amount of variation within the abundance data (Table 2.3). Biota alone accounted for the greatest proportion of the variation at 16.9%, followed by depth 12.5% and seabed relief 10.5%. The dbRDA plot explained 59% of the variation of the fitted model and 14.5% of the total variation on dbRDA1 where abundance data of the continental slope was strongly correlated with depth (Fig. 2.6a, b). On dbRDA2 the fitted model explained 22.9% of the variation and 5.6% of the total variation where the habitat variables were correlated with sessile invertebrates at the continental margin. Kelp habitat (found exclusively on the shelf) and reef profiles with seabed relief were correlated with shallower water continental shelf communities (Fig.2. 6b).

**Table 2.2 Results of distance-based linear model (DistLM) relating species abundance with environmental indicators.**

| Indicator | SS(trace) | Pseudo-F | p value | Proportion | Res d.f |
|---|---|---|---|---|---|
| Depth | 24.371 | 40.366 | 0.001 | 0.125 | 282 |
| Biota | 33.070 | 19.104 | 0.001 | 0.169 | 280 |
| Seabed Relief | 20.541 | 11.012 | 0.001 | 0.105 | 280 |

**Table 2.3 Overall solution using best selection procedure with Akaikes Information Criterion (AIC).**

| AIC | $R^2$ | RSS | No of indicators | Selections |
|---|---|---|---|---|
| -171.15 | 0.2450 | 146.94 | 3 | 1,2,3 |

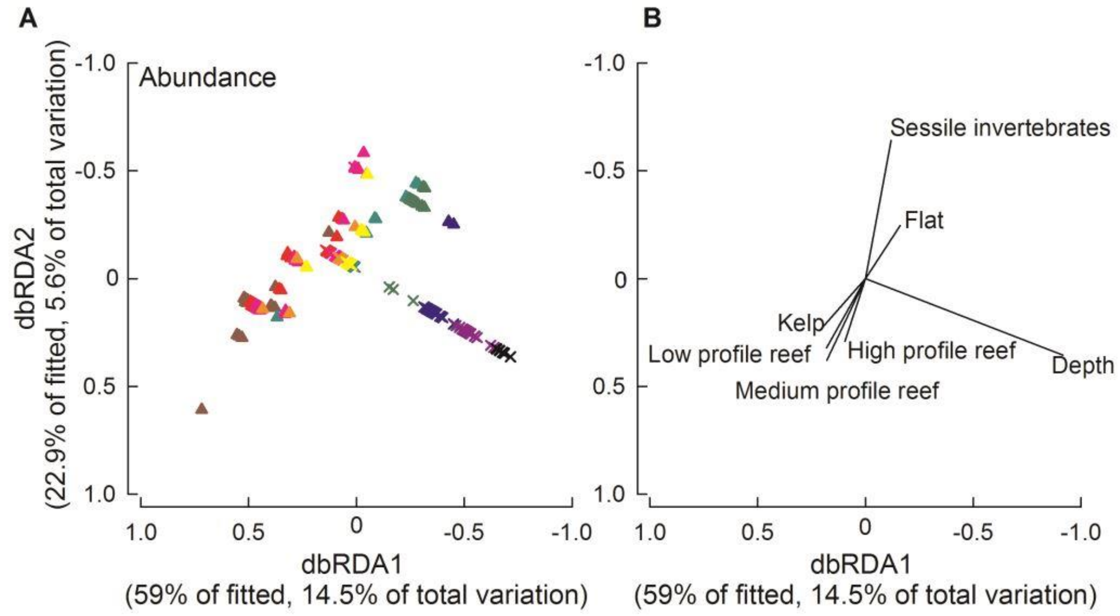

**Figure 2.6 a. A distance-based redundancy analysis (dbRDA) of the fish assemblage data with b. Corresponding strength and direction of spearman correlation ≥ 0.6 of environmental variables shown as line vectors. In all figures, the analysis was based on Modified Gower ($\log_{10}$) dissimilarities. Key as per Fig.2.5.**

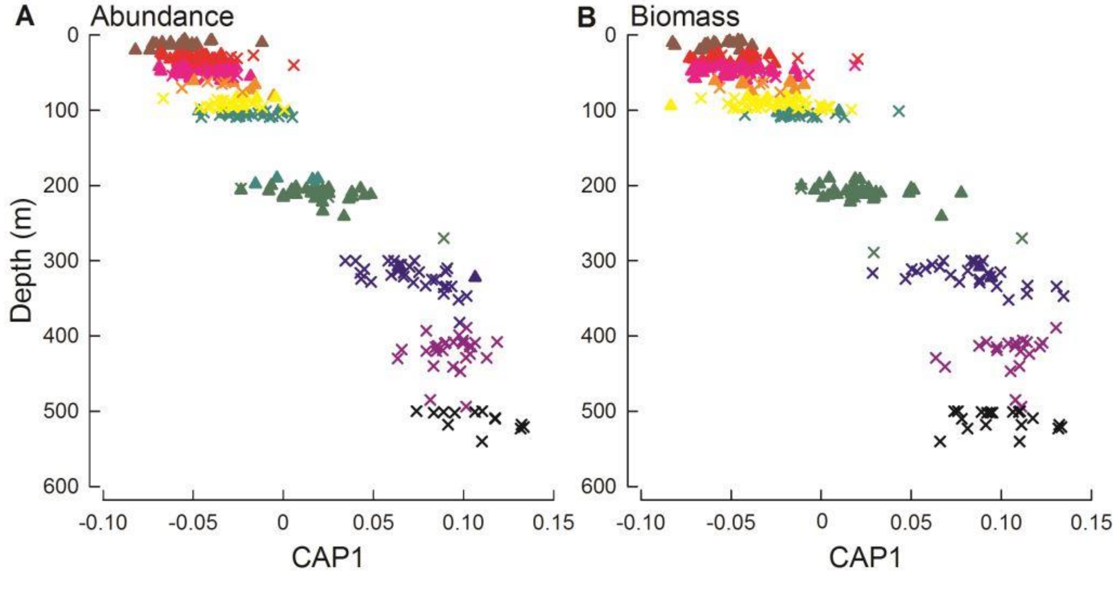

**Figure 2.7 Canonical analysis of principal coordinates (CAP) of a. Abundance and b. Biomass of fish assemblages based on Modified Gower ($\log_{10}$) dissimilarities in relation to depth and substrate type. Key as per Fig. 2.5.**

The distribution of data points in the CAP ordinations for both abundance and biomass exhibited distinct differences in assemblage compositions in relation to depth (Fig.2.7a, b). Three distinct assemblages were exhibited including those associated with both sand and reef substrate in depths < 150 m, a transitional group at the continental margin where reef substrate was dominant and the third in depths > 250 m on the upper continental slope associated with sand substrate.

## *Discussion*

Three distinct ecological fish communities were identified across a wide depth gradient (5–570 m) from shallow waters of a mid-shelf island to the upper continental slope of a submarine canyon, with depth being the principal variable explaining the differences in their assemblage compositions. The shallowest community had the highest species richness and predominantly consisted of more abundant and smaller-bodied species associated with complex benthic habitat structures on the continental shelf, with maximum depth ranges of these species rarely exceeding 200 m. A second fish community was evident at the continental margin (i.e. 200-300 m depth) with lower species richness that was dominated by a greater biomass of larger-bodied meso-predators (predominantly *C. auratus, O. woodwardi* and *N. ayraud*) and associated with sessile invertebrate dominated habitats. The deepest occurring fish community had similar level of species richness to the continental margin group; however, it comprised almost an entire new suite of species. The average fish lengths negatively correlated with depth in this flat seabed relief and sand dominated habitat. These patterns in fish community characteristics from the continental margin to upper slope are similar to those identified in trawl catches by Williams et al. (2001) at a similar latitude. Building on this knowledge, we incorporated changes in community structure from shallower continental shelf waters and link information on the habitat characteristics associated with each fish community. The trend of decreasing species richness with increasing depth in the ranges we sampled supported our hypothesis and were consistent with similar studies (Stefanescu et al., 1994; D'Onghia et al., 2004; Sih et al., 2017). However, biomass and mean fish lengths did not conform to our hypotheses of a monotonically decreasing trend with depth.

While fish assemblage structure was primarily driven by depth; biota and seabed relief also had a proportional effect on composition with all three factors significantly explaining 47% of the variance within the full model. The peak in total biomass of fishes between 190 and 240 m depth was related to the presence of sessile invertebrate dominated habitats at the continental margin. Habitat structure in deeper water environments can support higher abundance, biomass and species richness of fishes through mechanisms such as increased productivity or food resources, refuge and bioturbation (Williams et al., 2008). Benthic structures can alter water flows as well as support larval supply, geochemical and substrate conditions (Stefanescu et al., 1993; D'Onghia et al., 2004; Tolimieri, 2007). Removing the effects of each factor using the GAM did not change the presence of this rise in biomass at ~200 m. This indicates that despite depth, biota and seabed relief factors being significant, there may be others that influence fish assemblage patterns. An investigation of the average length of individual fishes across each depth range revealed a peak in average length that corresponded with the rise in biomass at 190-240m depth at the continental margin. Although some of the shallower and deeper water species exhibited narrow depth ranges in this study, several meso-predator species were shown to occupy a large depth range and diverse habitats across the continental shelf. The typifying species of the continental margin community (i.e. *Chrysophrys auratus, Nelusetta ayraud* and *Oplegnathus woodwardi*) suggest it was predominantly larger meso-predators accounting for the higher biomass and mean fish length.

These larger meso-predators that typified the continental margin community exhibit various life history attributes. *Chrysophrys auratus* is a recreationally and commercially important species in western Australia found offshore to depths of 320 m with spawning aggregations occurring in sheltered nearshore marine embayments (Wakefield, 2010; Wakefield et al., 2011). Adults have strong molar like teeth capable of consuming a range of hard-shelled invertebrates and small fishes. *Nelusetta ayraud* is the largest leatherjacket species in southern Australia (70 cm TL), found in depths of up to 360 m across the shelf and upper slope, and is considered endemic to Australia. With large, strong teeth, their diet is varied, commonly consisting of gastropods, fish, molluscs, crustaceans and salps (Froese and Pauly, 2019). *Oplegnathus woodwardi* is a deep-bodied offshore demersal species (depth range 50-400 m) common in temperate southern Australian waters with a beak-like jaw adapted for predation of invertebrates with a hard shell. They typically grow to an average of 48 cm TL (Gomon et al., 2008). It is likely that such plasticity in feeding strategies may provide some species greater flexibility to occur across multiple habitat types and depth profiles to access food resource availability.

The west coast of Australia is characterised by an oligotrophic marine environment that supports relatively low catches of demersal finfish species but with high species diversity and endemism by global standards (Williams et al., 2001; Lenanton et al., 2009; Molony et al., 2011). The overall trend in biomass shown in this study decreased with depth displaying substantially lower levels of biomass in depths of 300–570 m. Whilst this is likely a reflection of the relatively low epipelagic productivity in the region, the presence of the Perth Canyon and the effects of the nutrient poor, poleward-flowing Leeuwin current at the study site are influential in stimulating productivity in this otherwise oligotrophic environment (Rennie et al., 2006; Lenanton et al., 2009; Rennie et al., 2009a). Although upwelling does not normally extend into the euphotic zone within the Perth Canyon, higher productivity has been reported due to chlorophyll maxima at the base of the Leeuwin current (Hanson et al., 2007; Rennie et al., 2009a). Storm events and cyclonic eddies can also stimulate nutrients into the euphotic zone and together these processes are thought to support higher productivity factors within the canyon.

Relatively stable environmental conditions at greater depths (such as temperature) increase the likelihood of there being greater connectivity across areas, and thus similarity in species distributions (Tolimieri, 2007; Levin and Dayton, 2009). The fish families recorded in the continental margin community typically exhibited the largest depth ranges, and thus this habitat represented a transition from shelf to upper slope assemblages. There were three fish families that extended across all three communities; the Scyliorhinidae, Urolophidae and Sebastidae. The Squalidae was the only family inhabiting depth ranges that commenced at the continental margin and extended into the upper slope community. Families in waters greater than 300 m depth mainly consisted of species with no shallow water congener. These distributions highlight the rapid and distinct change in fish assemblage composition at the continental margin.

This is the first time stereo-BRUVs have been deployed to study demersal fish assemblages and ecological features over such a large depth range and in deepwater slope environments within Western Australia. Stereo-BRUVs are a useful sampling technique that can address knowledge gaps in understanding assemblages, distributions and behaviour of demersal fishes, including rare species, linking them with benthic habitat data and a host of other parameters to contribute toward ecosystem-based fisheries management (Wellington et al., 2017). Governance of deepwater fisheries resources would benefit from an integrated ecosystem-based approach across jurisdictions, especially where overlapping resource use can impact trophic levels and considering discarded bycatch from these depths most likely have a much greater mortality rate. Specific management of this transition zone may be required if it becomes an area increasingly targeted by multi-sector fisheries.

This makes stereo-BRUVs an appealing sampling tool; by using non-extractive, *in situ* imaging techniques we can determine and link fine-scale fishes' distribution patterns with characteristics of their habitats, thus continuing to test ecological theories in remote and deeper areas where ecosystem data is fragmented or comparatively little is known. By incorporating surveys of shallow reef ecosystems with deepwater ecosystems beyond the continental shelf these fish/habitat linkages can be made explicit.

There remains distinct spatial heterogeneity in deepwater fish assemblage structure. In this study, the demersal fish assemblages of the continental shelf and slope ecosystem are stratified with depth, biota and seabed relief. Additionally, we identified a peak in biomass dominated by larger-bodied meso-predator fish species within a narrow depth range. This assemblage was likely supported by associated sessile invertebrate habitats and the geomorphology of the submarine canyon on the continental margin.

## *Supplementary Material*

Supplementary material includes a full list of fish species identified in the study detailing minimum and maximum depths (m) and the number of stereo-BRUVs in which each species was observed (Table S 2.1). Also included is a summary of the number of stereo-BRUVs deployments in each depth range (Table S 2.2).

**Table S 2.1 List of fish species identified in stereo baited remote underwater video systems (stereo-BRUVs) from shallow waters around Rottnest Island (~5 m) to the continental slope of the Perth Canyon (~570 m) detailing minimum and maximum depth (m) and the number of stereo-BRUVs in which each species was observed.**

| **Family** | **Genus Species** | **min depth (m)** | **max depth (m)** | **No. of deployments observed** |
|---|---|---|---|---|
| Acropomatidae | *Malakichthys sp* | 410 | 510 | 4 |
| Aplodactylidae | *Aplodactylus westralis* | 6 | 20 | 2 |
| Aracanidae | *Anoplocapros amygdaloides* | 103 | 109 | 4 |
| Aracanidae | *Anoplocapros lenticularis* | 8 | 104 | 13 |
| Aracanidae | *Anoplocapros robustus* | 63 | 63 | 1 |
| Arripidae | *Arripis georgianus* | 12 | 14 | 2 |
| Aulopidae | *Aulopus purpurissatus* | 35 | 96 | 12 |
| Balistidae | *Balistoides viridescens* | 40 | 40 | 1 |
| Berycidae | *Centroberyx gerrardi* | 35 | 210 | 7 |
| Berycidae | *Centroberyx lineatus* | 13 | 82 | 6 |
| Carangidae | *Pseudocaranx dentex* | 14 | 109 | 86 |
| Carangidae | *Pseudocaranx georgianus* | 102 | 222 | 26 |
| Carangidae | *Pseudocaranx sp* | 6 | 18 | 15 |
| Carangidae | *Seriola dumerili* | 205 | 205 | 1 |
| Carangidae | *Seriola hippos* | 6 | 289 | 44 |
| Carangidae | *Seriola lalandi* | 10 | 12 | 2 |
| Carangidae | *Seriola rivoliana* | 86 | 88 | 2 |
| Carangidae | *Seriola sp* | 104 | 104 | 1 |
| Carangidae | *Trachurus novaezelandiae* | 84 | 109 | 10 |
| Carcharhinidae | *Carcharhinus brachyurus* | 9 | 13 | 5 |
| Carcharhinidae | *Carcharhinus obscurus* | 210 | 210 | 1 |
| Carcharhinidae | *Carcharhinus sp* | 6 | 106 | 2 |

| | | | | |
|---|---|---|---|---|
| Centriscidae | *Centriscops humerosus* | 322 | 322 | 1 |
| Centrolophidae | *Hyperoglyphe antarctica* | 305 | 441 | 4 |
| Centrophoridae | *Centrophorus moluccensis* | 408 | 540 | 8 |
| Centrophoridae | *Centrophorus sp* | 382 | 508 | 6 |
| Centrophoridae | *Centrophorus westraliensis* | 418 | 510 | 3 |
| Chaetodontidae | *Chaetodon auriga* | 8 | 8 | 1 |
| Chaetodontidae | *Chaetodon lineolatus* | 12 | 12 | 1 |
| Chaetodontidae | *Chelmonops curiosus* | 6 | 83 | 15 |
| Cheilodactylidae | *Cheilodactylus gibbosus* | 38 | 84 | 7 |
| Cheilodactylidae | *Cheilodactylus rubrolabiatus* | 12 | 20 | 2 |
| Cheilodactylidae | *Dactylophora nigricans* | 11 | 46 | 4 |
| Cheilodactylidae | *Nemadactylus valenciennesi* | 20 | 192 | 23 |
| Chimaeridae | *Hydrolagus lemures* | 420 | 521 | 2 |
| Dasyatidae | *Dasyatis brevicaudata* | 8 | 215 | 46 |
| Dasyatidae | *Dasyatis sp* | 270 | 270 | 1 |
| Dinolestidae | *Dinolestes lewini* | 43 | 43 | 1 |
| Enoplosidae | *Enoplosus armatus* | 27 | 83 | 2 |
| Epinephelidae | *Hyporthodus octofasciatus* | 108 | 300 | 10 |
| Etmopteridae | *Etmopterus brachyurus* | 509 | 509 | 1 |
| Euclichthyidae | *Euclichthys polynemus* | 314 | 540 | 5 |
| Gempylidae | *Rexea solandri* | 325 | 523 | 12 |
| Gempylidae | *Ruvettus pretiosus* | 510 | 540 | 2 |
| Gempylidae | *Thyrsites atun* | 382 | 382 | 1 |
| Gerreidae | *Parequula melbournensis* | 12 | 101 | 14 |
| Glaucosomatidae | *Glaucosoma hebraicum* | 13 | 66 | 8 |
| Haemulidae | *Plectorhinchus flavomaculatus* | 32 | 46 | 7 |
| Heterodontidae | *Heterodontus portusjacksoni* | 7 | 108 | 48 |
| Hexanchidae | *Hexanchus nakamurai* | 300 | 408 | 3 |
| Kyphosidae | *Girella zebra* | 28 | 28 | 1 |
| Kyphosidae | *Kyphosus cornelii* | 8 | 10 | 2 |
| Kyphosidae | *Kyphosus sydneyanus* | 6 | 50 | 23 |
| Labridae | *Achoerodus gouldii* | 14 | 101 | 4 |

| | | | | |
|---|---|---|---|---|
| Labridae | *Anampses geographicus* | 8 | 42 | 11 |
| Labridae | *Austrolabrus maculatus* | 7 | 82 | 28 |
| Labridae | *Bodianus frenchii* | 6 | 82 | 34 |
| Labridae | *Bodianus vulpinus* | 84 | 241 | 13 |
| Labridae | *Chlorurus sordidus* | 8 | 8 | 1 |
| Labridae | *Choerodon rubescens* | 11 | 101 | 26 |
| Labridae | *Cirrhilabrus temminckii* | 55 | 105 | 10 |
| Labridae | *Coris auricularis* | 6 | 105 | 111 |
| Labridae | *Eupetrichthys angustipes* | 36 | 48 | 3 |
| Labridae | *Labropsis sp* | 32 | 32 | 1 |
| Labridae | *Notolabrus parilus* | 6 | 101 | 81 |
| Labridae | *Ophthalmolepis lineolatus* | 8 | 101 | 85 |
| Labridae | *Pictilabrus laticlavius* | 8 | 38 | 14 |
| Labridae | *Pictilabrus viridis* | 6 | 6 | 1 |
| Labridae | *Pseudolabrus biserialis* | 6 | 101 | 84 |
| Labridae | *Scarus chameleon* | 35 | 35 | 1 |
| Labridae | *Scarus ghobban* | 35 | 35 | 1 |
| Labridae | *Scarus schlegeli* | 20 | 20 | 1 |
| Labridae | *Suezichthys bifurcatus* | 87 | 103 | 2 |
| Labridae | *Suezichthys cyanolaemus* | 51 | 51 | 1 |
| Labridae | *Thalassoma lunare* | 10 | 27 | 3 |
| Labridae | *Thalassoma lutescens* | 8 | 20 | 6 |
| Labridae | *Xyrichtys sp* | 31 | 38 | 3 |
| Lamnidae | *Carcharodon carcharias* | 42 | 42 | 1 |
| Macrouridae | *Coelorinchus mirus* | 314 | 521 | 12 |
| Macrouridae | *Coryphaenoides sp* | 321 | 321 | 1 |
| Macrouridae | *Lepidorhynchus denticulatus* | 406 | 510 | 6 |
| Macrouridae | *Lucigadus nigromaculatus* | 334 | 521 | 15 |
| Molidae | *Mola ramsayi* | 308 | 508 | 2 |
| Molidae | *Mola sp* | 347 | 347 | 1 |
| Monacanthidae | *Acanthaluteres spilomelanurus* | 51 | 91 | 2 |
| Monacanthidae | *Eubalichthys mosaicus* | 20 | 20 | 1 |

|  |  |  |  |  |
|---|---|---|---|---|
| Monacanthidae | *Meuschenia flavolineata* | 20 | 36 | 5 |
| Monacanthidae | *Meuschenia galii* | 6 | 48 | 43 |
| Monacanthidae | *Meuschenia hippocrepis* | 10 | 47 | 16 |
| Monacanthidae | *Nelusetta ayraud* | 55 | 241 | 61 |
| Monacanthidae | *Parika scaber* | 65 | 105 | 4 |
| Monodactylidae | *Schuettea woodwardi* | 10 | 12 | 2 |
| Moridae | *Pseudophycis barbata* | 322 | 322 | 1 |
| Mullidae | *Parupeneus spilurus* | 8 | 66 | 5 |
| Mullidae | *Upeneichthys vlamingii* | 32 | 101 | 10 |
| Muraenidae | *Gymnothorax prasinus* | 6 | 90 | 16 |
| Muraenidae | *Gymnothorax woodwardi* | 12 | 206 | 59 |
| Myliobatidae | *Myliobatis australis* | 6 | 108 | 35 |
| Myliobatidae | *Myliobatis sp* | 109 | 109 | 1 |
| Neosebastidae | *Neosebastes pandus* | 8 | 96 | 12 |
| Neosebastidae | *Neosebastes bougainvillii* | 54 | 109 | 8 |
| Odacidae | *Olisthops cyanomelas* | 6 | 40 | 19 |
| Odontaspididae | *Odontaspis ferox* | 410 | 440 | 3 |
| Ophidiidae | *Dannevigia tusca* | 308 | 308 | 1 |
| Ophidiidae | *Genypterus blacodes* | 334 | 502 | 2 |
| Oplegnathidae | *Oplegnathus woodwardi* | 63 | 335 | 70 |
| Orectolobidae | *Orectolobus halei* | 199 | 199 | 1 |
| Orectolobidae | *Orectolobus hutchinsi* | 7 | 20 | 4 |
| Orectolobidae | *Orectolobus maculatus* | 20 | 109 | 5 |
| Orectolobidae | *Orectolobus sp* | 34 | 210 | 3 |
| Parascylliidae | *Parascyllium variolatum* | 60 | 60 | 1 |
| Paraulopidae | *Paraulopus nigripinnis* | 352 | 523 | 4 |
| Pempherididae | *Pempheris klunzingeri* | 6 | 56 | 13 |
| Pempherididae | *Pempheris multiradiata* | 20 | 42 | 2 |
| Pentacerotidae | *Parazanclistius hutchinsi* | 96 | 96 | 1 |
| Pentacerotidae | *Zanclistius elevatus* | 103 | 103 | 1 |
| Phosichthyidae | *Polymetme corythaeola* | 540 | 540 | 1 |
| Pinguipedidae | *Parapercis sp* | 55 | 212 | 2 |

|  |  |  |  |  |
|---|---|---|---|---|
| Platycephalidae | *Platycephalus bassensis* | 108 | 108 | 1 |
| Platycephalidae | *Platycephalus conatus* | 270 | 270 | 1 |
| Platycephalidae | *Platycephalus sp* | 107 | 347 | 4 |
| Platycephalidae | *Platycephalus speculator* | 31 | 109 | 24 |
| Plesiopidae | *Paraplesiops meleagris* | 82 | 82 | 1 |
| Polymixiidae | *Polymixia sp* | 418 | 518 | 4 |
| Pomacentridae | *Chromis klunzingeri* | 11 | 48 | 13 |
| Pomacentridae | *Chromis westaustralis* | 18 | 51 | 19 |
| Pomacentridae | *Parma bicolor* | 46 | 46 | 1 |
| Pomacentridae | *Parma mccullochi* | 6 | 47 | 31 |
| Pomacentridae | *Parma occidentalis* | 14 | 32 | 2 |
| Rajidae | *Dipturus oculus* | 502 | 502 | 1 |
| Rajidae | *Dipturus sp* | 409 | 409 | 1 |
| Rhinidae | *Rhynchobatus djiddensis* | 48 | 96 | 2 |
| Scombridae | *Acanthocybium solandri* | 35 | 35 | 1 |
| Scorpididae | *Neatypus obliquus* | 6 | 101 | 102 |
| Scorpididae | *Scorpis aequipinnis* | 10 | 66 | 10 |
| Scorpididae | *Scorpis georgiana* | 8 | 46 | 23 |
| Scorpididae | *Tilodon sexfasciatus* | 13 | 90 | 9 |
| Scyliorhinidae | *Asymbolus occiduus* | 212 | 213 | 2 |
| Scyliorhinidae | *Aulohalaelurus labiosus* | 28 | 66 | 5 |
| Scyliorhinidae | *Galeus boardmani* | 202 | 440 | 30 |
| Sebastidae | *Helicolenus barathri* | 322 | 523 | 10 |
| Sebastidae | *Helicolenus percoides* | 108 | 329 | 4 |
| Sebastidae | *Helicolenus sp* | 109 | 508 | 5 |
| Serranidae | *Acanthistius serratus* | 6 | 8 | 3 |
| Serranidae | *Caesioperca sp* | 40 | 60 | 11 |
| Serranidae | *Callanthias australis* | 20 | 35 | 3 |
| Serranidae | *Epinephelides armatus* | 6 | 103 | 47 |
| Serranidae | *Lepidoperca filamenta* | 322 | 322 | 1 |
| Serranidae | *Lepidoperca occidentalis* | 210 | 210 | 1 |
| Serranidae | *Othos dentex* | 8 | 66 | 10 |

|  |  |  |  |  |
|---|---|---|---|---|
| Sillaginidae | *Sillaginodes punctata* | 26 | 66 | 6 |
| Sparidae | *Chrysophrys auratus* | 13 | 316 | 120 |
| Sphyraenidae | *Sphyraena obtusata* | 6 | 47 | 7 |
| Sphyrnidae | *Sphyrna lewini* | 95 | 96 | 2 |
| Squalidae | *Squalus edmundsi* | 204 | 523 | 62 |
| Squalidae | *Squalus megalops* | 203 | 518 | 44 |
| Squalidae | *Squalus montalbani* | 202 | 510 | 47 |
| Squalidae | *Squalus nasutus* | 300 | 518 | 14 |
| Squalidae | *Squalus sp* | 222 | 500 | 11 |
| Synaphobranchidae | *Synaphobranchus kaupii* | 334 | 334 | 1 |
| Synaphobranchidae | *Synaphobranchus sp* | 408 | 523 | 4 |
| Synodontidae | *Synodus variegatus* | 52 | 84 | 3 |
| Tetraodontidae | *Lagocephalus sceleratus* | 27 | 106 | 8 |
| Tetraodontidae | *Omegophora armilla* | 94 | 103 | 2 |
| Tetraodontidae | *Torquigener vicinus* | 32 | 95 | 8 |
| Trachichthyidae | *Hoplostethus latus* | 300 | 510 | 12 |
| Triakidae | *Furgaleus macki* | 37 | 41 | 3 |
| Triakidae | *Mustelus antarcticus* | 204 | 328 | 6 |
| Triakidae | *Mustelus sp* | 234 | 329 | 5 |
| Triglidae | *Chelidonichthys kumu* | 95 | 95 | 1 |
| Trygonorrhinidae | *Aptychotrema vincentiana* | 106 | 108 | 2 |
| Trygonorrhinidae | *Trygonorrhina dumerilii* | 101 | 222 | 18 |
| Trygonorrhinidae | *Trygonorrhina fasciata* | 27 | 106 | 35 |
| Urolophidae | *Trygonoptera mucosa* | 63 | 95 | 2 |
| Urolophidae | *Trygonoptera ovalis* | 8 | 88 | 54 |
| Urolophidae | *Trygonoptera personata* | 32 | 101 | 4 |
| Urolophidae | *Trygonoptera sp* | 409 | 440 | 2 |
| Urolophidae | *Urolophus paucimaculatus* | 206 | 206 | 1 |
| Zeidae | *Zenopsis nebulosus* | 325 | 325 | 1 |

**Table S 2.2 Summary table of stereo baited remote underwater video systems (stereo-BRUVs) in each depth range from shallow waters around Rottnest Island (~5 m) to the continental slope of the Perth Canyon (~599 m).**

| Depth range (m) | Number of deployments |
|---|---|
| 0-20 | 24 |
| 21-40 | 48 |
| 41-60 | 39 |
| 61-80 | 9 |
| 81-99 | 29 |
| 100-199 | 31 |
| 200-299 | 31 |
| 300-399 | 35 |
| 400-499 | 24 |
| 500-599 | 14 |

# Chapter 3 Latitude, depth and environmental variables shape deepwater fish assemblages along the broad and continuous coastline on the west coast of Australia

## *Abstract*

Continental shelf and upper slope fishes represent valuable resources globally. Understanding the drivers of their abundance and distribution are fundamental to sustainable management. Deepwater demersal fish assemblages were sampled using Baited Remote Underwater Stereo Video systems (stereo-BRUVs, n = 417 deployments) between depths of 9 -570 m at six locations along the Western Australian coastline spanning 16° of latitude (i.e. 17-34°S at the Rowley Shoals, Montebello Islands, Ningaloo Reef, Abrolhos Islands, Perth Canyon and South West Capes). A total of 5,965 individual fishes (i.e. ΣMaxN) were identified belonging to 252 species and 92 families. Assemblage composition data were assessed against modelled temperature, salinity, current speed and direction variables, and *in-situ* habitat data. Multivariate statistical analyses revealed that the composition of fish assemblages was mostly influenced by latitude (9.5% of variation), depth (7.3%) and salinity (7.2%). Three distinct assemblages were defined in response to latitude; a tropical, a sub-tropical and a southern temperate bioregion. Species richness declined with increasing latitude, and biomass was highest in the southern bioregion. A mid-depth peak in biomass and lengths indicated the dominance of meso-predator species in the 300-399 m depth range. The information provided by this study on the factors influencing the abundance and distribution of fish assemblages over an exceptionally broad depth and latitudinal range along a continuous coastline will be useful for predicting the effects of future climate shifts on this and similar teleost species occupying tropical and temperate oceans elsewhere.

Keywords: Stereo-BRUVs, abundance, biomass, continental shelf, continental slope, demersal.

## *Introduction*

The margins of continental and insular shelves (including outer shelf and upper slope regions) have a high diversity of organisms, a range of benthic and pelagic habitats and are recognised as areas of exceptional biological value (Levin and Dayton, 2009; Ramirez-Llodra et al., 2011). These regions are also the focus for a range of competing resource sectors (particularly commercial fishing), with overlapping economic and regulatory elements compounded the impacts and pressure on this resource (Levin and Sibuet, 2012; Newman et al., 2017). As a consequence, the continental shelf and upper slope is a focal point for fisheries and natural resource management. It is also a region that is data deficient even for larger well-known orders like fishes (Koslow, 2007) with studies on fish ecology rarely spanning shelf and slope habitats across tropical to temperate environments.

Fish assemblages of the continental shelf and upper slope are linked not only through shared species and assemblage turnover, but by oceanic processes that determine the contemporaneous physical and environmental parameters (Levin and Sibuet, 2012; Gaertner et al., 2013). Predictors of fish distributions have primarily focussed on the effects of latitude, depth, ocean hydrology and bathymetry (Last et al., 2011; Zintzen et al., 2017; Travers et al., 2018). Depth is a robust predictor of fish distributions (Zintzen et al., 2017). However, across large spatial scales, latitude has been documented to be a key determinant in the composition and distribution of fish assemblages at larger scales. These broad-scale changes in latitude are correlated with fine-scale changes in water temperature, salinity and ocean currents. Decreasing biological diversity towards the poles is regarded as a fundamental ecological paradigm for both terrestrial and marine environments (Macpherson and Duarte, 1994; Willig et al., 2003). Benthic habitats and local geomorphologies in the form of submarine canyons, precipitous transition in bathymetry from shelf to slope, and offshore islands also shape assemblage patterns and ecology (Fabio et al., 2014; Bennett et al., 2018).

Sampling in deepwater ecosystems can be challenging, as it is logistically complex as well as time and resource intensive. Sampling using trawls, traps and longline fishing gear have long been, and are still, the fundamental means of data collection for sampling fish providing valuable information on species identification, genetics and individuals for the assessment of population biology (Newman et al., 2015; Newman et al., 2017). However, these extractive techniques do not provide direct links between fish assemblages and detailed habitat characteristics (Moran and Stephenson, 2000; Fabri et al., 2014; Amoroso et al., 2018). Comparison of results between surveys using trawls, traps or longlines can be inconsistent due to gear selectivity, target species and other technical constraints (Gaertner et al., 2013). Non-extractive monitoring techniques that reduce benthic impacts and allow the collection of data on associated biota in a non-destructive manner can be advantageous in certain environments (Murphy and Jenkins, 2010; Merritt et al., 2011).

Many deepwater fish assemblages exist within fragile and sparse habitats requiring an alternative approach from traditional extractive techniques (Moran and Stephenson, 2000; Mallet and Pelletier, 2014). Baited remote underwater stereo-video systems (stereo-BRUVs) have been used extensively in shallow water shelf environments and provide a non-extractive means of gathering information and monitoring of threatened, rare and data deficient fish species (Wellington et al., 2017; Harvey et al., 2018; Wiltshire et al., 2018).

Local ocean hydrology and geomorphic factors contribute significantly to the structure and diversity of assemblages demonstrating the need to study a region’s unique processes in order to assess the influences on assemblage patterns and drivers of abundance and biomass (D'Onghia et al., 2004; Menezes et al., 2006; Williams et al., 2010). On the west coast of Australia, the continental shelf and upper slope waters are strongly influenced by the Leeuwin current, a poleward-flowing eastern boundary current bringing warm, low salinity waters southwards (Caputi et al., 1996). The relatively shallow, low nutrient Leeuwin current flows strongly during the austral autumn and spring, bringing tropical marine fauna further south than expected for these latitudes (Pearce and Feng, 2013). The narrow equatorial-flowing Leeuwin undercurrent occurs between 250 and 450 m depth and contours strongly along the continental slope during the austral summer (Pattiaratchi, 2006). These two currents combine to shape crucial heterogeneous habitats supporting high rates of fish diversity and endemism in an otherwise oligotrophic environment. Range shifts have been observed across latitudes and depth gradients along the west coast of Australia (Pearce and Feng, 2013; Wakefield et al., 2013b), facilitating vagrancy of tropical fishes and other marine fauna poleward to higher (cooler) latitudes. The extensive and continuous coastline within a single state-based management jurisdiction along the west coast of Australia provides an ideal model for exploring the ways in which the abundance and distribution of fish assemblages vary with latitude and depth. Management of marine resources in Western Australia utilises ecosystem-based fisheries management (EBFM) approaches. EBFM is a holistic approach that considers all ecological resources, from fish to habitats and protected species, as well as economic and social factors in determining fishery management arrangements. A primary step in this approach is to elucidate the underlying ecosystem structure by identifying the significant variables driving assemblage abundance and distribution.

The objectives of this study were to assess how the demersal fish assemblages on the continental shelf and upper slope change with latitude and depth, and from tropical to temperate environments, along the west coast of Australia (over 16° latitude). Specifically, this study aimed to investigate the effect of ocean variables such as temperature, salinity and currents, as well as benthic habitat characteristics on demersal fish assemblage structure across depth and latitude. Clear latitudinal trends between tropical and temperate regimes are anticipated, with a decrease in species richness predicted with depth and with latitude. Overall, the study provides valuable input into fisheries management of the continental shelf and upper slope in Western Australia, as well as contributes toward ecological frameworks relating to fish distributions globally.

## *Materials and methods*

### ***Study sites***

The deepwater fish assemblages of the continental shelf to upper slope along the west coast of Australia were surveyed between March 2010 and July 2012. Survey locations spanned 16° of latitude from tropical (17°S) to temperate (34°S) bioregions. Locations were selected based around geomorphic features encompassing submarine canyons, terraces, offshore islands and atolls along the Western Australian coastline (Fig. 3.1). Depth ranges sampled within each location included the continental shelf (90-170 m depth), continental margin (170-300 m) and the upper continental slope (300-570 m). Details of the locations sampled, dates, number of deployments and depth range for each survey are listed in Table 3.1.

In early 2011, the west coast of Australia experienced a marine heatwave event affecting much of the states shallow coastal waters. Of relevance to our study, the sampling of Ningaloo Reef and Montebello Islands took place during the peak of the heatwave event on the north west coast in March 2011 (Pearce and Feng, 2013; Wernberg et al., 2013). There is potential for temporal bias associated with sampling different locations at different times, and we acknowledge that the environmental conditions may have changed over the 27-month survey period. However, we believe that the spatial scale of sampling incorporates larger variations in fish assemblage structure mitigating the potential for minor temporal bias.

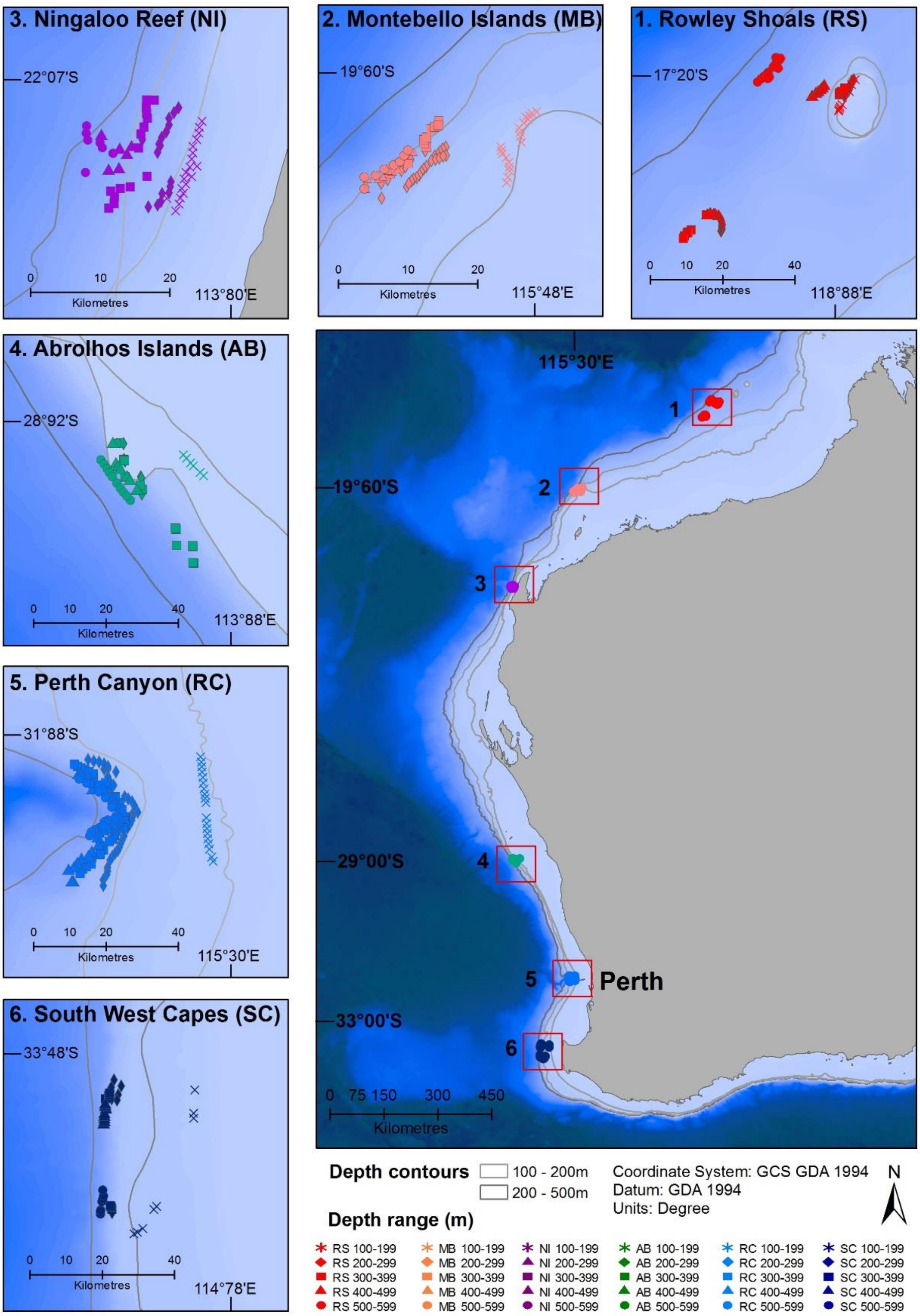

**Figure 3.1 Map of surveys of stereo-BRUV deployments along the western Australian coast from 2010 to 2012. Key to locations: 1. Rowley Shoals (RS), 2. Montebello Islands (MB), 3. Ningaloo Reef (NI), 4. Abrolhos Islands (AB), 5. Perth Canyon (RC), 6. South West Capes (SC).**

**Table 3.1 Table summary of locations and dates surveyed, approximate latitude and longitude and minimum and maximum depth in which stereo-BRUVs were deployed between March 2010 and July 2012. The total number of samples across a location and depth range are in bold.**

| **Survey and Dates** | **approx. latitude** | **approx. longitude** | **min depth** | **max depth** | **100-199 m** | **200-299 m** | **300-399 m** | **400-499 m** | **500-599 m** | **total** |
|---|---|---|---|---|---|---|---|---|---|---|
| Rowley Shoals, September 2011 (RS) | -17.339°S | 118.577°E | 91 | 516 | 8 | 15 | 12 | 12 | 14 | **61** |
| Montebello Islands, March 2011 (MB) | -19.715°S | 115.362°E | 98 | 572 | 19 | 26 | 11 | 8 | 8 | **72** |
| Ningaloo Reef, March 2011 (NI) | -22.193°S | 113.728°E | 99 | 540 | 19 | 17 | 15 | 6 | 7 | **64** |
| Abrolhos Islands, November 2010 (AB) | -28.599°S | 113.469°E | 111 | 535 | 6 | 8 | 18 | 7 | 10 | **49** |
| Perth Canyon, March & Nov 2010 (RC) | -32.012°S | 115.219°E | 101 | 570 | 19 | 35 | 33 | 26 | 15 | **128** |
| South West Capes, March & July 2012 (SC) | -34.084°S | 114.562°E | 102 | 553 | 8 | 12 | 8 | 8 | 7 | **43** |
| **Total:** | | | | | **79** | **113** | **97** | **67** | **61** | **417** |

### *Sampling regime*

Non-extractive stereo-BRUVs were used to record the imagery from which fish could be identified, counted, and length measurements undertaken. Benthic habitat characteristics were also quantified from the stereo video imagery (substrate type, seabed relief, and benthic biota). A total of 417 stereo-BRUVs were deployed during daylight (0800-1700 h) in sets of up to ten stereo-BRUV units. Sampling was stratified into depth categories deploying 1-2 sets (10-20 samples) in consecutive 100 m depth increments between 100-600 m. Each stereo-BRUV was spaced a minimum distance of 500 m from each other in order to reduce the potential overlap in bait plume dispersal and thus reduce the chance of species movements between BRUVs (Cappo et al., 2001; Harvey et al., 2007; Langlois et al., 2011). A balanced sampling design was prepared, *a priori*, to target a variety of reliefs and substrate types (i.e. soft sediment or hard rocky) within each depth range based on detailed bathymetry (i.e. depth contours) and backscatter (i.e. substrate density) maps.

The stereo-BRUV systems used two high-definition cameras (Sony® CX7 or CX12 models) mounted securely inside waterproof camera housings. Blue LEDs were used to illuminate the field of view. The configurations of the cameras and the information pertaining to the use of the blue LED lights can be found in Wellington et al. (2018). Each bait bag was filled with 800 to 1000 g of Australian pilchards (*Sardinops sagax*), crushed to amplify the bait plume (Westerberg and Westerberg, 2011; Dorman et al., 2012). Stereo-BRUVs were deployed for approximately two hours to allow longer analysis timeframes (90 minutes) and to allow for the time needed for the system to reach the seafloor. In deepwater, marine taxa tend to move slower and be more sparsely distributed than in shallow water habitats, which required longer sampling durations to achieve species saturation (McLean et al., 2015; Zintzen et al., 2017).

### *Data collection*

Stereo-BRUVs were calibrated before and after each survey using CAL software (www.seagis.com.au) to enable accurate length measurements during video analysis, following the procedures outlined by Harvey and Shortis (1998). The relative abundance of fish and fish lengths were measured using EventMeasure Stereo software (see www.seagis.com.au). The relative abundances of fish were defined using MaxN, the maximum number of any one species recorded within the field of view at any one time.

Fish species were identified to the lowest possible taxa using the available literature (Gomon et al., 2008; Last and Stevens, 2009; Froese and Pauly, 2019) and in consultation with expert scientific knowledge. Weight estimates were calculated using the length measurement of individual fish and length-weight relationship estimates obtained from local fisheries unpublished data or via FishBase (Froese and Pauly, 2019). Where species-specific relationships were not available, the relationship of a similar congener was used as a proxy. Biomass estimates for each species were summed for each deployment.

Images from each video deployment were used to score benthic habitat using TransectMeasure (www.seagis.com.au). Percentage scores were determined using a 20-point grid division within each image. Identification of the dominant habitat (within each grid) was recorded using Collaborative and Automated Tools for Analysis of Marine Imagery (CATAMI) classification definitions (Althaus et al., 2013). Categories were defined as; substrate type (consolidated and unconsolidated), seabed relief (gradients 0-5) and benthic biota (macroalgae, sponge, coral).

Average temperature, salinity, current direction and speed were derived from data taken from Bluelink ReANalysis (BRAN). The global ocean model that underpins BRAN is called the Ocean Forecasting Australia Model (OFAM), and OFAM is combined with a data assimilation system that blends ocean observations of satellite altimetry, satellite sea-surface temperature, and temperature and salinity from floats and moorings (see http://wp.csiro.au/bluelink/global/bran/). The resulting BRAN provides a time-varying picture of the ocean circulation over the past 20 years. Subsets of BRAN data were extracted from the National Computing Infrastructure (NCI) Thredds server using the command-line program netCDF Kitchen Sink (ncks ) from the netCDF Operators (NCO ) program suite (see http://nco.sourceforge.net/; (Oke et al., 2013; THREDDS Data Server, 2015). Data were extracted to match the date, depths and spatial coordinates of each stereo-BRUV deployment (see Table 3.1). BRAN data were matched to the closest corresponding BRUV depth and averaged across depth range categories between 100-599 m.

### *Statistical analyses*

Multivariate statistical analyses were performed using PRIMER 7 (version 7.0.10) (Clarke et al., 2014) with the PERMANOVA+ add on (version 1) (Anderson et al., 2008). The analysis of abundance and biomass data for each transect involved constructing a Bray Curtis similarity matrix following a square root transformation. Bray Curtis is a suitable measure for use in assemblage data sets where maintaining relative abundances and species composition are important (Anderson et al., 2011). Permutational multivariate analysis of variance (PERMANOVA) (Anderson, 2001) provided an initial test for significant differences in latitude and depth (fixed, two factors) using type III sums of squares with 9999 permutations. Pair-wise comparisons were used to identify functional groups within depth ranges and latitudes.

A distance-based linear model (DistLM) measured the relationship between the fish assemblage structure and environmental variables. A draftsman plot revealed a high correlation (> 0.9) between depth and temperature. In subsequent analyses we removed temperature as a covariate. The resulting DistLM and associated distance-based redundancy analysis (dbRDA) plot determined how much of the variability is attributable to the remaining predictor variables (Anderson et al., 2008). The BEST selection procedure was used to examine the value of the selection criterion for all possible combinations using normalised predictor variables (Clarke et al., 2014). The best overall model was found using the Akaike Information Criterion (AIC) to display the most parsimonious combination of variables influencing the assemblage composition (Akaike, 1973; Anderson et al., 2008).

Canonical analyses of principal coordinates (CAP) ordinations (Anderson and Willis, 2003) investigated trends in the relative abundance of fish assemblages in relation to depth and latitude at a family (choice of m: 18) and species level (choice of m: 38), both with 417 samples. This constrained ordination allowed *a priori* classifications to be maintained, providing a visual assessment of the PERMANOVA results, namely the interaction between latitude and depth. Pearson correlations of ≥ 0.4 were used to graphically present potential correlations between the assemblage data and variables relative to the canonical axes. Leave-one-out allocation (LOOA) tests were generated during the CAP analysis to assess the misclassification error based on the constrained analysis (i.e. minimising the misclassification error, which maximises the allocation success).

The average number of species, number of individuals, mean length of individual fishes and relative total biomass were calculated for each depth range and across each survey (± 1 SE). A list is provided in the Supplementary Materials detailing species identified during the study. The table details species that were recorded outside their known depth range (depth extensions) along with the scientific name, common name, habitat, distribution, known depth ranges and observed depth range, whether they are endemic species, and their respective IUCN classification (IUCN, 2012). The known depth ranges and locations were sourced from FishBase and compared to Fishes of Australia records, and other available literature (Last and Stevens, 2009; Gomon, 2015; Froese and Pauly, 2019).

## *Results*

### ***Assemblage composition***

A total of 5,965 individual fishes (i.e. ΣMaxN) were identified belonging to 252 species and 92 families. Carangidae, Squalidae, Carcharhinidae, Labridae and Epinephelidae were most ubiquitous, each being identified in all six surveys. Fifty-six percent of the fishes counted were from five families; Carangidae (19.13%), Squalidae (11.89%), Sparidae (9.81%), Lutjanidae (8.05%) and Monacanthidae (7.96%). The remaining 43% of the fishes counted represented 69 families with another 18 families represented by single observations of species (0.3%). The two most abundant species were *Nelusetta ayraud* (∑MaxN = 475) recorded across the shelf break (100-247 m depth) and *Oplegnathus woodwardi* (∑MaxN = 453), recorded across the shelf break and upper slope (103-416 m depth).

Assemblage composition at a family and species level displayed significant differences by latitude (PERMANOVA, p < 0.0001) and depth (p < 0.0001), and for the interaction between these two factors (latitude x depth, p < 0.0001) (Table 3.2). Pair-wise comparisons of the interaction term (latitude x depth) in the family abundance data showed all combinations of pairs were significantly different except between the 400-499 and 500-599 m depth ranges for the South West Capes (SC, p > 0.6125) (Supplementary Material Table S 3.1). Pair-wise comparisons in the species abundance data showed all combinations of pairs were significantly different except between the 200-299 and 300-399 m depth ranges for the Rowley Shoals (RS, p > 0.0894), the 400-499 and 500-599 m depth ranges for the Montebello Islands (MB, p > 0.163) and between the 400-499 and 500-599 m depth ranges for the South West Capes (SC, p > 0.5838) (Supplementary Material Table S 3.1).

**Table 3.2 PERMANOVA table of results of fish assemblages using a two-factor design (latitude, fixed, 6 levels) (depth range, fixed 5 levels), type III sums of squares with 9999 permutations performed on family and species classifications of abundance data.**

| **Abundance data** | **Family** | | | | | | **Species** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Source** | **df** | **SS** | **MS** | **pseudo-F** | **P(perm)** | **Unique perms** | **df** | **SS** | **MS** | **pseudo-F** | **P(perm)** | **Unique perms** |
| Latitude | 5 | 35.564 | 7.1127 | 19.301 | **0.0001** | 9810 | 5 | 299120 | 59823 | 27.317 | **0.0001** | 9806 |
| depth range | 4 | 38.792 | 9.698 | 26.317 | **0.0001** | 9849 | 4 | 179030 | 44757 | 20.437 | **0.0001** | 9804 |
| latitude x depth range | 20 | 56.042 | 2.8021 | 7.6039 | **0.0001** | 9676 | 20 | 413790 | 20690 | 9.4473 | **0.0001** | 9629 |
| Residuals | 387 | 142.61 | 0.3685 | | | | 387 | 847530 | 2190 | | | |
| Total | 416 | 292.27 | | | | | 416 | 2E+06 | | | | |

### *Environmental influences on the distribution of fish composition*

The distance-based linear model (DistLM) identified the top one (latitude, 9.5%), two (latitude and depth, 16.9%) and three combinations of variables (latitude, depth, salinity; total contribution 20.3%, AIC = 3415.4, $r^2$=0.2) influencing assemblage compositions (Table 3.3). In marginal tests from the DistLM all variables had p values > 0.0001, with the exception of macroalgae (p > 0.6896) and coral (p > 0.0693) (Table 3.4). The total contribution of all variables was 44.2% (Table 3.4). A BEST solution model determined that the most parsimonious explanation of environmental influences was associated with nine variables, contributing 29.3% of the proportional variation in the assemblage (AIC = 3377.8, $r^2$=0.29). In decreasing order of contribution, these were latitude, depth, salinity, current direction, current speed, longitude, sponge (habitat), unconsolidated (benthos), and consolidated (benthos).

**Table 3.3 DistLM solution using best selection procedure with Akaikes Information Criterion (AIC) for the top one, two and three combination of variables.**

| AIC | R2 | RSS | Number of variables | Selections |
|---|---|---|---|---|
| 3463.8. | 0.09552 | 6.73E+09 | 1 | latitude |
| 3430.6 | 0.16882 | 5.37E+09 | 2 | latitude, depth |
| 3415.4 | 0.20255 | 4.75E+09 | 3 | latitude, depth, salinity |

**Table 3.4 Marginal tests from DistLM for each variable showing SS(trace), Pseudo-F, p values (significant values (p < 0.05) are in bold) and proportion of variation explained as a percentage.**

| No. | Variable | SS(trace) | Pseudo-F | p | Prop. | % |
|---|---|---|---|---|---|---|
| 1 | Relief (flat) | 13822 | 3.1251 | **0.0001** | 0.0074741 | 0.74741 |
| 2 | Relief (grade 1) | 34070 | 7.789 | **0.0001** | 0.018423 | 1.8423 |
| 3 | Relief (grade 2) | 35386 | 8.0957 | **0.0001** | 0.019134 | 1.9134 |
| 4 | Macro algae | 4207.5 | 0.94633 | 0.6896 | 0.0022751 | 0.22751 |
| 5 | Coral | 6360.3 | 1.4322 | 0.0693 | 0.0034392 | 0.34392 |
| 6 | Sponge | 40762 | 9.3532 | **0.0001** | 0.022041 | 2.2041 |
| 7 | Unconsolidated benthos | 35353 | 8.0879 | **0.0001** | 0.019116 | 1.9116 |
| 8 | Consolidated benthos | 16886 | 3.8243 | **0.0001** | 0.009131 | 0.9131 |
| 9 | Salinity | 1.34E+05 | 32.304 | **0.0001** | 0.072218 | 7.2218 |
| 10 | Current speed | 63589 | 14.778 | **0.0001** | 0.034385 | 3.4385 |
| 11 | Direction | 77343 | 18.114 | **0.0001** | 0.041822 | 4.1822 |
| 12 | Depth | 1.35E+05 | 32.567 | **0.0001** | 0.072764 | 7.2764 |
| 13 | Latitude | 1.77E+05 | 43.83 | **0.0001** | 0.095525 | 9.5525 |
| 14 | Longitude | 44072 | 10.131 | **0.0001** | 0.023831 | 2.3831 |

A distance-based redundancy analysis (dbRDA) of the fish assemblage data showed dbRDA1 explained 37.1% of fitted and 10.9% of total variation and dbRDA2 described 26.5% of fitted and 7.7% of total variation (Fig. 3.2). Clear correlations were evident in the dbRDA ordination with data points distributed primarily in response to latitude along dbRDA1 and secondarily depth along dbRDA2 (Fig. 3.2a & b). The data points within the ordination were generally distributed into three groups with latitude sequentially correlated along the first axis, such that the two most southern and cooler water locations (i.e. South West Capes and Perth Canyon) were closely grouped to one side. The three northernmost locations (i.e. Rowley Shoals, Montebello Islands and Ningaloo Reef) were closely grouped at the opposite side, with the Abrolhos Islands data points grouped between them (Fig. 3.2a).

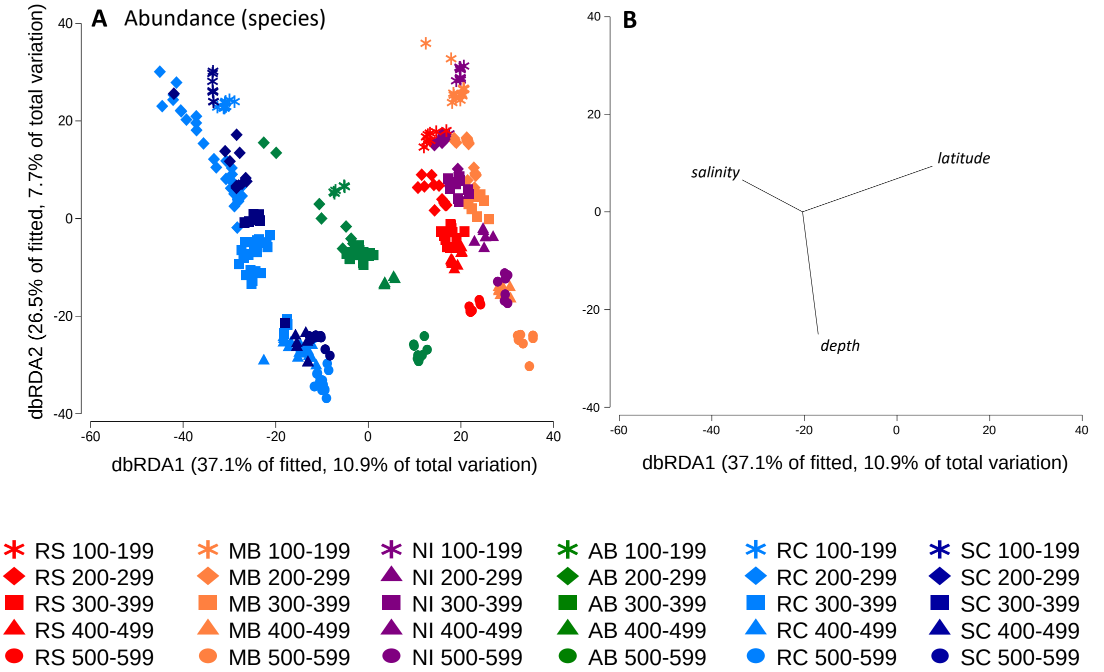

**Figure 3.2 A distance-based redundancy analysis (dbRDA) of** A. **fish assemblage data with** B. **Corresponding strength and direction of Pearson correlation ≥ 0.4 environmental variables shown as line vectors. The analysis was based on Bray Curtis resemblance after a square root transformation.**

### *Interaction of latitude and depth on family & species composition*

Both family and species level compositions displayed distinct differences in relation to latitude and depth in the CAP ordinations (Fig. 3.3. p value < 0.0001, Trace statistic 7.02, delta $1^2$ test statistic 0.9, Fig. 3.4. p value < 0.0001, Trace statistic 12.2, delta $1^2$ test statistic 0.96, respectively). The data points within the family level CAP ordination were generally distributed into three distinct groups (Fig. 3.3a). Samples from the Rowley Shoals, Montebello Islands, and Ningaloo Reef surveys were strongly distributed by depth along the CAP2 axis and were separated by higher abundances of Carcharhinidae and Sparidae in shallower waters (Fig. 3.3a & b). Samples from the Perth Canyon and the South West Capes surveys were strongly grouped by two distinct depth ranges; 100-199 m and 300-599 m. Abrolhos Islands samples were distributed centrally through the data cloud with respect to latitudinal correlations with the primary axis (Fig. 3.3a). The more southern surveys were separated by higher abundances of Squalidae, Centrophoridae and Macrouridae associated with the 300-599 m depth ranges, while the Monacanthidae and Oplegnathidae were correlated with shallower water assemblages (Fig. 3.3b).

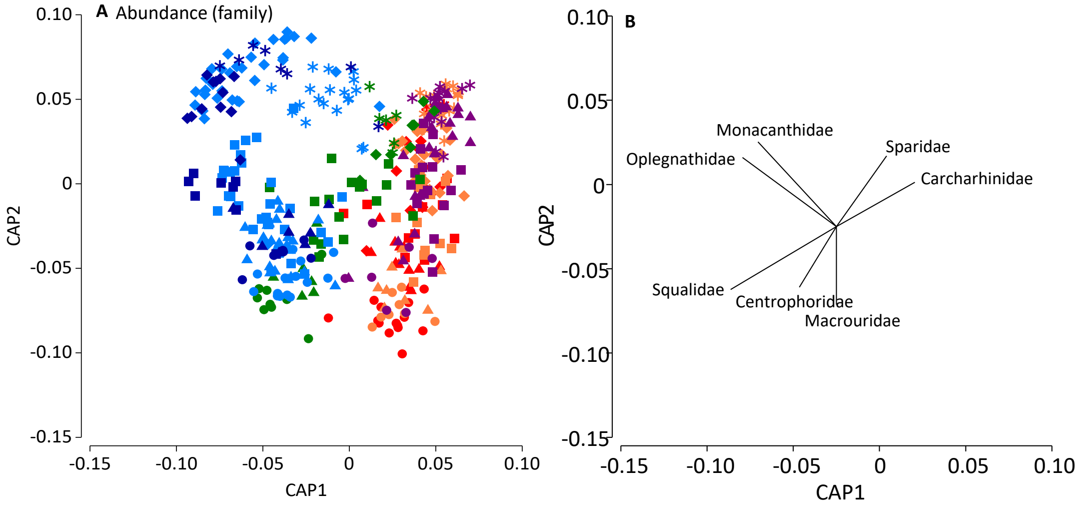

**Figure 3.3 Canonical analysis of principal coordinates (CAP) of** A. **Abundance of fish assemblages using family level classifications, based on square-root transformed Bray-Curtis resemblance measure in relation to latitude and depth.** B. **Corresponding strength and direction of Pearson correlation ≥ 0.4 shown as line vectors. Key as per Fig. 3.2.**

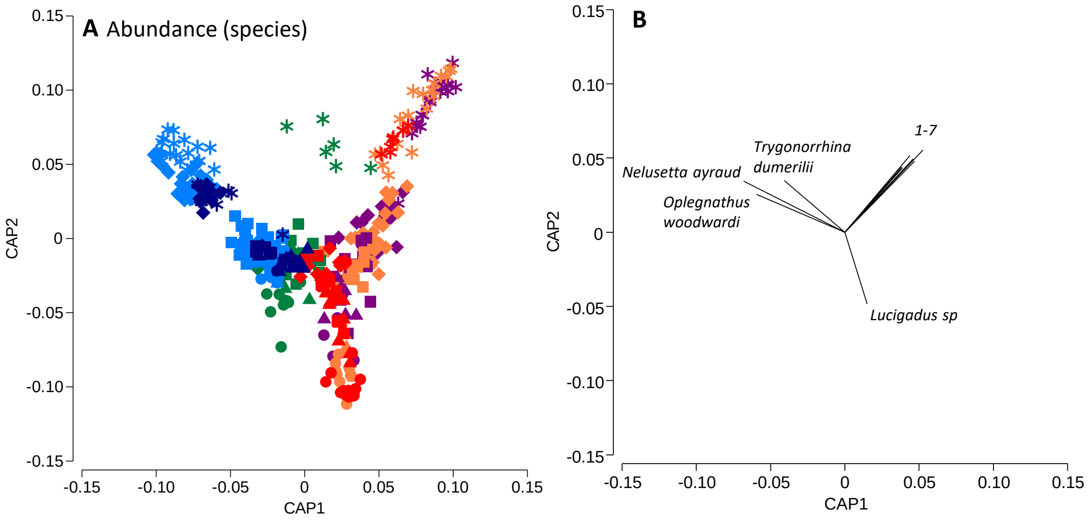

**Figure 3.4 Canonical analysis of principal coordinates (CAP) of A. Abundance of fish assemblages using species level classifications based on Bray Curtis resemblance measure after square root transformation in relation to latitude and depth. B. Corresponding strength and direction of Pearson correlation ≥ 0.4 shown as line vectors. 1-7: *Seriola rivoliana, Pristipomoides multidens, Gymnocranius grandoculis, Carangoides chrysophrys, Lutjanus sebae, Argyrops spinifer, Pristipomoides typus.* Key as per Fig. 3.2.**

The CAP ordination of species abundance was strongly structured by depth and latitude. The CAP1 axis delineated variations in latitude separating shallow-water assemblages in the north from those in the south (Fig. 3.4a). The three northernmost surveys (Rowley Shoals, Montebello Islands and Ningaloo Reef) were distributed sequentially by depth along the secondary axis (CAP2 axis) (Fig. 3.4a). Species composition was more similar with increasing depth shown by the convergence of points from all survey locations in depths between 300-599 m. Pearson correlations indicated that higher abundances of *Seriola rivoliana, Pristipomoides multidens, Gymnocranius grandoculis, Carangoides chrysophrys, Lutjanus sebae, Argyrops spinifer* and *Pristipomoides typus* were more strongly associated with shallower water assemblages of the three northern surveys (Fig. 3.4b). In contrast, higher abundances of *Oplegnathus woodwardi, Nelusetta ayraud* and *Trygonorrhina dumerili* were more strongly associated with the shallower water assemblages of the temperate locations in the Perth Canyon, South West Capes and the Abrolhos Islands surveys. Abundances of *Lucigadus sp*. were the only correlation ≥ 0.4 associated with depth ranges 300-599 m across all surveys (Fig. 3.4b).

The Leave One Out Allocation tables showed that the overall percentage allocation success at a family classification level to be 53.7% (Supplementary Material Table S 3.2). Family level allocation success was generally highest in the shallow water 100 m depth ranges, e.g.

Rowley Shoals 87.5%, Perth Canyon 89.5%. However, there appeared to be no consistent pattern in the allocation success across depth or latitude with the Abrolhos Islands 500-599 m depth range (90.0%) recording the highest overall percentage success. Remaining allocation successes ranged between 14.3% and 80.0%. The overall allocation success was highest at the species level (62.6%, Table 3.5). Allocation success was highest in the 100-199 m depth ranges (63.2–100.0%) with the exception of the South West Capes (25.0%). Allocation success was 100.0% in the Rowley Shoals 100-199 m, and the Abrolhos 100-199 and 200-299 m ranges. The lowest allocation success occurred at the Ningaloo 300-399 m (20.0%). Misclassifications were contained within the north and within the south bioregions, whereby the three northernmost surveys in the tropical region (RS, MB, NI) had no misclassifications in the two southernmost surveys (RC and SC), and Perth Canyon and South West Capes misclassifications were exclusive within the three temperate locations (AB, RC, SC). Whereas, the centrally located Abrolhos Islands samples were misclassified among all other locations (Table 3.5).

**Table 3.5 Leave-one-out allocation to groups from canonical analysis of principal coordinates (CAP) using species level classifications of abundance data. Light green shading indicates the correct allocation group; dark green indicates samples successfully allocated to their group; orange shading indicates where samples were misclassified. Average allocation success across all groups was 65.59%.**

| Original group | RS100 | RS200 | RS300 | RS400 | RS500 | MB100 | MB200 | MB300 | MB400 | MB500 | NI100 | NI200 | NI300 | NI400 | NI500 | AB100 | AB200 | AB300 | AB400 | AB500 | RC100 | RC200 | RC300 | RC400 | RC500 | SC100 | SC200 | SC300 | SC400 | SC500 | Total | % correct |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RS100 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 100.00 |
| RS200 | 0 | 11 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 73.33 |
| RS300 | 0 | 5 | 4 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 33.33 |
| RS400 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 58.33 |
| RS500 | 0 | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14 | 78.57 |
| MB100 | 0 | 0 | 0 | 0 | 0 | 12 | 2 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | 63.16 |
| MB200 | 0 | 0 | 0 | 0 | 0 | 0 | 14 | 3 | 0 | 0 | 0 | 6 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 26 | 53.85 |
| MB300 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 5 | 1 | 0 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | 45.46 |
| MB400 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 4 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 50.00 |
| MB500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 6 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 75.00 |
| NI100 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 15 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | 78.95 |
| NI200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 88.24 |
| NI300 | 0 | 1 | 3 | 1 | 0 | 0 | 2 | 3 | 0 | 0 | 0 | 1 | 3 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 20.00 |
| NI400 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 50.00 |
| NI500 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 28.57 |
| AB100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 100.00 |
| AB200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 100.00 |
| AB300 | 0 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 18 | 55.56 |
| AB400 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 7 | 71.43 |
| AB500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 10 | 80.00 |
| RC100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | 89.47 |
| RC200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 19 | 1 | 0 | 0 | 7 | 6 | 0 | 0 | 0 | 35 | 54.29 |
| RC300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 22 | 7 | 3 | 0 | 0 | 1 | 0 | 0 | 33 | 66.67 |
| RC400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | 0 | 0 | 3 | 15 | 3 | 0 | 0 | 0 | 0 | 1 | 26 | 57.69 |
| RC500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 2 | 4 | 7 | 0 | 0 | 0 | 0 | 0 | 15 | 46.67 |
| SC100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | 3 | 0 | 0 | 0 | 8 | 25.00 |
| SC200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 10 | 1 | 0 | 0 | 12 | 83.33 |
| SC300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 1 | 0 | 8 | 87.50 |
| SC400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 3 | 8 | 37.50 |
| SC500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 2 | 7 | 28.57 |

### *Trends in species abundance, lengths and biomass*

The average number of species decreased with increasing depth, with the highest number of species occurring in the 100-199 m depth range (8.3 ± 0.45 SE) (Fig. 3.5a). The lowest average number of species occurred at 300-399 m (3.9 ± 0.19), increasing slightly at 400-499 m (4.5 ± 0.22) and 500-599 m (5.1 ± 0.27). The average number of individuals followed a similar trend, with the highest average in the 100-199 m (24.1 ± 2.0 SE) depths, before dropping to 7.8 (± 0.5 SE) in 300-399 m, then increased slightly in the 400-499 and 500-599 m depths (Fig. 3.5b). The average length of fishes increased with depth to a maximum of 482 mm (± 12 SE) at 300-399 m, before decreasing to a minimum average of 374 mm (±- 15 SE) in 500-599 m (Fig. 3.5c). Average biomass per deployment decreased sequentially with increasing depth categories from 36 kg (± 0.6 SE) in 100-199 m to 4 kg (± 0.8 SE) in 500-599 m depth (Fig. 3.5d).

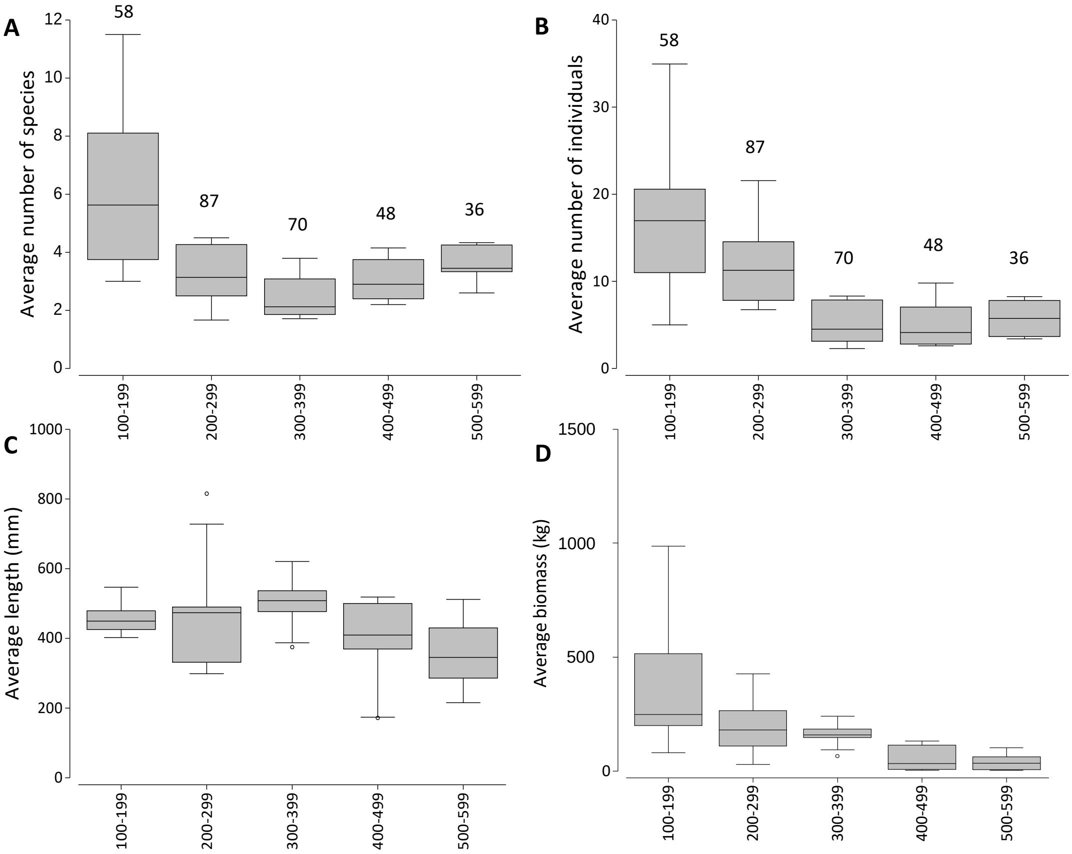

**Figure 3.5 Box plots display the average number of A) species, B) individuals, C) length (mm) and D) biomass weight (kg) over depth ranges from 100-199 to 500-599 m (L – R), sample numbers are displayed above box plots A and B.**

In contrast, the trends in fish assemblage characteristics were not as consistent with latitude. The average number of species was highest in the Montebello Islands (6.4 ± 0.4 SE) and lowest in the South West Capes (3.6 ± 0.3 SE) (Fig. 3.6a). The average number of individuals within each survey was highest in the South West Capes (19.9 ± 2.6 SE) and lowest in the Rowley Shoals (10.6 ± 2.5 SE) (Fig. 3.6b). The highest average length of fishes within each survey were recorded in the three southern temperate regions of the Abrolhos Islands, South West Capes and Perth Canyon (462 mm ± 20 SE, 458 mm ± 10 SE, 452 mm ± 5 SE respectively) (Fig. 3.6c). The Montebello Islands and Perth Canyon surveys displayed the highest average biomass per deployment (24 kg ± 6 SE and 23 kg ± 3 SE respectively) and the Abrolhos Islands the lowest (10 kg ± 4 SE) (Fig. 3.6d).

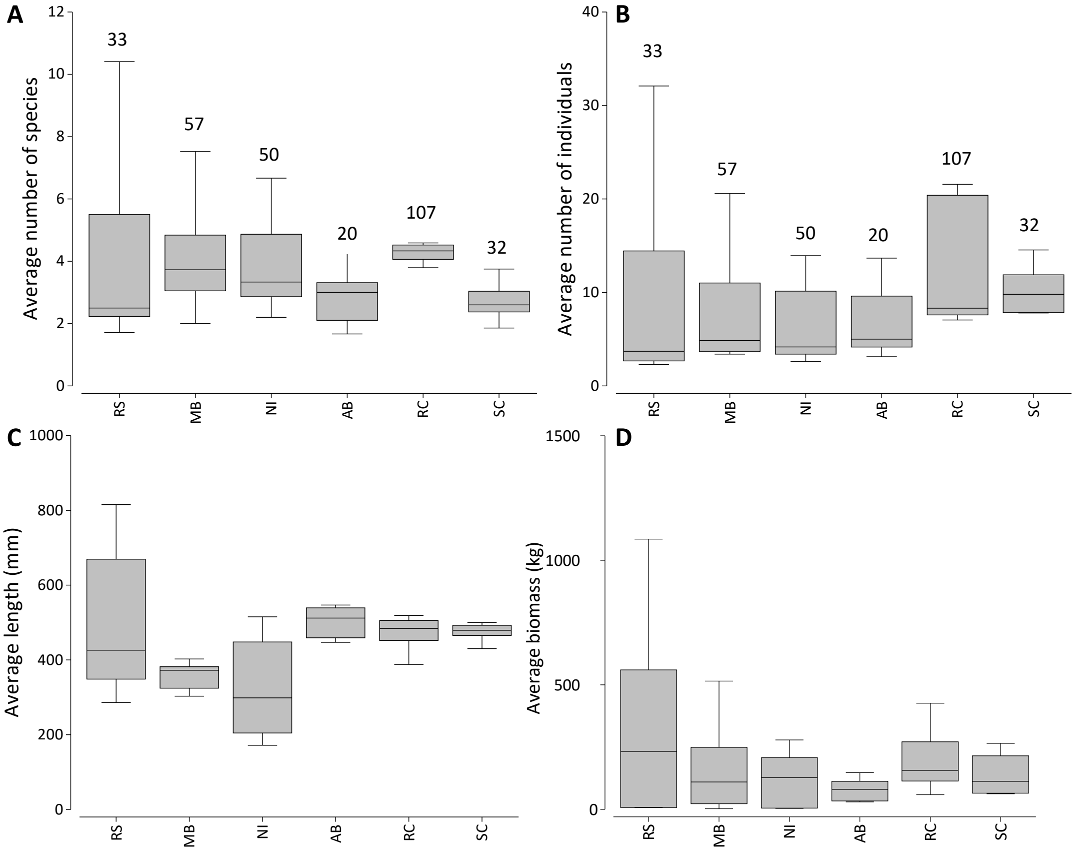

**Figure 3.6 Box plots display the average number of A) species, B) individuals, C) length (mm) and D) biomass weight (kg) across surveys (latitude) from north to south. Key from left to right Rowley Shoals (RS), Montebello Islands (MB), Ningaloo Reef (NI), Abrolhos Islands (AB), Perth Canyon (RC), South West Capes (SC).**

Depth range extensions were recorded for 76 species (Supplementary Material Table S 3.3). Of fishes identified to species level, 32 (17. 3%) were endemic to Australia. Twenty species (10.8%) were classified to significant categories by the IUCN Red List of Threatened Species; Near Threatened (n=8), Vulnerable (n=9), Endangered (n=2) and Critically Endangered (n=1) (Froese and Pauly, 2019; IUCN, 2019). The remaining species identified were classified as Least Concern (LC, 54.0%), 29.2% were Not Evaluated (NE) and 6.0% identified as Data Deficient (DD) (Supplementary Material Table S 3.3).

## *Discussion*

### ***Assemblages defined by latitude***

Data collected with non-extractive stereo-BRUVs across 16-degrees of latitude (encompassing tropical and temperate ecosystems) between depths of ~100 to 600 metres exhibited distinct patterns in the composition of fish assemblages at both the family and species level primarily associated with latitude and depth. Fish assemblages were distributed into three broad latitudinal areas; a northern tropical bioregion 17-22°S (RS, MB, NI), a sub-tropical bioregion 28°S (AB) and a southern temperate bioregion 32-34°S (RC, SC), indicating significant differences in assemblage structure in response to latitude. This is a delineation supported by trawl studies in Western Australia. Last et al. (2011) identified three shelf provinces, while Williams et al. (2001) identified distinct community structures delineated at 26-28°S. Across Western Australia, the continental shelf and slope fish assemblages are rich and diverse in composition. Except for the Perth Canyon, species richness declined towards higher latitudes, a trend supported by numerous studies globally (Macpherson and Duarte, 1994; Zintzen et al., 2017). Average biomass was highest in the Rowley Shoals, driven predominantly by the 100-199 m depth range. Biomass decreased in mid-latitudes before it rose slightly in the southern two surveys along with higher average fish lengths. In this, we differed somewhat from the study of Williams et al. (2001) who found that fish density was lowest in northern latitudes and increased monotonically with latitude. We acknowledge that there are likely to be methodological biases associated with comparing studies using different survey methods.

Depth driven structure of deepwater fishes is well defined in the literature (Koslow et al., 1994; Zintzen et al., 2012). This structure is evident in our study, where assemblages were delineated by depth within the three latitudinal regions identified above. In the northern tropical region, there was distinct vertical structure; surveys (RS, MB, NI) revealed a linear and gradual distribution (over a greater magnitude) in response to depth with delineation evident between the shelf (100-199 m) and the rest of the assemblage. The southern temperate three surveys (AB, RC, SC) exhibited two distinct assemblages; one grouped continental shelf and margin depths together (100-199 m & 200-299 m), the other grouped remaining depth ranges on the slope (300-399 m, 400-499 m and 500-599 m). For the comparative depth ranges, Williams et al. (2001) delineated two groups within the shelf break, and a single cluster at the upper slope communities to ~350-500 m with both groups present in northern and southern latitudes. The patterns depicted in the current study are likely attributable to regional oceanography. The shelf margin coincides with the lower limit of the Leeuwin Current at 300 m and also the boundary between the south-flowing warm, low salinity Leeuwin Current and a deeper, northwards moving undercurrent (Pearce, 1991; Waite et al., 2007).

### *Environmental influences*

Many environmental covariates were interrelated, being driven by the same physical processes. Here, the most influential variables were latitude, depth and salinity, noting that temperature was subsequently excluded from the DistLM model due to its high correlation with depth (> 0.9). Variations in temperature and salinity control water density, which in turn is responsible for driving ocean and climate circulation on a global level (Riser et al., 2008; Chen et al., 2018). Salinity was lowest at the Rowley Shoals, where Tropical Surface Water (TSW) brings low salinity water southwards, and higher rainfalls provide additional freshwater input (Fig. 3.7). In the 100-199 m depth range, salinity increased with increasing latitude. Surface waters are most strongly influenced by atmospheric events such as evaporation and precipitation, which readily impact salinity and temperature dynamics. Below 200 m, salinity values decreased with increasing depth, most notably in the southern temperate three surveys (AB, RC, SC) with values from all surveys converging to a similar range at a depth of 500-599 m (Fig. 3.7). In deepwater areas, ocean dynamics play a dominant role where deepwater currents and forces such as horizontal advection, mixing and entrainment drive localised ocean hydrology (Pattiaratchi, 2006; Chen et al., 2018).

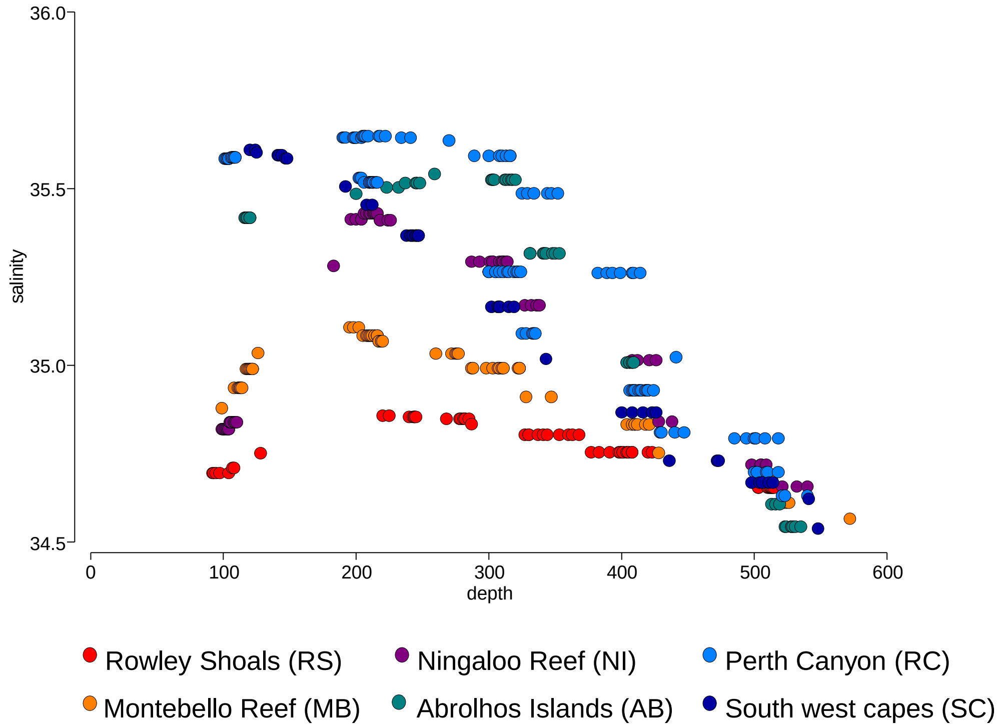

**Figure 3.7 Average salinity (ppt) over depth for each stereo-BRUV deployment based on Bluelink ReANalysis data.**

Ocean temperature is often highly correlated with depth and latitude. In this case, it was synonymous with depth. Overall, temperature decreased with increasing depth within each survey (Fig. 3.8). However, strong latitudinal patterns existed for temperature with decreasing average temperatures expected from tropical to temperate regions. An exception to this pattern occurred at a latitudinal range where the highest temperatures were recorded for the shallow shelf waters (100-199 m) at the Montebello Islands and Ningaloo Reef surveys (Fig. 3.8). This was most likely due to temporal differences as these two surveys were sampled during March 2011, coinciding with the marine heatwave event affecting the west Australian coast (Pearce and Feng, 2013; Wernberg et al., 2013). Currents, in both surface and intermediate-depth water masses continuously influence the mixing and distribution of fishes along the west coast of Australia (Pattiaratchi, 2006; Lenanton et al., 2009). Current speed and direction were significant variables contributing to the best solution model of assemblage distribution. Habitat factors, in particular, sponge (benthic biota), unconsolidated and consolidated benthos (substrate type), were minor components in the overall model, indicating that at large spatial scales benthic habitat and substrate type played only a minor role in determining fish assemblage distribution. This is in contrast to Wellington et al. (2018) where benthic biota, depth and seabed relief were the determining factors in assemblage distribution over depth. This contrast highlights the importance of spatial scales, indicating that at scales of tens of kilometres, benthic habitat factors are important drivers of assemblage structure. The patterns and causal mechanisms detected in any study are dependent upon the spatial scales defined *a priori* (Newman et al., 2017).

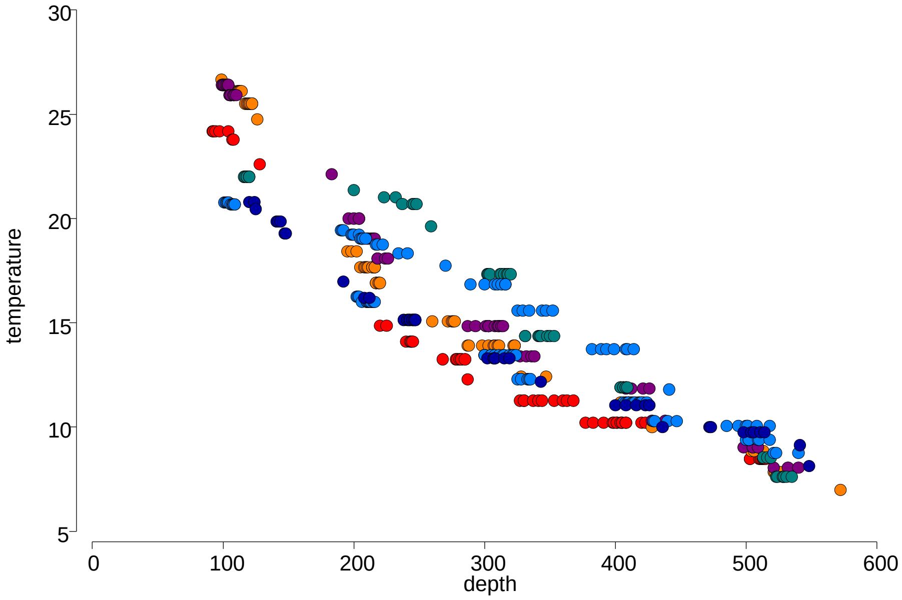

**Figure 3.8 Average temperature (°C) over depth for each stereo-BRUV deployment based on Bluelink ReANalysis data. Key as per Fig. 3.7.**

### ***Trends in species composition***

An inflexion point was evident at the 300-399 m depth range in the average number of individuals, species and lengths across all surveys. Specifically, this depth range represented the lowest average number of species and individuals, yet the highest average lengths. Average biomass remained steady between the 200-299 m and the 300-399 m depth ranges spanning the continental margin and upper slope, before decreasing substantially. The decrease in the average number of species and individuals within the 300-399 m depth range coupled with increased average fish length and biomass indicate the higher abundance of larger-bodied meso-predator species.

Some of the typifying species in this 300-399 m depth range included the cryptic *Etelis carbunculus/E.* sp in the north, *Oplegnathus woodwardi* and *Seriola* sp. in the mid and south bioregions, with four species of *Squalus* present throughout the full latitudinal range. These meso-predator species are important commercial and recreational species in Western Australia. *Squalus* are also a significant by-catch species of several fisheries in Australia (Graham et al., 2001). Similarly, on the south-eastern slope of Australia, a few relatively large pelagic species of similar trophic level dominate the slope community (May and Blaber, 1989; Koslow, 1997). This pattern has also been observed at high latitudes in the north Pacific (Pearcy et al., 1982). Williams et al. (2001) found that fish density in Western Australia was highest at the shelf break (200-400 m), which contrasts with other studies where peak density was at depths between 750-1400 m (Merrett et al., 1991; Gordon, 2001). Globally, fishing effort has intensified, and species tend to be more commercially valuable in the first ~700 m, highlighting the significance of the continental margin for fisheries, and the increased pressure on catch and effort in this depth zone (Graham et al., 2001; Clarke et al., 2015; Newman et al., 2016). These findings support Wellington et al. (2018), where a small number of larger-bodied meso-predators dominated mid-depth ranges at 200-299 m in the Perth Canyon in the temperate region. Although a shallower depth range than the present study, this may have been attributable to the presence of the Perth Canyon where a confluence of the Leeuwin Current, increased biota and upwelling support higher productivity and species diversity at a slightly shallower depth (Wellington et al. 2018).

### *Assemblage composition and species*

Eleven species were identified as being data deficient (DD) through their IUCN categorisation. This study provides information on relative abundance, distribution, lengths and habitat use along the coast of Western Australia. Seven of these were sharks (*Carcharhinus altimus, Centrophorus moluccensis, Centrophorus westraliensis, Etmopterus brachyurus, Hexanchus nakamurai, Squalus megalops and Squalus nasutus*). *Centrophorus westraliensis*, endemic to Western Australia, *and Centrophorus moluccensis* were identified as species requiring urgent evaluation in regard to the location and size of gulper shark populations in Australia (Williams et al., 2012). Populations in Western Australia are deemed sustainable; however, the population on the east coast of Australia is considered Near Threatened, having been subject to more intense fishing pressure in recent decades (Graham and Daley, 2011). Due to increasing pressure from fishing, and vulnerability due to life history traits (such as late maturation, low fecundity and slow growth rates) certain species of sharks and rays are experiencing significant population declines (Finucci et al., 2019). Of the 20 species identified in this study to have an IUCN classification of concern, 19 were species of sharks or rays. The teleost *Polyprion americanus* has a high inherent vulnerability to fishing exploitation (e.g. (Wakefield et al., 2013a) and is considered Critically Endangered in some locations according to IUCN, with most populations considered Data Deficient (Cornish and Peres 2003). Stereo-BRUVs have provided a valuable and effective means of gathering critical information on these deepwater species without the need for extractive measures.

Over 40% of the fish identified to species level in this study were found in depths outside of their published ranges. Accurate records on depth distributions are possible through the use of stereo-BRUVs, providing data that can be precisely matched to habitat information and bathymetric features. Furthermore, accurate depth distributions are increasingly valuable as climate driven range shifts (across both latitude and depth) potentially become more frequently reported.

The relatively high number of species and families identified are an indicator of the high diversity of the shelf and upper slope species in Western Australia (Lenanton et al., 2009; Langlois et al., 2011; Last et al., 2011). The high species diversity in the northern warmer latitudes is likely a product of overlapping tropical species with Indo-Pacific origins, in contrast to southern temperate fishes with higher levels of endemism, having evolved from ancient marine fish lineages and coupled with low primary productivity conditions (Langlois et al., 2011; Molony et al., 2011). Although the fish assemblage patterns are similarly defined to other Western Australian studies, the species identified are different (Williams et al., 1996; Last et al., 2011). For example, few species of demersal fish were found in depths below 400 m. Instead, sharks, eels, hagfish and small whiptails dominated assemblages. Differences in species composition between studies are likely an effect of sampling techniques (i.e. trawl vs stereo-BRUVs), and the inclusion of different depth ranges between studies. Where slow trawls can omit larger, more mobile species, overall, they can detect a greater number of species and individuals (Williams et al., 1996). Stereo-BRUVs may also miss some of the more sparsely dispersed, cryptic species that are spatially discreet in deepwater environments. While deepwater stereo-BRUVs are adept at capturing the broad ecological patterns at regional and geographical scales, a combination of techniques may be valuable in capturing the full ecological suite of fish assemblage information (Stat et al., 2019).

## *Conclusion*

Finding cost-effective, non-extractive ways to assess the distribution and ecology of deepwater fish assemblages is vital for an ecosystem already impacted by intersecting economic interests and environmental influences. At large spatial scales (100 kilometres), latitude, depth (highly correlated with temperature) and salinity were the primary determinants of assemblage composition and distribution. Studies encompassing large latitudinal ranges and depths in the distribution of marine species such as this are rare. We used a structured sampling design spanning depth ranges linking the continental shelf and upper slope, encompassing an extensive latitudinal range from tropical to temperate regions. The occurrence of the marine heatwave may have revealed valuable insights into how readily oceanic hydrology can affect fish distributions, beyond expected latitudinal patterns (Feng et al., 2013). However, only through repeated sampling will we know if these deepwater assemblages were affected by this climatic event and whether any effects are temporary or persistent. Nonetheless, it raises crucial questions regarding resilience to future climate shifts, and whether depth and latitude may provide a refuge for deepwater fish assemblages.

## *Supplementary Material*

**Table S 3.1 Pair-wise comparison tests between depth ranges across all surveys using family and species classifications of square root transformed abundance data. Significant values (P< 0.05) are in bold. Key: Rowley Shoals (RS), Montebello Islands (MB), Ningaloo Reef (NI), Abrolhos Islands (AB), Perth Canyon (RC), South West Capes (SC).**

| | **Family** | | | | | | **Species** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **RS** | **MB** | **NI** | **AB** | **RC** | **SC** | **RS** | **MB** | **NI** | **AB** | **RC** | **SC** |
| **Groups (depth ranges)** | **P(perm)** | **P(perm)** | **P(perm)** | **P(perm)** | **P(perm)** | **P(perm)** | **P(perm)** | **P(perm)** | **P(perm)** | **P(perm)** | **P(perm)** | **P(perm)** |
| 100-199, 200-299 | **0.0001** | **0.0001** | **0.0001** | **0.0007** | **0.0001** | **0.0007** | **0.0001** | **0.0001** | **0.0001** | **0.0004** | **0.0001** | **0.001** |
| 100-199, 300-399 | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0004** | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0003** |
| 100-199, 400-499 | **0.0001** | **0.0001** | **0.0001** | **0.0007** | **0.0001** | **0.0002** | **0.0001** | **0.0001** | **0.0001** | **0.0005** | **0.0001** | **0.0003** |
| 100-199, 500-599 | **0.0001** | **0.0001** | **0.0001** | **0.0002** | **0.0001** | **0.0003** | **0.0001** | **0.0001** | **0.0001** | **0.0006** | **0.0001** | **0.0003** |
| 200-299, 300-399 | **0.0186** | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0001** | 0.0894 | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0001** |
| 200-299, 400-499 | **0.0001** | **0.0001** | **0.0001** | **0.0002** | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0002** | **0.0001** | **0.0001** |
| 200-299, 500-599 | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0001** | **0.0002** | **0.0001** | **0.0001** | **0.0001** |
| 300-399, 400-499 | **0.0004** | **0.0088** | **0.0016** | **0.0001** | **0.0001** | **0.0003** | **0.0034** | **0.0019** | **0.0011** | **0.0044** | **0.0001** | **0.0009** |
| 300-399, 500-599 | **0.0001** | **0.0003** | **0.0005** | **0.0001** | **0.0001** | **0.0016** | **0.0001** | **0.0001** | **0.0004** | **0.0001** | **0.0001** | **0.0005** |
| 400-499, 500-599 | **0.0001** | **0.0498** | **0.0016** | **0.0012** | **0.0016** | 0.6125 | **0.0001** | 0.163 | **0.0007** | **0.0023** | **0.003** | 0.5838 |

**Table S 3.2 Leave-one-out allocation to groups from canonical analysis of principal coordinates (CAP) using family level classifications of abundance data. Light green shading indicates the correct allocation group, dark green indicates samples successfully allocated to their group, orange shading indicates where samples were misclassified. Average allocation success across all groups was 53.72%.**

| Original group | RS100 | RS200 | RS300 | RS400 | RS500 | MB100 | MB200 | MB300 | MB400 | MB500 | NI100 | NI200 | NI300 | NI400 | NI500 | AB100 | AB200 | AB300 | AB400 | AB500 | RC100 | RC200 | RC300 | RC400 | RC500 | SC100 | SC200 | SC300 | SC400 | SC500 | Total | % correct |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RS100 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 87.50 |
| RS200 | 0 | 12 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 80.00 |
| RS300 | 0 | 5 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 25.00 |
| RS400 | 0 | 0 | 0 | 6 | 1 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 50.00 |
| RS500 | 0 | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14 | 78.57 |
| MB100 | 3 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 6 | 4 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | 26.32 |
| MB200 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 2 | 0 | 0 | 0 | 6 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 26 | 50.00 |
| MB300 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 6 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | 54.55 |
| MB400 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 4 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 50.00 |
| MB500 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 2 | 3 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 37.50 |
| NI100 | 2 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 13 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | 68.42 |
| NI200 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 12 | 0 | 1 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 70.59 |
| NI300 | 0 | 1 | 3 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 2 | 5 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 33.33 |
| NI400 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 50.00 |
| NI500 | 0 | 0 | 0 | 1 | 2 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 14.29 |
| AB100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 50.00 |
| AB200 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 75.00 |
| AB300 | 0 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 8 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 18 | 44.44 |
| AB400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 7 | 57.14 |
| AB500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 90.00 |
| RC100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 19 | 89.47 |
| RC200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | 0 | 0 | 0 | 7 | 7 | 0 | 1 | 0 | 35 | 54.29 |
| RC300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 8 | 4 | 2 | 0 | 0 | 11 | 1 | 5 | 33 | 24.24 |
| RC400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 0 | 0 | 0 | 2 | 13 | 3 | 0 | 0 | 0 | 2 | 2 | 26 | 50.00 |
| RC500 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 1 | 15 | 66.67 |
| SC100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 3 | 2 | 0 | 0 | 0 | 8 | 37.50 |
| SC200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 8 | 1 | 0 | 0 | 12 | 66.67 |
| SC300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 6 | 0 | 1 | 8 | 75.00 |
| SC400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 3 | 1 | 8 | 37.50 |
| SC500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 2 | 3 | 7 | 42.86 |

**Table S 3.3 Family, genus and species name, common name, habitat, known distribution and published depth range (min and max), maximum observed depth range in this study**, whether there is an extension in depth ranges from these observations, classification = species endemic to Australia, and IUCN categories.**

| Family | Genus species | Common name | Habitat | Distribution | min (m) | max (m) | depth (m)** | Depth Extension? | Classification | IUCN Categories |
|---|---|---|---|---|---|---|---|---|---|---|
| Acanthuridae | *Naso annulatus* | Ringtail Unicornfish | reef | Indo-Pacific Tropical | 1 | 60 | 91.9 | DEPTH EXT | | LC (Least Concern) |
| | *Naso brevirostris* | Spotted Unicornfish | reef | Indo-Pacific Tropical | 1 | 122 | 107 | | | LC (Least Concern) |
| | *Naso lopezi* | Slender Unicornfish | reef | Western Pacific Tropical | 20 | 50 | 92.6 | DEPTH EXT | | LC (Least Concern) |
| Aracanidae | *Anoplocapros amygdaloides* | Western Smooth Boxfish | demersal | Eastern Indian Ocean | 5 | 100 | 109 | DEPTH EXT | endemic | NE (Not Evaluated) |
| | *Anoplocapros lenticularis* | Whitebarred Boxfish | demersal | Eastern Indian Ocean | 10 | 220 | 104 | | endemic | NE (Not Evaluated) |
| Ariidae | *Neoarius graeffei* | Blue Catfish | marine-estuarine | Western Pacific Tropical | 18 | 30 | 122 | DEPTH EXT | | NE (Not Evaluated) |
| | *Netuma thalassina* | Giant Sea Catfish | marine-estuarine | Indian Ocean | 10 | 195 | 120 | | | NE (Not Evaluated) |
| Balistidae | *Abalistes stellatus* | Starry Triggerfish | reef | Indo-Pacific Tropical | 7 | 350 | 126 | | | NE (Not Evaluated) |
| | *Sufflamen fraenatum* | Bridled Triggerfish | reef | Indo-Pacific Tropical | 8 | 186 | 120 | | | LC (Least Concern) |
| | *Xanthichthys caeruleolineatus* | Blueline Triggerfish | reef | Indo-Pacific Tropical | 50 | 200 | 92.6 | | | NE (Not Evaluated) |
| Berycidae | *Beryx splendens* | Alfonsino | benthopelagic | Circumglobal | 25 | 1300 | 524 | | | LC (Least Concern) |
| | *Centroberyx australis* | Yelloweye Redfish | benthopelagic | Eastern Indian Ocean | 80 | 300 | 120 | | endemic | NE (Not Evaluated) |
| | *Centroberyx gerrardi* | Bight Redfish | reef | Eastern Indian Ocean | 10 | 500 | 210 | | endemic | NE (Not Evaluated) |
| | *Centroberyx lineatus* | Swallowtail | rocky reefs | Indian Ocean | 15 | 280 | 120 | | | NE (Not Evaluated) |
| Bramidae | *Brama brama* | Ray’s Bream | pelagic neritic | Indian Ocean | 0 | 1000 | 336 | | | LC (Least Concern) |
| Carangidae | *Carangoides chrysophrys* | Longnose Trevally | reef | Indo-Pacific | 30 | 60 | 141 | DEPTH EXT | | LC (Least Concern) |
| | *Carangoides caeruleopinnatus* | Onion Trevally | reef | Indo-West Pacific | 1 | 60 | 204 | DEPTH EXT | | LC (Least Concern) |
| | *Carangoides orthogrammus* | Thicklip Trevally | reef | Indo-Pacific | 3 | 168 | 128 | | | LC (Least Concern) |
| | *Carangoides plagiotaenia* | Barcheek Trevally | reef | Indo-Pacific | 2 | 200 | 110 | | | LC (Least Concern) |
| | *Caranx lugubris* | Black Trevally | benthopelagic | Circumtropical | 12 | 354 | 128 | | | LC (Least Concern) |

| Family | Genus species | Common name | Habitat | Distribution | min (m) | max (m) | depth (m)** | Depth Extension? | Classification | IUCN Categories |
|---|---|---|---|---|---|---|---|---|---|---|
| Carangidae | *Gnathanodon speciosus* | Golden Trevally | reef | Indo-Pacific | 0 | 80 | 110 | DEPTH EXT |  | LC (Least Concern) |
|  | *Pseudocaranx georgianus* | Silver Trevally | reef | Indo-Pacific | 10 | 238 | 222 |  |  | LC (Least Concern) |
|  | *Seriola dumerili* | Amberjack | reef | Indo-West Pacific | 1 | 360 | 246 |  |  | LC (Least Concern) |
|  | *Seriola hippos* | Samsonfish | pelagic neritic | Indo-Pacific | 1 | 100 | 320 | DEPTH EXT | endemic | LC (Least Concern) |
|  | *Seriola lalandi* | Yellowtail Kingfish | benthopelagic | Indo-Pacific | 3 | 825 | 200 |  |  | LC (Least Concern) |
|  | *Seriola rivoliana* | Highfin Amberjack | reef | Indo-West Pacific | 4 | 245 | 303 | DEPTH EXT |  | LC (Least Concern) |
|  | *Seriolina nigrofasciata* | Blackbanded Amberjack | reef | Indo-West Pacific | 20 | 150 | 120 |  |  | LC (Least Concern) |
| Carcharhinidae | *Carcharhinus albimarginatus* | Silvertip Shark | reef | Indo-Pacific | 1 | 800 | 128 |  |  | VU (Vulnerable) |
|  | *Carcharhinus altimus* | Bignose Shark | reef | Circumglobal | 12 | 810 | 276 |  |  | DD (Data Deficient) |
|  | *Carcharhinus falciformis* | Silky Shark | reef | Circumtropical | 0 | 4000 | 332 |  |  | NT (Near Threatened) |
|  | *Carcharhinus galapagensis* | Galapagos Shark | reef | Circumtropical | 1 | 286 | 117 |  |  | NT (Near Threatened) |
|  | *Carcharhinus limbatus* | Common Blacktip Shark | reef | Indo-Pacific | 0 | 100 | 336 | DEPTH EXT |  | NT (Near Threatened) |
|  | *Carcharhinus obscurus* | Dusky Whaler | reef | Indo-West Pacific | 0 | 400 | 210 |  |  | VU (Vulnerable) |
|  | *Carcharhinus plumbeus* | Sandbar Shark | benthopelagic | Indo-Pacific | 0 | 500 | 421 |  |  | VU (Vulnerable) |
|  | *Galeocerdo cuvier* | Tiger Shark | benthopelagic | Circumglobal | 0 | 800 | 91.9 |  |  | NT (Near Threatened) |
|  | *Rhizoprionodon acutus* | Milk Shark | benthopelagic | Indo-West Pacific | 1 | 200 | 110 |  |  | LC (Least Concern) |
| Centrolophidae | *Hyperoglyphe antarctica* | Blue-eye Trevalla | benthopelagic | Western Australia | 40 | 1500 | 519 |  |  | NE (Not Evaluated) |
|  | *Centrophorus moluccensis* | Endeavour Dogfish | bathydemersal | Indian Ocean | 125 | 823 | 540 |  |  | DD (Data Deficient) |
|  | *Centrophorus westraliensis* | Western Gulper Shark | bathydemersal | Western Australia | 616 | 750 | 513 | DEPTH EXT | endemic | DD (Data Deficient) |
| Chaetodontidae | *Chaetodon lineolatus* | Lined Butterflyfish | reef | Indo-Pacific | 2 | 171 | 92.6 |  |  | LC (Least Concern) |

| Family | Genus species | Common name | Habitat | Distribution | min (m) | max (m) | depth (m)** | Depth Extension? | Classification | IUCN Categories |
|---|---|---|---|---|---|---|---|---|---|---|
| Chaetodontidae | *Heniochus acuminatus* | Longfin Bannerfish | reef | Indo-Pacific | 2 | 178 | 128 |  |  | LC (Least Concern) |
| Cheilodactylidae | *Nemadactylus valenciennesi* | Blue Morwong | demersal | Australia | 40 | 240 | 192 |  | endemic | NE (Not Evaluated) |
| Chimaeridae | *Chimaera argiloba* | Whitefin Ghostshark | bathydemersal | Northwestern Australia | 370 | 520 | 408 |  | endemic | LC (Least Concern) |
|  | *Hydrolagus lemures* | Blackfin Ghostshark | bathydemersal | Indo-West Pacific | 146 | 510 | 548 | DEPTH EXT |  | LC (Least Concern) |
| Dasyatidae | *Bathytoshia brevicaudata* | Smooth Stingray | demersal | Indo-West Pacific | 0 | 476 | 215 |  |  | LC (Least Concern) |
|  | *Taeniurops meyeni* | Blotched Fantail Ray | reef | Indo-West Pacific | 1 | 500 | 92.6 |  |  | VU (Vulnerable) |
| Echeneidae | *Echeneis naucrates* | Sharksucker | reef | Circumtropical | 1 | 85 | 121 | DEPTH EXT |  | LC (Least Concern) |
| Enoplosidae | *Enoplosus armatus* | Old Wife | reef | Indo-Pacific | 0 | 90 | 120 | DEPTH EXT | endemic | NE (Not Evaluated) |
| Epinephelidae | *Cephalopholis miniata* | Coral Rockcod | reef | Indo-Pacific | 2 | 150 | 120 |  |  | LC (Least Concern) |
|  | *Cephalopholis sonnerati* | Tomato Rockcod | reef | Indo-Pacific | 0 | 150 | 102 |  |  | LC (Least Concern) |
|  | *Epinephelus amblycephalus* | Banded Grouper | reef | Northwestern Australia | 80 | 130 | 120 |  |  | LC (Least Concern) |
|  | *Epinephelus areolatus* | Yellowspotted Rockcod | reef | Indo-Pacific | 6 | 200 | 121 |  |  | LC (Least Concern) |
|  | *Epinephelus bleekeri* | Duskytail Grouper | demersal | Indo-West Pacific | 30 | 105 | 122 | DEPTH EXT |  | DD (Data Deficient) |
|  | *Epinephelus malabaricus* | Blackspotted Rockcod | reef | Indo-Pacific | 0 | 150 | 107 |  |  | LC (Least Concern) |
|  | *Epinephelus miliaris* | Netfin Grouper | reef | Indo-West Pacific | 1 | 200 | 128 |  |  | LC (Least Concern) |
|  | *Epinephelus multinotatus* | Rankin Cod | reef | Indian Ocean | 1 | 110 | 336 | DEPTH EXT |  | LC (Least Concern) |
|  | *Epinephelus radiatus* | Radiant Rockcod | demersal | Indo-West Pacific | 18 | 383 | 244 |  |  | LC (Least Concern) |
|  | *Epinephelus tukula* | Potato Rockcod | reef | Indo-West Pacific | 10 | 400 | 94.3 |  |  | LC (Least Concern) |
|  | *Hyporthodus octofasciatus* | Eightbar Grouper | bathydemersal | Indo-West Pacific | 150 | 300 | 302 | DEPTH EXT |  | LC (Least Concern) |
|  | *Variola louti* | Yellowedge Coronation Trout | reef | Indo-Pacific | 3 | 300 | 126 |  |  | LC (Least Concern) |

| Family | Genus species | Common name | Habitat | Distribution | min (m) | max (m) | depth (m)** | Depth Extension? | Classification | IUCN Categories |
|---|---|---|---|---|---|---|---|---|---|---|
| Etmopteridae | Etmopterus brachyurus | Short-Tail Lanternshark | bathydemersal | Indo-West Pacific | 400 | 610 | 509 | | | DD (Data Deficient) |
| | *Etmopterus evansi* | Blackmouth Lanternshark | bathypelagic | Eastern Indian Ocean | 430 | 550 | 522 | | | LC (Least Concern) |
| Euclichthyidae | *Euclichthys polynemus* | Eucla Cod | bathydemersal | Australia North West Shelf | 250 | 920 | 540 | | endemic | NE (Not Evaluated) |
| Gempylidae | *Rexea solandri* | Gemfish | benthopelagic | Southwestern Australia | 100 | 800 | 523 | | | NE (Not Evaluated) |
| | *Ruvettus pretiosus* | Oilfish | benthopelagic | Circumtropical and Temperate Seas | 100 | 800 | 572 | | | LC (Least Concern) |
| | *Thyrsites atun* | Barracouta | benthopelagic | Eastern Indian Ocean | 0 | 550 | 382 | | | NE (Not Evaluated) |
| Ginglymostomatidae | *Nebrius ferrugineus* | Tawny Shark | reef | Indo-Pacific | 0 | 70 | 108 | DEPTH EXT | | VU (Vulnerable) |
| Glaucosomatidae | *Glaucosoma buergeri* | Northern Pearl Perch | benthopelagic | Western Australia | 0 | 146 | 200 | DEPTH EXT | | NE (Not Evaluated) |
| Haemulidae | *Diagramma pictum labiosum* | Painted Sweetlips | benthopelagic | Indo-West Pacific | 0 | 88 | 108 | DEPTH EXT | | NE (Not Evaluated) |
| Heterodontidae | *Heterodontus portusjacksoni* | Port Jackson Shark | demersal | Oceanodromous | 0 | 275 | 108 | | | LC (Least Concern) |
| Hexanchidae | *Hexanchus griseus* | Bluntnose Sixgill Shark | bathydemersal | Oceanodromous | 1 | 2500 | 210 | | | NT (Near Threatened) |
| | *Hexanchus nakamurai* | Bigeye Sixgill Shark | bathydemersal | Indian Ocean | 0 | 600 | 408 | | | DD (Data Deficient) |
| Kyphosidae | *Neatypus obliquus* | Footballer Sweep | reef | Eastern Indian Ocean | 0 | 60 | 120 | DEPTH EXT | endemic | NE (Not Evaluated) |
| | *Tilodon sexfasciatus* | Moonlighter | demersal | Eastern Indian Ocean | 1 | 120 | 199 | DEPTH EXT | endemic | NE (Not Evaluated) |
| Labridae | *Bodianus bilunulatus* | Saddleback Pigfish | reef | Indo-West Pacific | 3 | 160 | 119 | | | LC (Least Concern) |
| | *Bodianus perditio* | Goldspot Pigfish | reef | Australia | 10 | 120 | 119 | | | LC (Least Concern) |
| | *Bodianus vulpinus* | Western Pigfish | reef | Eastern Indian Ocean | 100 | 250 | 259 | DEPTH EXT | endemic | LC (Least Concern) |
| | *Coris auricularis* | Western King Wrasse | reef | Eastern Indian Ocean | 1 | 45 | 120 | DEPTH EXT | endemic | LC (Least Concern) |
| | *Halichoeres chloropterus* | Pastel-green Wrasse | reef | Indo-Malayan Region | 0 | 10 | 92.6 | DEPTH EXT | | LC (Least Concern) |
| | *Labroides dimidiatus* | Common Cleanerfish | reef | Indo-Pacific | 1 | 40 | 91.9 | DEPTH EXT | | LC (Least Concern) |

| Family | Genus species | Common name | Habitat | Distribution | min (m) | max (m) | depth (m)** | Depth Extension? | Classification | IUCN Categories |
|---|---|---|---|---|---|---|---|---|---|---|
| Labridae | *Suezichthys bifurcatus* | Striped Rainbow Wrasse | demersal | Eastern Indian Ocean | 80 | 100 | 103 | DEPTH EXT | endemic | DD (Data Deficient) |
| Leiognathidae | *Gazza minuta* | Toothed Ponyfish | demersal | Indo-Pacific | 10 | 110 | 332 | DEPTH EXT |  | LC (Least Concern) |
| Lethrinidae | *Gymnocranius euanus* | Paddletail Seabream | reef | Indo-Pacific | 15 | 50 | 112 | DEPTH EXT |  | LC (Least Concern) |
|  | *Gymnocranius grandoculis* | Robinson’s Seabream | reef | Indo-Pacific | 20 | 170 | 128 |  |  | LC (Least Concern) |
|  | *Lethrinus amboinensis* | Ambon Emperor | reef | Northwestern Australia | 5 | 30 | 128 | DEPTH EXT |  | LC (Least Concern) |
|  | *Lethrinus miniatus* | Redthroat Emperor | reef | Northwestern Australia | 5 | 30 | 108 | DEPTH EXT |  | LC (Least Concern) |
|  | *Lethrinus nebulosus* | Spangled Emperor | reef | Indo-West Pacific | 10 | 75 | 120 | DEPTH EXT |  | LC (Least Concern) |
|  | *Lethrinus olivaceus* | Longface Emperor | reef | Indo-West Pacific | 1 | 185 | 119 |  |  | LC (Least Concern) |
|  | *Lethrinus rubrioperculatus* | Spotcheek Emperor | reef | Indo-Pacific | 10 | 198 | 108 |  |  | LC (Least Concern) |
|  | *Lethrinus xanthochilus* | Yellowlip Emperor | reef | Indo-Pacific | 5 | 150 | 94.3 |  |  | LC (Least Concern) |
|  | *Wattsia mossambica* | Mozambique Seabream | reef | Indo-West Pacific | 100 | 200 | 204 | DEPTH EXT |  | LC (Least Concern) |
| Lutjanidae | *Aphareus furca* | Smalltooth Jobfish | reef | Indo-Pacific | 1 | 122 | 107 |  |  | LC (Least Concern) |
|  | *Aprion virescens* | Green Jobfish | reef | Indo-Pacific | 0 | 180 | 108 |  |  | LC (Least Concern) |
|  | *Etelis carbunculus / E. sp.* | Ruby Snapper | benthopelagic | Indo-Pacific | 90 | 400 | 383 |  |  | LC (Least Concern) |
|  | *Lutjanus argentimaculatus* | Mangrove Jack | reef | Indo-West Pacific | 1 | 120 | 111 |  |  | LC (Least Concern) |
|  | *Lutjanus bohar* | Red Bass | reef | Indo-Pacific | 4 | 180 | 128 |  |  | LC (Least Concern) |
|  | *Lutjanus erythropterus* | Crimson Snapper | reef | Indo-West Pacific | 5 | 100 | 113 | DEPTH EXT |  | NE (Not Evaluated) |
|  | *Lutjanus malabaricus* | Saddletail Snapper | reef | Indo-West Pacific | 12 | 100 | 126 | DEPTH EXT |  | NE (Not Evaluated) |
|  | *Lutjanus sebae* | Red Emperor | reef | Indo-West Pacific | 5 | 180 | 122 |  |  | LC (Least Concern) |
|  | *Lutjanus vitta* | Brownstripe Snapper | reef | Indo-West Pacific | 10 | 72 | 102 | DEPTH EXT |  | LC (Least Concern) |
|  | *Pinjalo pinjalo* | Pinjalo | reef | Indo-West Pacific | 15 | 100 | 128 | DEPTH EXT |  | NE (Not Evaluated) |

| Family | Genus species | Common name | Habitat | Distribution | min (m) | max (m) | depth (m)** | Depth Extension? | Classification | IUCN Categories |
|---|---|---|---|---|---|---|---|---|---|---|
| Lutjanidae | *Pristipomoides auricilla* | Goldflag Snapper | benthopelagic | Indo-Pacific | 90 | 360 | 244 | | | LC (Least Concern) |
| | *Pristipomoides filamentosus* | Rosy Snapper | benthopelagic | Indo-Pacific | 40 | 400 | 217 | | | LC (Least Concern) |
| | *Pristipomoides multidens* | Goldband Snapper | demersal | Indo-Pacific | 40 | 350 | 220 | | | LC (Least Concern) |
| | *Pristipomoides typus* | Sharptooth Snapper | demersal | Eastern Indian Ocean | 40 | 120 | 277 | DEPTH EXT | | LC (Least Concern) |
| | *Pristipomoides zonatus* | Oblique-banded Snapper | benthopelagic | Indo-Pacific | 70 | 300 | 244 | | | LC (Least Concern) |
| | *Symphorus nematophorus* | Chinamanfish | reef | Northern Australia | 20 | 100 | 120 | DEPTH EXT | | LC (Least Concern) |
| Macroramphosidae | *Centriscops humerosus* | Banded Bellowsfish | bathydemersal | Circumglobal Temperate | 35 | 1000 | 322 | | | LC (Least Concern) |
| Macrouridae | *Coelorinchus mirus* | Gargoyle Fish | demersal | Indo-Pacific | 130 | 400 | 523 | DEPTH EXT | endemic | NE (Not Evaluated) |
| | *Lepidorhynchus denticulatus* | Toothed Whiptail | bathypelagic | Eastern Indian Ocean | 180 | 1000 | 510 | | | NE (Not Evaluated) |
| | *Lucigadus nigromaculatus* | Blackspot Whiptail | bathydemersal | Indo-West Pacific | 200 | 1463 | 521 | | | NE (Not Evaluated) |
| Malacanthidae | *Branchiostegus sawakinensis* | Freckled Tilefish | demersal | Indo-West Pacific | 45 | 180 | 311 | DEPTH EXT | | NE (Not Evaluated) |
| | *Malacanthus brevirostris* | Flagtail Blanquillo | reef | Indo-Pacific | 5 | 50 | 92.6 | DEPTH EXT | | NE (Not Evaluated) |
| Molidae | *Mola ramsayi* | Short Sunfish | pelagic-oceanic | Indian Ocean | 0 | 300 | 508 | DEPTH EXT | | NE (Not Evaluated) |
| Monacanthidae | *Nelusetta ayraud* | Ocean Jacket | demersal | Eastern Indian Ocean | 0 | 360 | 247 | | endemic | NE (Not Evaluated) |
| Moridae | *Pseudophycis barbata* | Bearded Rock Cod | demersal | Southern Australia | 0 | 300 | 322 | DEPTH EXT | | NE (Not Evaluated) |
| Mullidae | *Parupeneus spilurus* | Blacksaddle Goatfish | reef | Western Australia | 10 | 80 | 112 | DEPTH EXT | | LC (Least Concern) |
| Muraenidae | *Gymnothorax cribroris* | Sieve Moray | reef | Indo-West Pacific | 1 | 78 | 119 | DEPTH EXT | | NE (Not Evaluated) |
| | *Gymnothorax javanicus* | Giant Moray | reef | Indo-Pacific | 0 | 50 | 102 | DEPTH EXT | | NE (Not Evaluated) |
| | *Gymnothorax rueppellii* | Banded Moray | reef | Indo-Pacific | 1 | 40 | 113 | DEPTH EXT | | NE (Not Evaluated) |
| | *Gymnothorax woodwardi* | Woodward's Moray | reef | Eastern Indian Ocean | 0 | 182 | 259 | DEPTH EXT | endemic | NE (Not Evaluated) |

| Family | Genus species | Common name | Habitat | Distribution | min (m) | max (m) | depth (m)** | Depth Extension? | Classification | IUCN Categories |
|---|---|---|---|---|---|---|---|---|---|---|
| Myctophidae | *Electrona risso* | Risso's Lanternfish | bathypelagic | Oceanodromous | 90 | 1485 | 404 | | | LC (Least Concern) |
| Myliobatidae | *Myliobatis australis* | Australian Eagle Ray | reef | Eastern Indian Ocean | 1 | 85 | 108 | DEPTH EXT | | NE (Not Evaluated) |
| Nemipteridae | *Nemipterus bathybius* | Yellowbelly Threadfin Bream | demersal | Northwestern Australia | 35 | 300 | 224 | | | NE (Not Evaluated) |
| Neosebastidae | *Neosebastes pandus* | Bighead Gurnard Perch | reef | Eastern Indian Ocean | 15 | 593 | 124 | | endemic | NE (Not Evaluated) |
| Odontaspididae | *Odontaspis ferox* | Sandtiger Shark | benthopelagic | Indo-Pacific | 10 | 2000 | 440 | | | VU (Vulnerable) |
| Ophidiidae | *Dannevigia tusca* | Tusk | benthopelagic | Eastern Indian Ocean | 115 | 400 | 308 | | | NE (Not Evaluated) |
| | *Genypterus blacodes* | Pink Ling | bathydemersal | Southern Australia | 22 | 1000 | 502 | | | NE (Not Evaluated) |
| Oplegnathidae | *Oplegnathus woodwardi* | Knifejaw | demersal | Eastern Indian Ocean | 50 | 400 | 416 | DEPTH EXT | endemic | DD (Data Deficient) |
| Orectolobidae | *Orectolobus halei* | Gulf Wobbegong | demersal | Eastern Indian Ocean | 0 | 195 | 312 | DEPTH EXT | endemic | LC (Least Concern) |
| | *Orectolobus maculatus* | Spotted Wobbegong | reef | Eastern Indian Ocean | 0 | 248 | 243 | | | LC (Least Concern) |
| | *Orectolobus ornatus* | Banded Wobbegong | reef | Indo-Pacific | 0 | 100 | 105 | DEPTH EXT | | LC (Least Concern) |
| Paraulopidae | *Paraulopus nigripinnis* | Blacktip Cucumberfish | demersal | Australia and New Zealand | 50 | 600 | 529 | | | NE (Not Evaluated) |
| Pentacerotidae | *Zanclistius elevatus* | Blackspot Boarfish | demersal | Southern Australia | 30 | 500 | 103 | | | NE (Not Evaluated) |
| Phosichthyidae | *Polymetme corythaeola* | Rendezvous Fish | benthopelagic | Indo-West Pacific | 165 | 800 | 540 | | | NE (Not Evaluated) |
| Platycephalidae | *Platycephalus bassensis* | Southern Sand Flathead | demersal | Indo-Pacific | 1 | 100 | 108 | DEPTH EXT | endemic | NE (Not Evaluated) |
| | *Platycephalus conatus* | Deepwater Flathead | demersal | Indo-Pacific | 70 | 490 | 408 | | endemic | NE (Not Evaluated) |
| | *Platycephalus speculator* | Southern Bluespotted Flathead | demersal | Eastern Indian Ocean | 1 | 30 | 108 | DEPTH EXT | endemic | NE (Not Evaluated) |
| Polymixiidae | *Polymixia berndti* | Berndt's Beardfish | demersal | Indo-Pacific | 18 | 585 | 524 | | | NE (Not Evaluated) |
| Polyprionidae | *Polyprion americanus* | Bass Groper | demersal | Oceanodromous | 40 | 600 | 423 | | | CR (Critically Endangered) |
| | *Polyprion oxygeneios* | Hapuku | demersal | Circumglobal Southern Waters | 50 | 854 | 472 | | | NE (Not Evaluated) |
| Pomacanthidae | *Apolemichthys trimaculatus* | Threespot Angelfish | reef | Indo-West Pacific | 3 | 60 | 92.6 | DEPTH EXT | | LC (Least Concern) |

| **Family** | **Genus species** | **Common name** | **Habitat** | **Distribution** | **min (m)** | **max (m)** | **depth (m)**** | **Depth Extension?** | **Classification** | **IUCN Categories** |
|---|---|---|---|---|---|---|---|---|---|---|
| Pomacanthidae | *Chaetodontoplus personifer* | Yellowtail Angelfish | reef | Indo-West Pacific | 8 | 40 | 112 | DEPTH EXT | endemic | LC (Least Concern) |
| Priacanthidae | *Priacanthus sagittarius* | Arrow Bigeye | demersal | Indo-West Pacific | 10 | 350 | 406 | DEPTH EXT |  | LC (Least Concern) |
| Pristiophoridae | *Pristiophorus cirratus* | Common Sawshark | demersal | Eastern Indian Ocean | 37 | 310 | 147 |  | endemic | LC (Least Concern) |
| Rajidae | *Dipturus oculus* | Ocellate Skate | benthopelagic | Eastern Indian Ocean | 200 | 389 | 502 | DEPTH EXT |  | LC (Least Concern) |
| Rhinobatidae | *Aptychotrema vincentiana* | Western Shovelnose Ray | demersal | Eastern Indian Ocean | 0 | 125 | 108 |  | endemic | LC (Least Concern) |
|  | *Trygonorrhina dumerilii* | Southern Fiddler Ray | demersal | Eastern Indian Ocean | 5 | 205 | 222 | DEPTH EXT | endemic | LC (Least Concern) |
| Rhynchobatidae | *Rhynchobatus australiae* | Whitespotted Guitarfish | demersal | Indo-West Pacific | 0 | 60 | 112 | DEPTH EXT |  | VU (Vulnerable) |
| Scaridae | *Hipposcarus longiceps* | Longnose Parrotfish | reef | Rowley Shoals | 2 | 40 | 112 | DEPTH EXT |  | LC (Least Concern) |
| Scombridae | *Gymnosarda unicolor* | Dogtooth Tuna | reef | Oceanodromous | 10 | 250 | 240 |  |  | LC (Least Concern) |
|  | *Scomberomorus commerson* | Spanish Mackerel | pelagic-neritic | Indo-West Pacific | 10 | 70 | 183 | DEPTH EXT |  | NT (Near Threatened) |
| Scyliorhinidae | *Asymbolus occiduus* | Western Spotted Catshark | pelagic-oceanic | Eastern Indian Ocean | 98 | 400 | 213 |  |  | LC (Least Concern) |
|  | *Figaro boardmani* | Sawtail Catshark | bathydemersal | Indo-West Pacific | 128 | 823 | 504 |  | endemic | LC (Least Concern) |
| Sebastidae | *Helicolenus barathri* | Bigeye Ocean Perch | bathydemersal | Southern Australia | 285 | 739 | 523 |  |  | NE (Not Evaluated) |
|  | *Helicolenus percoides* | Reef Ocean Perch | demersal | Southern Australia | 50 | 750 | 535 |  |  | NE (Not Evaluated) |
| Serranidae | *Epinephelides armatus* | Breaksea Cod | reef | Eastern Indian Ocean | 0 | 100 | 120 | DEPTH EXT | endemic | NT (Near Threatened) |
|  | *Lepidoperca filamenta* | Western Orange Perch | demersal | Eastern Indian Ocean | 128 | 220 | 322 | DEPTH EXT |  | LC (Least Concern) |
|  | *Lepidoperca occidentalis* | Slender Orange Perch | demersal | Eastern Indian Ocean | 40 | 200 | 210 | DEPTH EXT |  | NE (Not Evaluated) |
|  | *Pseudanthias sheni* | Shen's Basslet | reef | Eastern Indian Ocean | 25 | 46 | 120 | DEPTH EXT | endemic | NE (Not Evaluated) |
| Sparidae | *Argyrops notialis* | Western Frypan Bream | demersal | Indo-West Pacific | 1 | 450 | 126 |  |  | LC (Least Concern) |
|  | *Chrysophrys auratus* | Snapper | reef | Indo-Pacific | 0 | 200 | 327 | DEPTH EXT |  | LC (Least Concern) |

| **Family** | **Genus species** | **Common name** | **Habitat** | **Distribution** | **min (m)** | **max (m)** | **depth (m)**** | **Depth Extension?** | **Classification** | **IUCN Categories** |
|---|---|---|---|---|---|---|---|---|---|---|
| Sparidae | *Dentex carpenteri* | Yellow Snout Seabream | benthopelagic | Indo-Pacific | 100 | 264 | 331 | DEPTH EXT | | LC (Least Concern) |
| Sphyraenidae | *Sphyraena barracuda* | Great Barracuda | reef | Indo-Pacific | 1 | 100 | 97.3 | | | LC (Least Concern) |
| Sphyrnidae | *Sphyrna lewini* | Scalloped Hammerhead | pelagic-oceanic | Circumglobal | 0 | 1000 | 310 | | | VU (Vulnerable) |
| | *Sphyrna mokarran* | Great Hammerhead | pelagic-oceanic | Oceanodromous | 1 | 300 | 383 | DEPTH EXT | | EN (Endangered) |
| Squalidae | *Squalus edmundsi* | Edmund's Spurdog | pelagic-oceanic | Eastern Indian Ocean | 204 | 850 | 535 | | | NT (Near Threatened) |
| | *Squalus megalops* | Spikey Dogfish | demersal | Eastern Indian Ocean | 30 | 750 | 535 | | | DD (Data Deficient) |
| | *Squalus montalbani* | Philippine Spurdog | bathydemersal | Eastern Indian Ocean | 154 | 1370 | 535 | | | VU (Vulnerable) |
| | *Squalus nasutus* | Western Longnose Spurdog | pelagic-oceanic | Eastern Indian Ocean | 300 | 850 | 535 | | | DD (Data Deficient) |
| Stegostomatidae | *Stegostoma fasciatum* | Zebra Shark | reef | Indo-West Pacific | 0 | 90 | 121 | DEPTH EXT | | EN (Endangered) |
| Sternoptychidae | *Argyropelecus gigas* | Giant Hatchetfish | bathypelagic | Indian Ocean | 300 | 1000 | 514 | | | LC (Least Concern) |
| Synaphobranchidae | *Synaphobranchus kaupii* | Kaup's Cut-throat Eel | bathydemersal | Indo-West Pacific | 120 | 4800 | 513 | | | LC (Least Concern) |
| Synodontidae | *Saurida undosquamis* | Largescale Saury | reef | Eastern Indian Ocean | 1 | 350 | 216 | | | LC (Least Concern) |
| Tetraodontidae | *Lagocephalus lunaris* | Rough golden Toadfish | demersal | Indo-West Pacific | 5 | 150 | 215 | DEPTH EXT | | LC (Least Concern) |
| | *Lagocephalus sceleratus* | Silver Toadfish | reef | Indo-West Pacific | 18 | 100 | 212 | DEPTH EXT | | LC (Least Concern) |
| | *Omegophora armilla* | Ringed Toadfish | demersal | Eastern Indian Ocean | 0 | 146 | 103 | | endemic | LC (Least Concern) |
| Trachichthyidae | *Hoplostethus latus* | Palefin Sawbelly | bathypelagic | Eastern Indian Ocean | 146 | 586 | 510 | | | NE (Not Evaluated) |
| Triakidae | *Hemitriakis falcata* | Sicklefin Houndshark | demersal | Eastern Indian Ocean | 0 | 150 | 244 | DEPTH EXT | | LC (Least Concern) |
| | *Mustelus antarcticus* | Gummy Shark | demersal | Eastern Indian Ocean | 0 | 350 | 328 | | | LC (Least Concern) |
| | *Mustelus ravidus* | Grey Gummy Shark | benthopelagic | Eastern Indian Ocean | 106 | 300 | 213 | | | LC (Least Concern) |
| Triglidae | *Bovitrigla leptacanthus* | Bullhead Gurnard | demersal | Indo-West Pacific | 0 | 500 | 307 | | | NE (Not Evaluated) |
| Urolophidae | *Urolophus paucimaculatus* | Sparsely-Spotted Stingaree | demersal | Eastern Indian Ocean | 5 | 150 | 206 | DEPTH EXT | | LC (Least Concern) |

| Family | Genus species | Common name | Habitat | Distribution | min (m) | max (m) | depth (m)** | Depth Extension? | Classification | IUCN Categories |
|---|---|---|---|---|---|---|---|---|---|---|
| Zeidae | *Zenopsis nebulosa* | Mirror Dory | benthopelagic | Indo-Pacific | 30 | 800 | 548 |  |  | NE (Not Evaluated) |

# Chapter 4 General Discussion

## *General thesis summary*

This thesis aimed to contribute to the knowledge of deepwater fish assemblages in Western Australia and our understanding of the ecological function and value of the continental shelf and upper slope environment. This work represents the first large scale deepwater stereo-BRUVs survey in Western Australia and the largest latitudinal range study for deepwater stereo-BRUVs in Australia to date. The following section outlines the major findings from each chapter and a summary of this research, limitations encountered and a brief discussion of future research directions as summarised in Figure 4.1.

In chapter two, I assessed the abundance, distribution and habitat factors affecting fish assemblages across a depth profile of ~600 m. This depth profile encompassed an offshore island, continental slope and submarine canyon, in an environment where a poleward flowing boundary current brings warmer water further south. Three distinct assemblages were identified consistent with the shelf, margin and upper slope depths of the continental shelf, with depth and habitat strong factors influencing assemblage composition. Benthic biota and depth had the greatest influence on the assemblage structure at this scale. It was also evident that large meso-predator species dominated the assemblage in the 200-400 m depth range coinciding with the presence of sessile invertebrate habitat and possible upwelling effects at the head of the Perth Canyon. This has important implications, not only for understanding biodiversity in this zone but for sustainable management of fishing stocks where boundaries overlap and straddling stocks can be, even unintentionally, overfished. Awareness of these influencing factors on a fine-scale have not only furthered our understanding of the ecological influences present in the region but consequently can influence our approaches to sustainable management of these environments.

This raised the question, do these trends with depth and patterns of high biomass and large meso-predator species exist at other latitudes in Western Australia? And if so, what other factors are influential? Globally it has been shown that temperature, salinity, current speed and direction, and habitat features all interact to influence the distribution of fish assemblages across latitude and depth (Levin and Dayton, 2009).

In chapter three, I assessed the distributions of deepwater fishes across six locations at depths between 100-600 m. I found that fish assemblages were distributed into three broad latitudinal areas; a north tropical bioregion, a sub-tropical bioregion and a south temperate bioregion. This was a demarcation supported by previous trawl studies in

Western Australia (Williams et al., 2001; Last et al., 2011) indicating significant differences in assemblage structure in response to latitude. The north tropical bioregion had distinct vertical structure in response to depth, with separation between the shallow water shelf (100-199 m) and the rest of the assemblage. In the sub-tropical and south temperate bioregions depth structure was separated into two distinct assemblages; grouping the continental shelf and margin depths (100-199 m & 200-299 m) and the remaining depth ranges on the upper slope (300-399 m, 400-499 m and 500-599 m). Latitude, depth and salinity were the three most influential variables impacting assemblage composition. Although removed from the final model, ocean temperature was highly correlated with depth in this study and temperature decreased with increasing depth within each survey. Currents, in both surface and intermediate-depth water masses continuously influence the mixing and distribution of fishes along the west coast of Australia (Pattiaratchi, 2006; Lenanton et al., 2009). The patterns depicted were likely attributable to regional oceanography, in particular where the shelf margin meets the lower limit of the Leeuwin Current and the deeper, northwards moving undercurrent at 300 m (Pearce, 1991; Waite et al., 2007).

In chapter three, current speed and direction were significant variables contributing to the assemblage distribution whereas habitat factors were minor components in the overall model, indicating that at large spatial scales benthic habitat and substrate type played only a minor role in determining fish assemblage distribution. The differences between the findings of chapter two and three highlight the importance of spatial scales. Across large spatial scales, latitude and depth appeared to be the most significant influences in deepwater fish abundance distributions across Western Australia. Ocean hydrology was also significant with salinity and temperature influencing spatial distributions in deepwater environments.

Over all six latitudes, the lowest average number of species and individuals occurred within the 300-399 m depth range coupled with increased average fish length and biomass, indicating the presence of larger-bodied meso-predator species. Some of the typifying meso-predator species in this 300-399 m depth range included important commercial and recreational species in Western Australia. In addition, through the novel application of stereo-BRUVs in deepwater, this work recorded many vulnerable, threatened and rare taxa, as well as numerous extensions to depth range records (over 40% of identification, see Chapter 3; Supplementary Material Table S 3.3). In particular, a number of deepwater sharks, some of which are subject to impacts from fisheries both as target species and bycatch, were recorded (Pajuelo et al., 2016). A notable identification in this regard was the recording of *Odontaspis ferox,* the smalltooth sandtiger shark*,* on three video deployments in the Perth Canyon. This species is both rarely caught or sighted, and listed as vulnerable by the IUCN categorisation, highlighting the importance of reporting range extensions and the value of non-extractive techniques for gathering data. The publication of this short note is reproduced in the Appendix.

In 2017 I had the opportunity to present and participate in an international workshop on advancing methods to overcome challenges associated with life history and stock assessments of data-poor deep-water snappers and groupers (Newman et al., 2017). The workshop provided a forum to discuss the use and application of stereo-BRUVs in deepwater, the limitations and challenges I had encountered and how techniques could be improved and combined with other existing methods to answer pivotal questions relating to stock assessment and management strategies for deepwater species. In particular, it raised questions about how can we improve the quality of data collection and techniques.

In Australia, ecosystem based fisheries management encompasses a broad, risk-based framework inclusive of all ecological resources and values within a bioregion to assess where management practices are warranted. Stock assessments, distributions and fishing related activities are a foundational aspect of this, along with assessments of impacts, habitats, ecosystem functioning and other external factors. Collectively the assessment of these factors and the risk they impose, provide a sound basis for regulatory prioritisation and planning (Fletcher et al., 2016). Outcomes from this body of work are providing much needed knowledge of deepwater fish assemblages and their ecosystem function that can inform appropriate catch and boundary limits, gear restrictions and conditions for sustainable management of fisheries resources. The following section details some of the limitations encountered in using stereo-BRUVs in this study and directions for future development and refinement.

## *Limitations of research*

Stereo-BRUVs have been found to provide valuable data for ecological studies, fisheries management, monitoring and biodiversity research inclusive of temporal and spatial factors in shallow shelf waters (Misa et al., 2016). They provide the ability to make depth specific identifications, and there has been a plethora of research into various aspects of methodology but, these are almost exclusively based on shallow water stereo-BRUV data (Mallet and Pelletier, 2014). Although deepwater stereo-BRUVs work (beyond 100 m) is still infrequent, there are specific aspects related to deepwater environs (light, water movement, target species biology, distribution and movement) that would benefit from further exploration.

Gathering a very large data set such as this comes with inherent challenges in balancing temporal aspects against logistical constraints and costs. Temporal differences for this sampling were unavoidable, with the most obvious impact on two surveys occurring during the unprecedented heatwave event in 2011. I planned a balanced sampling design across depths, sites and locations; however, the loss of stereo-BRUV units, camera and lighting failures, or post-processing issues resulted in variations to the final number of videos available for analysis. Nonetheless, this has resulted in a statistically robust dataset, which contributes to the knowledge of deepwater fishes in Western Australia, complementing existing data sets gathered from trawl, trap and line fisheries records in Australia.

### Lighting effects on deepwater fishes

Each stereo-BRUVs was fitted with a blue light (CREE Royal Navy at 420 nm). The use of blue light was chosen for use in deepwater as it struck a balance between the glare and potential impact of white light and the low attenuation of red light through the water column. Blue light at 420nm is considered to be below the visual sensitivity of most fish (Von der Emde et al., 2004), however evidence for the use of blue light for deepwater stereo-BRUVs is still scarce, and the consensus on appropriate lighting is divided (Kendrick et al., 2005; Fitzpatrick et al., 2013). Birt et al. (2019) found no effects of lighting choices (red, white or blue) on mesophotic fishes at depths between 109-142 m, concluding that white light provided the best image quality for fish identification. Lighting choices may have impacted on species attraction to the bait and observations within the stereo-BRUVs vision, but the effects are still not well understood for deepwater species (Harvey et al., 2018).

### Effects of bait

Stereo-BRUVs rely on opportunistic placement (habitat, other organisms) or attractant (bait). There exists evidence for their ability to attract and observe a range of trophic groups (herbivores, omnivores and predators) with the use of a relatively small amount of oily fish bait (e.g. *Sardinops sagax*) (Dorman et al., 2012; Hardinge et al., 2013; Wraith et al., 2013). In deepwater environments, many species are slow-moving, widely dispersed and take time to move within the vicinity of the attractant. These factors can, therefore, affect methods due to bait type, dispersal patterns and soak times. There is a need to better understand bait dispersal in deepwater environments to define the limitations and standardise methods in regards to bait type, dispersal method and amount across deepwater environments.

### Accuracy of identifications

Species identifications from imagery have always posed a challenge (Mallet and Pelletier, 2014). In the present study, there were many species, particularly small species such as in the family Myctophidae, as well as rarely encountered species that pose particular challenges in making precise identifications. Smaller fish with many congeners of similar morphological characteristics can be challenging to differentiate, even with taxonomic reference specimens. However, confidence in identifications can be greatly enhanced by robust baseline knowledge of the regional fisheries. Concurrent trap and longline sampling during field collection can aid this, where appropriate, in providing type specimens for imagery identifications and confirmations. Identification of cryptic and rare species may require other solutions such as the collection of eDNA water sampling in conjunction with stereo-BRUVs deployments (Stat et al., 2019).

### Deepwater stereo-BRUVs design

During the study, improvements were made to the stereo-BRUV design for deepwater environments to increase the robustness of the frame and allow additional weight to be added and repositioned to each side of the unit. These units were substantially heavier than their shallow-water counterparts (> ~90 kg), which was necessary for deepwater environments where rope drag, current, tide and wave energy at the surface substantially impacted on the movement of the units at depth. Additional weight and ‘footholds’ helped stabilise the BRUVs, but these issues continued to be a challenge under certain environmental conditions. Consequently, future developments in the deepwater stereo-

BRUV systems used in this study are exploring the feasibility of 'rope-less BRUVs' by employing alternative measures such as acoustic, timed or chemical release mechanisms (Harvey et al. 2018). The balance remains to find a relatively cheap yet reliable mechanism for each stereo-BRUV to maintain efficient cost per unit and reduce any loss of stereo-BRUVs at sea.

**Optimal length of analysis**

Another key aspect for efficient deepwater stereo-BRUVs research is defining the optimal length of analysis or 'soak time'. Video recordings were 90 minutes in lengths to maximise the opportunity to record at these depths. However, extending video analysis time is costly; both in the time taken to capture and analyse the data. Optimal soak time analysis has been conducted for many shallow-water communities, resulting in reductions to minimal analysis timeframes (Gladstone et al., 2012; Harasti et al., 2015).

Optimising the length of analysis time frames has several benefits, particularly in reducing the time required for analysis (and thereby reducing costs). Additionally, reductions in project turnaround times provide other opportunities such as the collection of more samples or alternative applications of time, staff and funds. There is also the potential for automated image processing to reduce the volume of image data required to be reviewed by analysts (Shafait et al., 2017; Siddiqui et al., 2017). However, there remains a trade-off between shorter soak times and more video samples, and the statistical power that comes from longer soak times, which in turn provide opportunities to take more length measurements of species within a video sample (Misa et al., 2016).

Optimal analysis time will always be dependent on the specific goals of the project, in species and size targets (Misa et al., 2016). Depth, habitat factors, bait plume dispersal and other environmental correlates likely influence optimal windows for analysis and need to be taken into account. I suspect that larger, common 'target' species are accurately represented within the first 40 minutes of analysis, even in deepwater, but in areas of the open ocean or when targeting rare, slow-moving species, or even the full biodiversity suite for a baseline, the window required for detection is likely longer (Santana-Garcon et al., 2014).

## *Future directions*

Aside from their fundamental economic value, deepwater fishes provide an integral ecological function, with their distribution and abundance affecting trophic changes across habitats and evolving environmental conditions. Further sampling in these deepwater regions will provide the ability to resamples these locations to see if there are changes in assemblage structure over time, and whether observed patterns are temporary or sustained in deepwater. Deeper deployments are also necessary to continue this work beyond the continental slope. Building from the knowledge gathered in this work, targeted sampling in the future will allow us to explore the fundamental questions surrounding sustainable management of deepwater fishes.

Further investigation into whether depth provides a sustainable refuge for certain deepwater species, and the limits of an expected poleward shift in fish distributions under varying climatic conditions in the future, are topics of much needed future research. The effect of the heatwave during 2011 was an unexpected influence in this study and highlights the need to explore deepwater resilience and the long-term effects of climate shifts.

We can continue to gather a more accurate and comprehensive picture of deepwater fish assemblages with improvements in the design of stereo-BRUVs, refinements in the methodology and by embracing technological developments. Information for fisheries management is required across many fields in understanding fishing exploitation levels, biology, population trends for key indicator species as well as environmental perturbations. Species information that is regionally specific and multi-scaled; across size classes, depths, latitudes and habitats, are therefore vital for sustainable management.

By combining techniques, such as ocean modelling data, *in-situ* water parameter measurements and, for example, collection of eDNA in conjunction with stereo-BRUVs, we can continue to expand the power of this data collection technique. Strategic planning in future research initiatives using stereo-BRUVs that complement extractive techniques such as trawl, trap and longline fishing can yield a powerful and comprehensive data set. Within appropriate boundaries and spatial scales, the optimisation and integration of multiple data collection tools can enhance the depth of analysis and continue to broaden understandings of deepwater fish ecology.

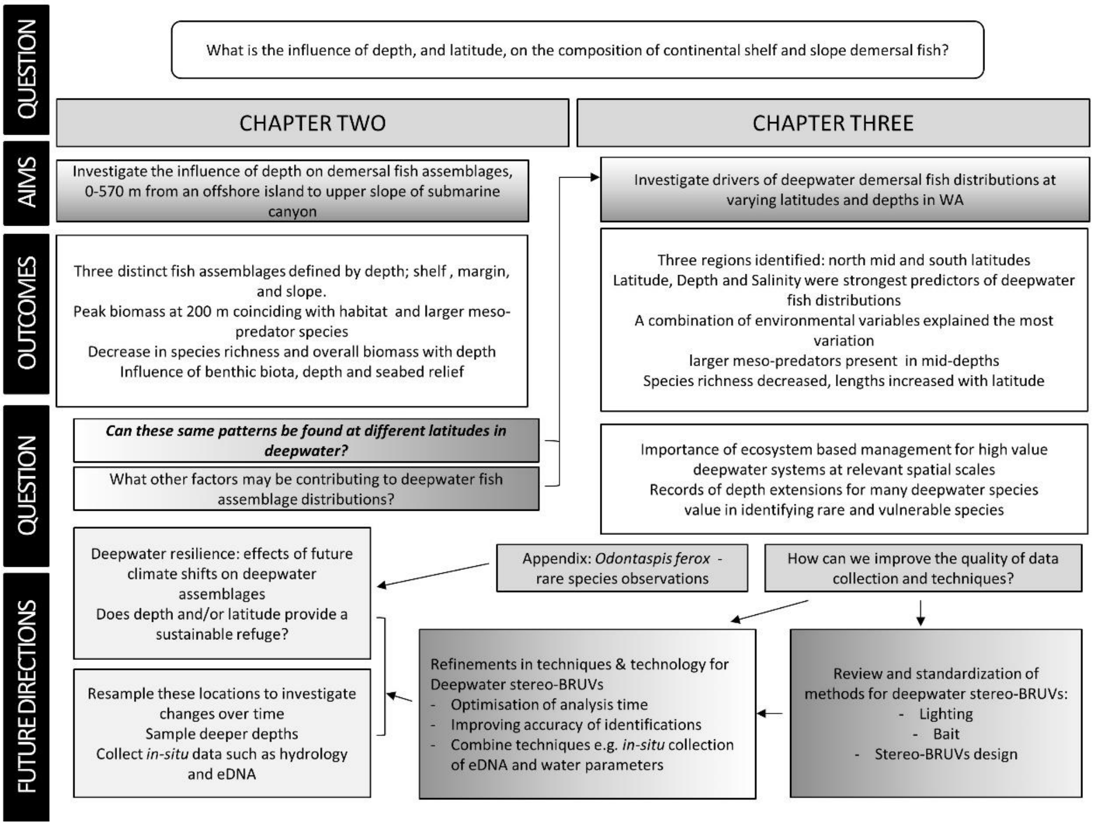

**Figure 4.1 Thesis flow diagram outlining the outcomes and future directions identified in this thesis.**

# Chapter 5 Appendix

## *First record of Odontaspis ferox (Risso, 1810) in the temperate south-eastern Indian Ocean from in situ observations in a deep-water canyon using baited video*

### *Introduction*

The smalltooth sandtiger shark *Odontaspis ferox* (Risso, 1810) is rarely encountered (or captured) and thus its relative abundance appears low, patchy and disjunct, despite a worldwide distribution in relatively deep-water (up to ~800 m) throughout warm-temperate to tropical oceans (Fergusson et al., 2008). Overall the biology of *O. ferox* is poorly understood. There are relatively few (~160) reported captures of *O. ferox* globally, along with only eight *in situ* observations that are limited to shallow waters by divers (Fergusson et al., 2008). Of these records, there is only a single capture of this species recorded from the west coast of Australia in the 1980s (Fergusson et al., 2008). Although this species inhabits shallower depths along insular shelf waters elsewhere (<100 m), there have been no reports of this species from the relatively wide continental shelf of north-western Australia, despite a long history of independent observations on commercial trawl vessels since the 1970s (Wakefield et al., 2014). In addition, there are no records of this species from the temperate waters of the south-eastern Indian Ocean, there have been no records in ~30 years from the west coast of Australia, and there have been no *in situ* observations in deep-water. This study presents a non-extractive method for collecting *in situ* behavioural observations, relative abundances and length measurements of a rare species in difficult to sample undulating topography of a deep-water canyon.

## Materials and Methods

### Study site

The Perth Canyon is the largest submarine canyon on the west coast of Australia and is incised into the continental slope in temperate waters at ~32°S, with the continental shelf being ~27 km wide at this latitude (Fig. 5.1). The steep embankments of this canyon fall from ~200 to 1000 m deep before opening onto an abyssal plain at >4000 m (Rennie et al., 2009b). This geomorphology facilitates increased productivity through a confluence of oceanic processes (e.g. upwelling) providing enhanced pelagic production and aggregation of plankton in the vicinity of the canyon (Rennie et al., 2009a). Whilst this is an attractant for many pelagic species, it also provides ideal habitat and a dietary source for deep-water demersal fishes (Rennie et al., 2009a; Nguyen et al., 2015).

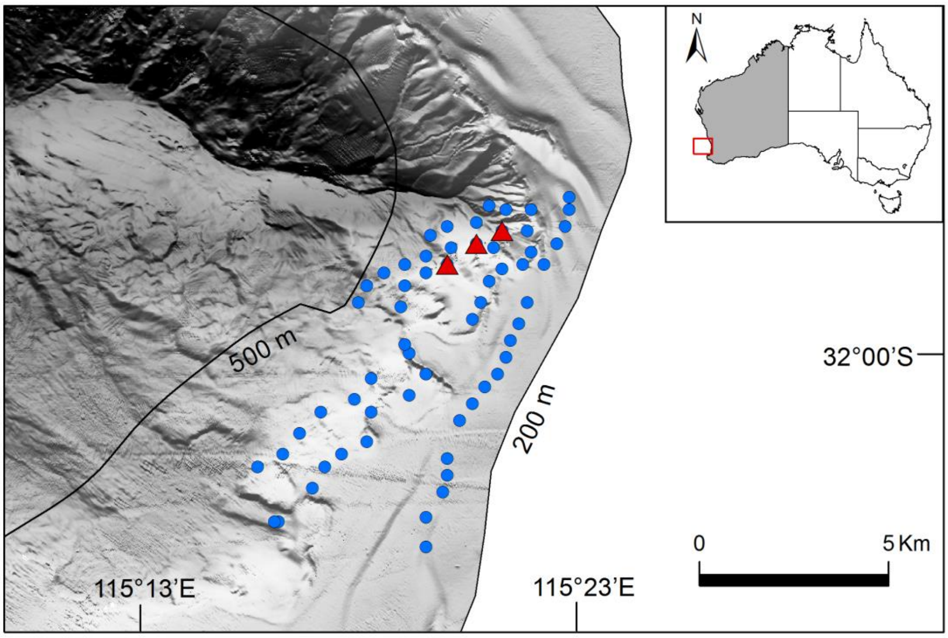

**Figure 5.1 Bathymetry map and sampling locations in the Perth Canyon (blue circles and red triangles, 200-540 m, n=66). Red triangles indicate stereo-BRUVs locations with *Odontaspis ferox* sightings (n=3).**

### Sampling

During a research survey in the Perth Canyon in March 2010, 66 stereo-BRUVs (baited remote underwater video systems) were deployed for 90 minutes each in depths of 200-540 m (Fig. 5.1), following the methods of (Harvey and Shortis, 1998). Each stereo-BRUV was situated a minimum distance of 500 m apart to avoid potential overlap in bait plume. Swath maps detailing bathymetry and backscatter (i.e. relative density of substratum) were used to identify various habitat types and thus position each stereo-BRUV accordingly.

The stereo-BRUVs were constructed of a base bar supporting two Sony® high-definition cameras (1920 x 1080, CX7 or CX12 models) inside waterproof camera housings, positioned horizontally within a trestle shaped galvanised metal frame (0.7 m apart, inwardly converged at 7° to optimise the field of view). This provided stereo-video coverage from 0.5 m to the maximum depth of field depending on light and turbidity. The use of two cameras in stereo facilitated obtaining length measurements of fish (Harvey et al., 2003). Each system was baited with approximately 800 g of Australian pilchards (*Sardinops sagax*) extended 1.2 m perpendicular from the cameras within the field of view, which was illuminated with blue LED lights (420 nm Royal Navy, CREE Inc.).

The stereo-BRUVs were calibrated pre- and post-field trips (CAL software; www.seagis.com.au) to facilitate accurate length measurements during video analyses following the procedures outlined by (Harvey and Shortis, 1998). Imagery software (EventMeasure, PhotoMeasure; www.seagis.com.au) was used to calculate the lengths of each fish from paired stereo images. Information on the relative abundances of *O. ferox*, the characteristics of their associated benthic habitat, and the type and timing of behavioural events were also recorded.

## *Results and Discussion*

*Odontaspis ferox* was observed on three concurrent videos deployed simultaneously in 410-440 m depth from 0616–0642 hr on 12 March 2010. The first observation was a single pass of a 265 cm total length (TL) individual in 410 m. On an adjacent video (750 m apart) 11 minutes later in 430 m, a 185 cm TL individual made several passes within the field of view (~8 m from the camera) before approaching the stereo-BRUV to within 1 m with an overall interaction time of 114 seconds (Fig. 5.2). The final observation occurred 14 minutes later on the next sequentially located video (960 m from the previous video) at a depth of 440 m. During this video, a single individual of 185 cm TL, thus the same length as the individual observed on the previous video, appeared from behind the camera. Within the same frame, a second *O. ferox* of indeterminate TL could be observed further from the camera (~6 m). It thus appears that at least two *O. ferox* individuals were recorded to move between three video samples covering a distance of 1.7 km during the 90 minute deployments. These sharks appeared to be attracted by the bait, but no feeding was observed.

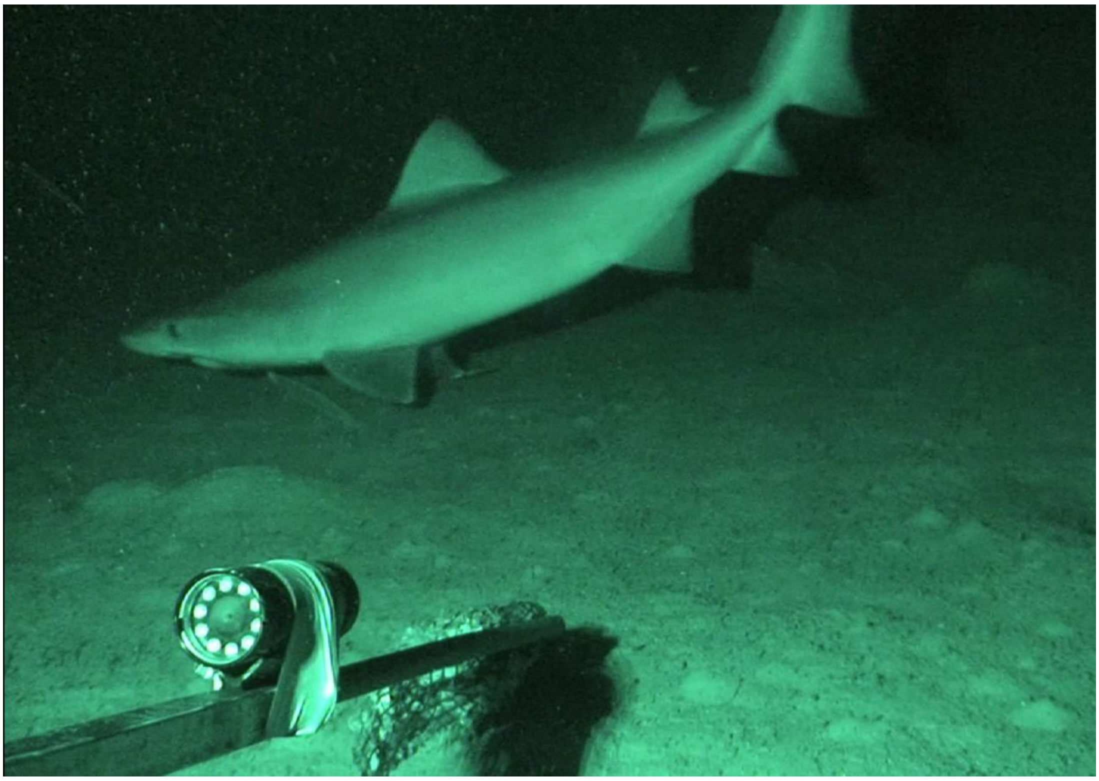

**Figure 5.2 *O. ferox* (185 cm TL) recorded using stereo-BRUVs in 430 m deep at 0628 hr on 12 March 2010.**

The estimated weights of these two individuals based on TLs of 185 and 265 cm, were 37 and 116 kg, respectively, using the relationship determined by Fergusson et al. (2008). Both of these *O. ferox* are within the range of the few immature individuals recorded elsewhere for females, i.e. 109-280 cm TL (n = 8), but larger than those for males, i.e. 107-168 cm TL (n=5, Fergusson et al., 2008). Claspers were not conspicuous on either of these *O. ferox* from video observations, which would be expected for mature males. Thus, it is likely that both these individuals were immature females.

These three recorded observations occurred on the southern margin (~1.5 km) of the head of the Perth Canyon, where it is incised into the continental shelf. Here the topography descends into the canyon with steep ravines extending precipitously to the canyon floor. The stereo-BRUVs were positioned at 410-440 m depth at the top of these ravines on rugose but relatively low profile terrain. Habitat imagery confirmed a layer of loose sediment with detritus evident on an undulating sea floor. There was an absence of any macro sessile invertebrates within the field of view of the three videos, although bioturbation and meiofauna were evident throughout. *Odontaspis ferox* appears to have a preference for locations proximal to steep and rough terrain that descends rapidly into deep-water, which may not be preferential for other sampling methods (e.g. trawling, Bonfil, 1995; Fergusson et al., 2008). These observations of *O. ferox* are consistent with those reported by Fergusson et al. (2008), whereby important nursery areas are commonly associated with deep offshore habitats of upper continental and insular slopes.

This is the first record of *O. ferox* within the temperate south-eastern Indian Ocean and the first record in ~30 years for the west coast of Australia. Considering, *O. ferox* is listed as Vulnerable on the IUCN's *Red List of Threatened Species* (Pollard et al., 2009); these observations provide important insights into the distribution of this species. On the west coast of Australia, populations of *O. ferox* are highly likely to be in a relatively unfished state considering the negligible amount of commercial fishing effort, particularly trawling, in continental slope waters in recent decades (Fletcher and Santoro, 2014).

Significant topographic seascapes, such as submarine canyons, may improve the potential for the occurrence of rarely encountered species that inhabit the continental slope given their increased productivity and greater prevalence of diverse habitat types. Technological advances and increased affordability of video equipment are improving the accessibility of *in-situ* observations of such species in these highly dynamic environments. Ongoing refinements of these methods will undoubtedly improve our understanding of distributions, relative abundances, ecology and behaviour of deep-water marine fauna, and continue to yield significant and/or novel observations and outcomes. The limited number of observations of *O. ferox* over many decades throughout its global distribution highlights the difficulties in assessing its conservation status and emphasises the importance of reporting range extensions and advances in non-extractive methods to document *in-situ* behavioural observations, relative abundances and length measurements of such rare species in difficult to sample habitats.

# Additional Materials

## *YouTube videos: Department of Fisheries WA channel*

***Underwater video of fish assemblages using baited cameras in the Perth Canyon, Western Australia***

*https://youtu.be/2d27m1ECzxA*

(over 194,773 views as of October 2019)

***Baited underwater video from the continental slope, Abrolhos Islands, Western Australia***

*https://youtu.be/Rt9awTJJ6UM*

(over 27,125 views as of October 2019)

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