Global-scale distribution of marine fish: An analysis of taxonomic richness, phylogenetic diversity, and functional traits in latitudinal and depth gradients

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Abstract

The latitudinal diversity gradient (LDG) has long interested biologists because it provides clues about where species have evolved and survived on evolutionary time scales. Depth is another factor affecting the distribution of marine species. Temperature is thought a critical factor to influence the latitudinal and depth gradients. Thus, the species-energy hypothesis, temperature-size rule (TSR), gill-oxygen limitation theory (GOLT), and temperature constraint hypothesis (TCH) have been proposed to explain the gradients of species richness, body size, and trophic level of marine species, respectively. This thesis used AquaMap's modelled distributed range data of worldwide marine fish, which minimised the bias of sampling effort, to describe the gradients of richness on five taxonomic levels, higher taxonomic richness, phylogenetic relationship, body size and trophic level in the 100 m depth band, and in the 5-degree latitude band of four depth zones. Also, this thesis tested whether these results support the aforementioned temperature-related hypotheses.

The results showed that LDGs of all taxonomic levels were not generally unimodal in all depth zones, and their peaks of richness moved poleward with higher taxonomic levels. However, the tropics across the equator still had 40% more species than high latitudes. Also, taxonomic richness from class to species was highest in warmer shallow depths, then decreased with depth. These results support the species-energy hypothesis. Species and higher taxonomic richness were positively correlated, and they were higher in the subtropics with a dip at the equator. Species assemblages had closer phylogenetic relationships in the warmer (low latitudes, shallow depths) than the colder environments (high latitudes, deep sea). In addition, below 200 m depth, both poles had distinct fish assemblages other than the rest of the world. Also, although the Arctic and the Antarctic are polar environments, their fish assemblages and endemism were different because of at least 23 different physical and biological conditions.

Mean body size and trophic level of marine fish were smaller and lower in the warmer latitudes and larger and higher in the high latitudes except for the Southern Ocean. These results support the hypotheses of TSR, GOLT, and TCH. Fish species' mean maximum body size declined with depth because of decreased dissolved oxygen. Fish species with trophic levels ≤ 2.80 were dominant in the warmer environment but absent in the colder environment. These results support the TCH hypotheses. Thus, because temperature seems the primary factor affecting the distribution and biological traits of marine fish, fish species and assemblages will change rapidly in response to climate change.

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Chapter 1

Thesis Overview

Chapter 1: Thesis overview

1.1. General introduction

Biodiversity is the sum of all biotic variation on Earth, from genes to the ecosystem (Purvis & Hector 2000). The most commonly considered facet of biodiversity is species richness: the number of species in a site, habitat or clade (Purvis & Hector 2000). However, biodiversity is not just a simple number of species. For example, consider two sites with the same number of species. Site A has species all from the same genus, but species in site B are from several genera. Thus, although both sites A and B have the same number of species, their phylogenetic biodiversity is different. The different phylogenetic diversity may suggest that the sites have different evolutionary histories (Faith, 1994). Apart from the taxonomic classification, ecological classification is even more complex, and may connect to the relationships between species, their surrounding environments and their occurrence (Costello, 2009). To adapt to their physical, chemical, and biological environments, species develop various functional traits (e.g., body size, trophic position) (Díaz & Cabido 2001; Reiss et al., 2009; Costello et al., 2015). The diversity of species' phylogeny and species' functional traits are usually connected. That is, it is to be expected that an area with high species richness will have a high diversity of phylogenetic and functional traits, but the relationships are not necessarily linear and may vary at different spatial scales (Flynn et al., 2011; Fritz & Rahbek 2012; Costello et al., 2015). To form a general theory about how the environment influences species evolution, it is preferable to look at a global scale to have the full picture. Marine fish, currently with 18000 described species (WoRMS Editorial Board, 2021), is the largest group of vertebrates in the global oceans, distributed from the tropics to the poles and from the shallow to the deep sea (Froese & Pauly, 2019). This study employs marine fish as a model taxon to further understanding of evolution of species richness, phylogenetic diversity, and functional ecological traits in relationship to their environment. Here, I outline the principal biodiversity topics, relationships, expectations, and hypotheses that will be addressed within this thesis.

1.1.1. Latitudinal gradients

The latitudinal diversity gradient (LDG), generalised over local and regional patterns, is one of the most widely studied gradients in both terrestrial and marine environments (Gaston, 2000; Willig et al., 2003; Hillebrand, 2004; Brown, 2014). The LDG varies with environments, especially the temperature in the Earth's past (Song et al., 2020; Yasuhara et al., 2020), and thus helps us to understand where species have evolved and survived on both ecological and evolutionary time scales (Ekman, 1953; Gaston, 2000; Willig et al., 2003; Pontarp et al., 2019). A unimodal LDG, with a species richness peak at the equator and decrease poleward (Figure

1.1), is found in most terrestrial plants and animals (Gaston, 2000; Weiser et al., 2007; Krug et al., 2009). However, recent studies have found that the LDG for marine taxa are now bimodal with a dip at or near the equator (Figure 1.1). This may be because marine species at the equator move away from the warming sea temperature (Chaudhary, 2019; Yasuhara et al., 2020; Chaudhary et al., 2021). Apart from the species richness, studies on latitudinal gradients of phylogenetic diversity, and functional traits of marine fish in different depth zones on a global scale have not been studied before. Therefore, this thesis presents and compares the results on these topics.

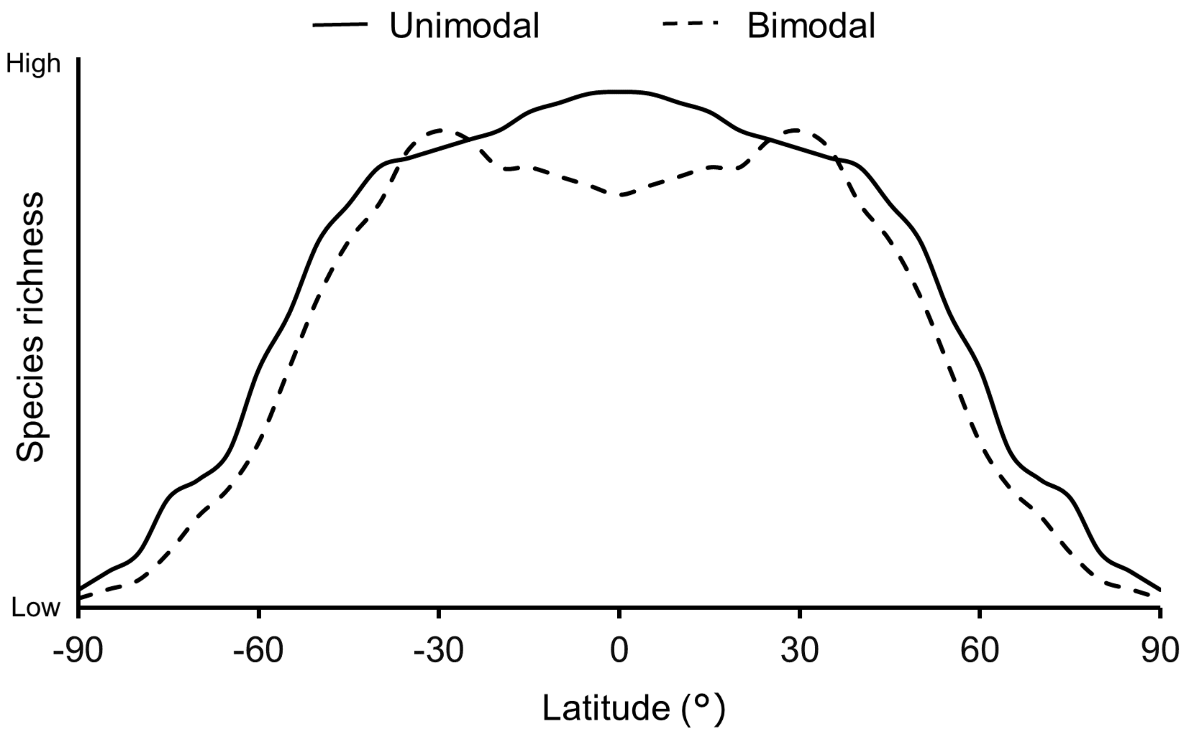


Figure 1.1. Diagram of unimodal (solid line) and bimodal (dashed line) latitudinal diversity gradients.

(a) Higher taxonomic levels

Higher taxonomic levels, from classes to genera, reflect the evolutionary relationships between species (Ruggiero et al., 2015). Studies of LDG on higher taxonomic levels, especially the genus level, are sometimes used as surrogates for species richness where species identification is ambiguous (Gladstone & Alexander, 2005; Mandelik et al., 2007). However, the LDGs of different taxonomic levels may not be consistent (Krug et al., 2009). Therefore, this thesis compares the LDGs of five taxonomic levels (classes, orders, families, genera, and species) to see whether they have synchronous gradients (Chapter 2).

(b) Phylogenetic diversity

Measures of phylogenetic diversity are based on phylogenetic relationships and provide a view of biodiversity that is related to evolutionary history (Faith, 1994; Purvis & Hector 2000; Clarke & Warwick 2001). This thesis uses average phylogenetic diversity (AvPD) (Clarke & Warwick, 2001), and creates two simple phylogenetic indices, the sum of the higher taxonomic levels (STL) and the sum of the higher taxonomic levels divided by the number of species (STL/spp), to understand the phylogenetic relationships (AvPD, STL/spp) and higher taxonomic richness (STL) of marine fish in a given latitude. Wu et al. (2016) showed that marine nematodes had higher species and genus richness and closer phylogenetic relationships at lower latitudes. This thesis describes whether marine fishes at low latitudes also have more species and higher taxonomic richness, and closer phylogenetic relationships (Chapter 3).

(c) Functional traits

Functional traits characterize an organism's phenotype, indicating how it may interact with the physical, chemical, and biological environments (Hooper et al., 2005). Body size and trophic level are the most widely used numerical functional traits and have relatively complete records for most fish species (Costello et al., 2015; Froese & Pauly, 2019). Previous studies found that body sizes of freshwater and marine ectotherms were smaller in the low latitudes and larger in the high latitudes (Lindsey, 1966; Fisher et al., 2010; Bartels et al., 2020; McLean et al., 2021). More freshwater and marine herbivorous or omnivorous fishes exist in the lower than higher latitudes (Floeter et al., 2005; Behrens & Lafferty 2007; González-Bergonzoni et al., 2012; Dantas et al., 2019). Therefore, this thesis tests whether the mean body sizes and trophic levels of marine fish are smaller and lower, respectively, in low latitudes than higher latitudes (Chapter 4).

1.1.2. Depth gradients

In the marine environment, species richness is also related to depth. Generally, species richness declines with depth, although it may peak at intermediate depths for some taxa in some places (Rex, 1981; McClain & Etter, 2005; Rosa et al., 2008; Costello & Chaudhary, 2017). It would be expected that richness of higher taxonomic levels also decreases with depth and thus influences the depth gradient of phylogenetic diversity. Previous regional studies found that relatively more fish species with larger body size and higher trophic level occurred with greater depth (Smith & Brown 2002; Lamprakis et al., 2008; Mindel et al., 2016). Therefore, this thesis compares the depth gradients of higher taxonomic levels, phylogenetic diversity, body sizes, and trophic levels of marine fish globally to see how they change with depth.

Depth may also influence the LDG. The sea surface environment is more variable than in the deep sea (Costello, Basher, et al., 2018). Sea surface temperature has higher variation in mid-latitudes than low and polar latitudes (Basher & Costello, 2020). In contrast, the deep-sea temperature has little difference across latitudes (Costello & Breyer, 2017; Sayre et al., 2017; Basher & Costello, 2020). Therefore, it would be expected that species richness, phylogenetic diversity, and functional traits vary across latitudes in the surface zone (0 – 200 m depth) but would be more constant in the relatively homogenous cold deep-sea environment.

1.1.3. Gamma and Beta diversity

This thesis presents the species richness at a regional scale (5° latitude bands) (Chapter 2), known as the gamma diversity, as the simplest way to measure biodiversity (Whittaker, 1975). Another method to assess the change of species composition (species turnover) is called beta diversity, and the Jaccard similarity index (Jaccard, 1912) is the simplest and most popular measure of species turnover (beta diversity) (Whittaker, 1975; Kreft & Jetz, 2010). A global-scale study showed that multiple marine taxa in 5° latitude bands could be divided into one tropical, two temperate, and two polar assemblages (Chaudhary, 2019). However, marine fish composition changes among latitudes and with depth, but exactly where boundaries between assemblages occur have not been identified. This thesis describes where species composition changes along latitude and depth, and the expectation is that species assemblages fit the boundaries of climate zones in the surface water, but not in the deep sea because of the consistently low temperature across latitudes (Chapter 3).

1.1.4. Hypotheses

Over 25 mechanisms have been presented to explain the formation of LDG, and many of these proposed mechanisms are intercorrelated (Gaston, 2000; Jørgensen et al., 2007). Studies found that temperature is related to many of those mechanisms, especially in the physiological process of species, and thus influence other mechanisms affecting the LDG (Rohde, 1992; Davies et al., 2004; Allen et al., 2006; Wright et al., 2006, 2011; Gillman et al., 2010; Brown, 2014) and functional traits of marine fish (Gaines & Lubchenco, 1982; Pauly & Cheung, 2018). There are also hypotheses not directly temperature related, such as biotic hypotheses, that suggest that species interactions (e.g., competition, predation, mutualism, and parasitism) are stronger in the tropics, thus promoting the species coexistence and specialization of species, leading to greater speciation in the tropics (Pianka, 1966; Fine, 2015). However, the information on species interactions is not included in the dataset used in this thesis. Therefore, in this thesis, I mainly test the temperature-related hypotheses. Here, I describe the hypotheses and their mechanisms.

The species-energy hypothesis suggests that warmer temperatures in the tropics (resulting in shorter generation times, higher metabolism rates, faster rates of mutation, and more rapid selection due to increasing competition for resources) can generate and maintain higher biodiversity (Rohde, 1992; Davies et al., 2004; Allen et al., 2006; Wright et al., 2006, 2011; Gillman et al., 2010; Brown, 2014). Also, the warmer temperature shortens the duration of planktonic larvae in the tropics (O'Connor et al., 2007), with the shortest dispersal distance in the subtropics (Álvarez-Noriega et al., 2020), potentially resulting in reduced spatial gene flow and higher rates of diversification and speciation in the tropics and subtropics (O'Connor et al., 2007). Based on the high diversity in the tropics, the out-of-the-tropics (OTT) hypothesis suggests that marine taxa originate in the tropics and expand to higher latitudes without losing their tropical presence (Jablonski et al., 2006). Thus, the tropical area may be both a "cradle" and a "museum" of biodiversity (Chown & Gaston, 2000; Jablonski et al., 2006; Fine, 2015).

For the relationship between body size and environments, the temperature-size rule (TSR) suggests that species have a smaller body size in the warm environment and a larger body size in the cold environment (Atkinson, 1994). This may be explained by the gill-oxygen limitation theory (GOLT) which posits that marine fish's body size is limited by oxygen supply (Pauly & Cheung, 2018). The ratio of gill surface area to body mass decreases when individuals grow. Therefore, an organism's body size is limited by the oxygen needed for maintaining its metabolic demands which is influenced by increased oxygen demand and decreased oxygen solubility at warmer temperatures (Pauly & Cheung, 2018). The temperature constraint hypothesis (TCH) posits that there are more marine herbivorous fishes in warmer water because low temperature constrains the efficiency of digestion for plant materials (Gaines & Lubchenco, 1982). Therefore, the species-energy hypotheses, TSR, TCH, and GOLT, are temperature-related hypotheses. Together, they suggest that temperature and dissolved oxygen are the two critical factors determining the latitudinal gradients of species richness, body size, and trophic level for marine fish. This thesis examines and describes their relationships and verifies whether the results support these hypotheses.

1.2. Modelled species range data

To study global biodiversity, the distribution of species is essential information. During the past decade, large databases with global, all-taxa records have been founded, notably the Global Biodiversity Information Facility (GBIF) and the Ocean Biodiversity Information System (OBIS) (Costello & Vanden Berghe, 2006). These databases use point occurrence (latitude and longitude) for recording the distribution of taxa and have been used in many LDG studies of marine taxa (Chaudhary et al., 2016; Saeedi, 2016; Saeedi et al., 2017; Chaudhary, 2019; Arfianti & Costello, 2020; Pamungkas, 2020). However, point occurrence data are biased by sampling effort and lack records where a species may occur but not be reported (Fernandez & Marques, 2017; Menegotto & Rangel, 2018). To avoid the problem of missing records, biogeographic studies often use species latitudinal and geographic ranges. However, a species does not occur everywhere within its range due to availability of suitable local habitat and environmental conditions, which themselves may change over time. Thus, species range maps are a more conservative indication of species distribution. Recognising these limitations, this thesis uses the modelled distributed ranges of marine fish from AquaMaps (Kaschner et al., 2019).

AquaMaps uses environmental niche modelling of species observations and known species ranges to predict the probability of occurrence of each species in each 0.5° × 0.5° latitude-longitude cell. Each species' environmental ranges are determined by depth, temperature, salinity, primary production, and ice concentration. These species' environmental envelopes are used to predict each species' suitable environments and to visualize geographic ranges by applying further restrictions in the form of bounding boxes based on known species ranges (Kaschner et al., 2019). The probabilities of a fish species' occurrence (P_c) in each 0.5° × 0.5° latitude-longitude cell is computed using the following equation:

$$P_c = P_{depth_c} \times P_{temperature_c} \times P_{salinity_c} \times P_{primary\ production_c} \times P_{ice\ concentration_c}$$

This multiplicative approach allows each environmental predictor to act as a "knock-out" criterion. The predicted probabilities produced by AquaMaps range from 0 to 1 for each 0.5° × 0.5° latitude-longitude cell. In this thesis, I converted AquaMaps predictions into binary presence and absence data using a probability threshold of 0.0 following the method in Kaschner et al. (2011).

The data from the probability thresholds of 0.0, 0.5, and 1.0 are significantly positively correlated (Table 1.1). Species richness among these probability thresholds is highest in the Central Indo-Pacific and the Gulf of Mexico (Figure 1.2). They are bimodal and have a dip at the equator for the number of records in 5-degree latitude bands (Figure 1.2). However, species ranges would overlap more, and sample size would be greater within latitudes by using a probability threshold of 0.0 when fish groups were divided up (Figure 1.2). Thus, the probability of occurrence threshold used in this study is conservative in terms of detecting variation in the LDG.

Table 1.1. Spearman correlations of species richness in the 0.5° × 0.5° latitude-longitude cells for three probability thresholds. *** *p*-value < 0.001.

Threshold (P)	0.0	0.5	1.0
0.0	1.00***		
0.5	0.97***	1.00***	
1.0	0.85***	0.91***	1.00***

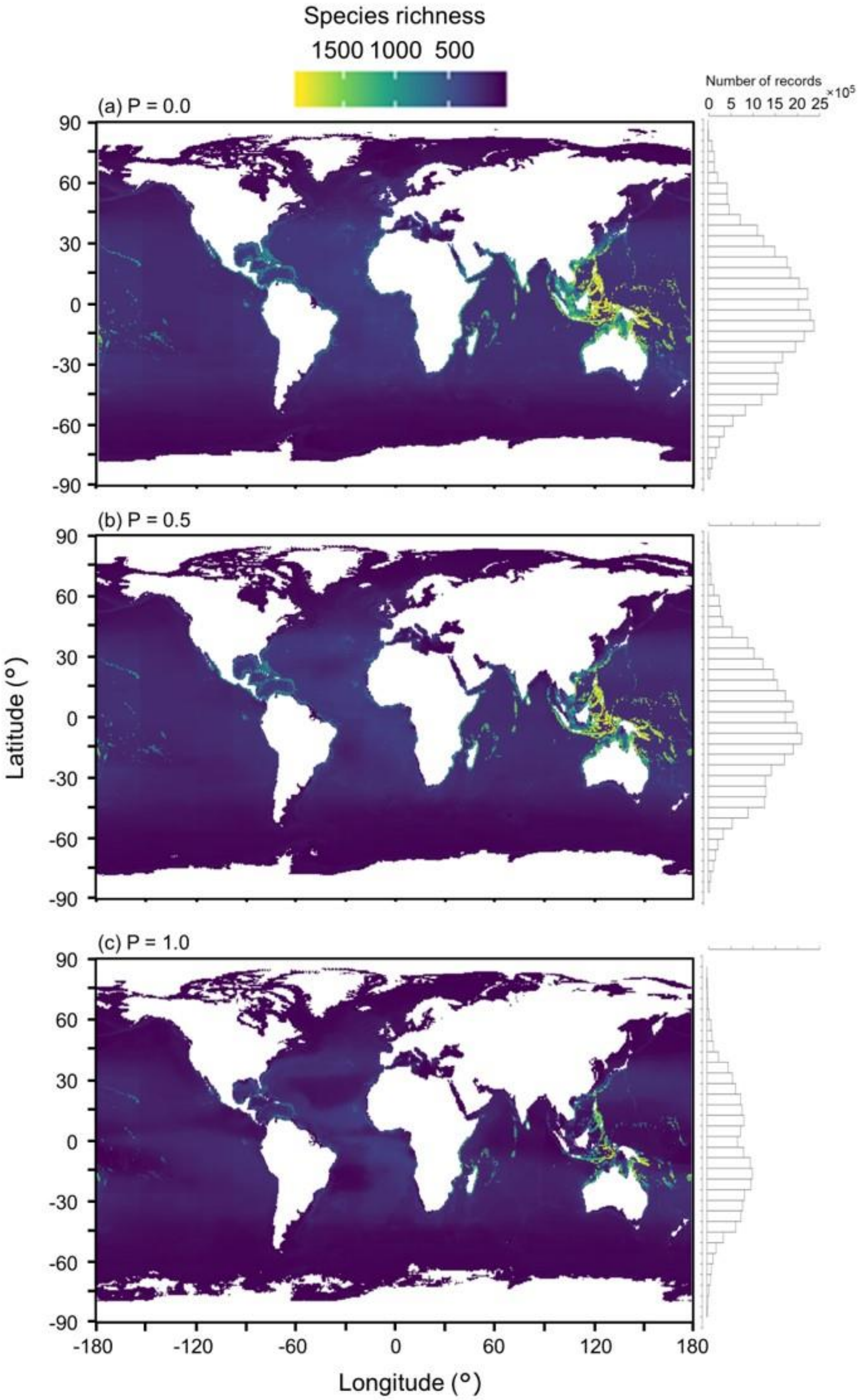


Figure 1.2. Map of species richness and number of records in 5-degree latitude bands from the 0.5° × 0.5° latitude-longitude cells of AquaMaps' modelled distribution of 5619 marine fish among three prediction thresholds (P). (a) P = 0.0, (b) P = 0.5, and (c) P = 1.0.

1.3. Objectives and thesis structure

This thesis describes the latitudinal gradients in different depth zones and depth gradients for five taxonomic levels, phylogenetic diversity, and functional traits of marine fish. Using modelled range data from the AquaMaps database, this is the first study to generalise these gradients and their relationships with environments at a global scale (Figure 1.3). This thesis has seven objectives, and they are structured into four chapters. Chapter 2 has been published (Lin et al., 2021).

1. To compare the richness gradients of five taxonomic levels (classes, orders, families, genera, and species) in latitudes in the whole water column and three depth zones among five marine fish groups (Chapter 2)

2. To determine how environmental conditions (temperature, salinity, and primary productivity) influence the latitudinal diversity gradient of marine fish (Chapter 2)

3. To compare latitudinal and depth gradients of phylogenetic diversity (phylogenetic relationships and higher taxonomic richness) of marine fish (Chapter 3)

4. To determine species turnover in latitudes and depths to figure out where the boundaries of distinct marine fish assemblages (Chapter 3)

5. To compare latitudinal and depth gradients of functional traits (body sizes and trophic levels) of marine fish (Chapter 4)

6. To determine what environmental variable (temperature, salinity, or dissolved oxygen) is the primary factor affecting the latitudinal gradient of functional traits for marine fish (Chapter 4)

7. To integrate the results from Chapters 2 to 4, present how the environmental variables affect the latitudinal gradients on species richness, phylogenetic diversity, and functional traits of marine fish. In addition, to verify whether these results support the temperature-related hypotheses of biodiversity distribution, and to connect these results to studies of climate change and marine conservation (Chapter 5)

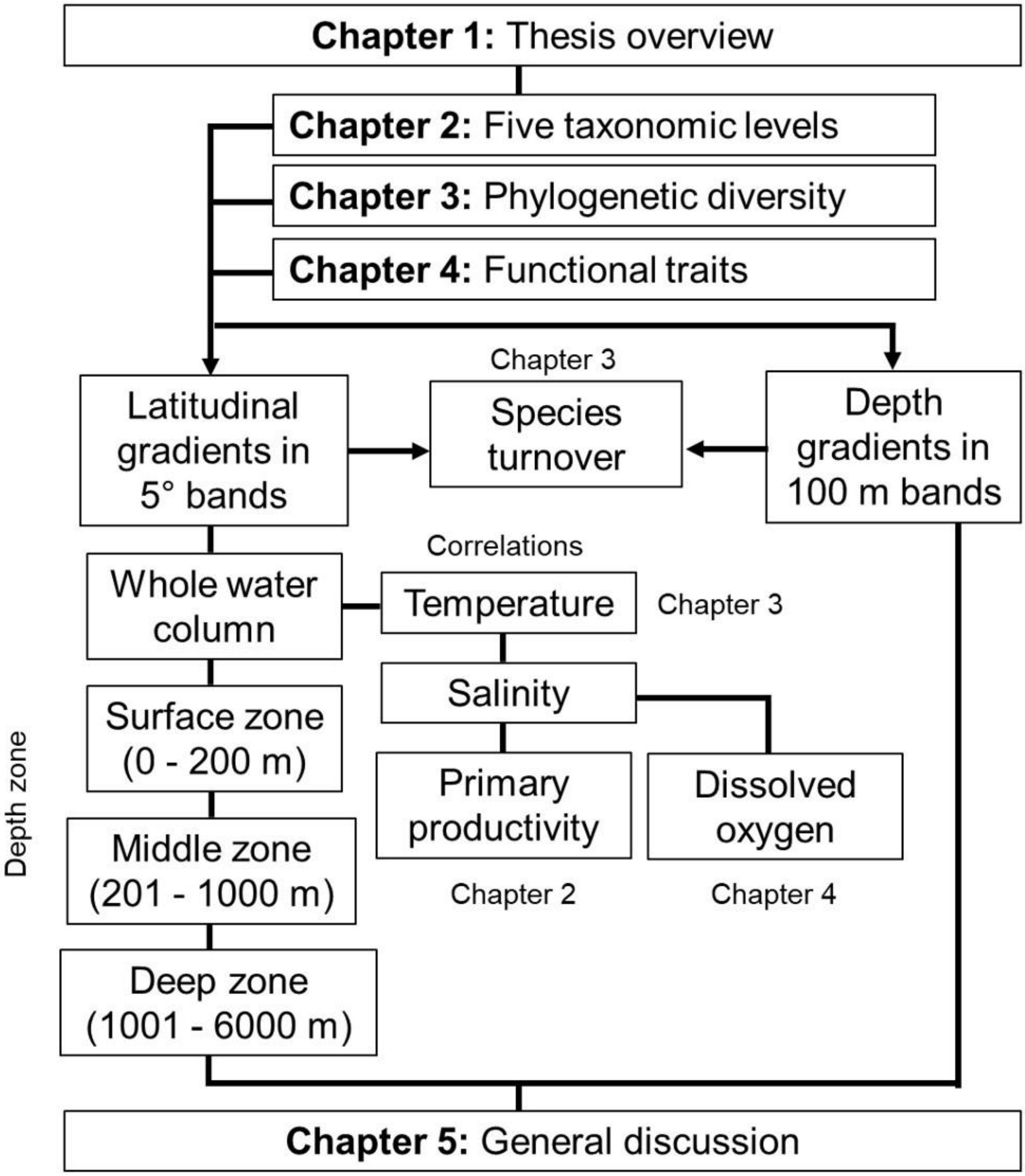


Figure 1.3. The structure and organisation of this thesis, indicating aspects within chapters.

Chapter 2

Latitudinal Diversity Gradients for Five Taxonomic Levels of Marine Fish in Depth Zones

Chapter 2: Latitudinal diversity gradients for five taxonomic levels of marine fish in depth zones

2.1. Introduction

The latitudinal diversity gradient (LDG) has long interested biologists because it provides clues as to where species have evolved and survived on evolutionary time scales (Ekman, 1953; Gaston, 2000; Willig et al., 2003; Pontarp et al., 2019). More than 25 mechanisms have been raised to explain the formation of the LDG and many of the proposed variables are intercorrelated (Gaston, 2000; Jørgensen et al., 2007). In addition to climatic conditions, habitat area, plant productivity, and ecological competition and predation, may also influence the apparent LDG (Rosenzweig, 1992; Gaston, 2000; Buzas et al., 2002). The typical LDG of declining species richness from the equator has been attributed to low extinction and high speciation rates in the tropics, with glaciations causing extinctions and retarding speciation rates in high latitudes (Costello & Chaudhary, 2017). Thus, understanding the variation of the LDG over time helps predict how climate change may affect the species' distribution (Mannion et al., 2014; Yasuhara et al., 2020). Because the LDG integrates biogeography across longitudes, it allows inference of a general theory of biodiversity that is not possible from analysis of local and regional scales.

In general, the LDG has been considered to be a unimodal gradient peaking around the equator. This has been considered the distribution pattern for terrestrial birds (Krug et al., 2009) and plants (Gaston, 2000; Weiser et al., 2007), corals (Connolly et al., 2003), as well as broad groupings of marine taxa (Tittensor et al., 2010). However, some other studies found that marine species richness peaked at middle latitudes rather than the equator (Hillebrand & Azovsky, 2001; Powell et al., 2012). Chaudhary et al. (2016) found that a more comprehensive dataset of 65000 marine species (including 2600 bony fish and 132 cartilaginous fish) showed a bimodal gradient with a dip at or near the equator.

Several hypotheses that had been proposed that may cause the formation of bimodal LDG. One is the bias of sampling effort that affects more data in the northern than southern hemisphere (Fernandez & Marques, 2017; Menegotto & Rangel, 2018). However, several studies rejected this hypothesis by statistically standardizing the sampling effort for several types of taxa and confirmed that the LDG was still bimodality (Rutherford et al., 1999; Rombouts et al., 2009;

Chaudhary et al., 2017; Yasuhara et al., 2020). A second hypothesis is habitat area. The continental shelf offers diverse types of habitats for organisms and the coverage is higher in the northern latitudes than the equatorial area and southern latitudes (Chaudhary, 2019; Reygondeau, 2019). In addition, temperature shapes the global spatial distribution of marine species and is highly correlated with global patterns of species richness (Rutherford et al., 1999; Kaspari et al., 2004; Krug et al., 2009; Tittensor et al., 2010; Saeedi et al., 2017; Chaudhary, 2019).

Fish in different groups, such as pelagic fish, demersal fish, bony or cartilaginous fish, may have different LDGs of species richness. Mora et al. (2003) reported that the species richness of coral reef bony fish peaked at the equator and declined with increased latitude (unimodal). In contrast, Lucifora et al. (2011) analysed 507 shark species and found that species richness in 1° × 1° cells peaked at mid-latitudes (30° – 40°) in both hemispheres (bimodal). These studies suggested that bony reef fish and sharks have dissimilar patterns, while the LDGs of other fish groups have not been studied globally.

Higher taxonomic levels (e.g., classes, orders, families, and genera), especially the genus level, are sometimes used as a surrogate for species richness where species identification is ambiguous (Gladstone & Alexander, 2005; Mandelik et al., 2007). However, the LDGs of different taxonomic levels may not be consistent. For example, Roy et al. (1996) found that the LDGs of families, genera, and species of eastern Pacific molluscs were all bimodal and peaked in the same area. In contrast, Krug et al. (2009) found that the LDG of species and genera of marine bivalves were bimodal but peaked at different latitudes. Therefore, this study compared the LDGs of fish species grouped at different taxonomic levels (ranging from class to species) and across different functional groupings to see whether the modality and peaks changed among taxonomic levels and different fish groups.

The average depth of the world’s oceans is about 3400 m (Costello, Cheung, et al., 2010). Marine species richness generally declines with depth (Smith & Brown, 2002; Piacenza et al., 2015; Costello & Chaudhary, 2017), including marine fish (Smith & Brown 2002; Coll et al., 2010; Anderson et al., 2013; Jankowski et al., 2015; Rodriguez et al., 2016). However, the species richness of some taxa can increase at mid-depths between 300 m and 4700 m in some locations (Rex, 1981; McClain & Etter, 2005; Rosa et al., 2008). Previous studies majorly focus on species level. However, how gradients of other higher taxonomic levels vary with depth for marine fish are lacking. Depth may also influence the modality of latitudinal species richness. The environment at the sea surface is more variable than in the deep sea (Sayre et al., 2017; Costello, Basher, et al., 2018). The temperature at the sea surface fluctuates with latitude, being high in the tropics and low near the poles. In contrast, the temperature is always low below 1000 m with no significant latitudinal gradient (Costello & Breyer, 2017; Sayre et al., 2017). Maximum values of primary production can be found in the surface (euphotic, epipelagic) zone, shallower than 200 m. The deep-sea (depth > 1000 m) is dark (aphotic), cold, and with lower oxygen than the pelagic zone (Costello & Breyer, 2017). Therefore, it might be expected that the number of species would vary in the surface zone among latitudes, but that in the more homogenous cold deep-sea environment, the number of species would be similar in each latitude. However, Woolley et al. (2016) found a unimodal LDG for species richness of brittle stars in continental shelf (20 m – 200 m) and upper-slope (200 m – 1200 m) depths, but a bimodal LDG in the deep sea (2000 m – 6500 m).

Previous studies focused on the latitudinal species richness of fish were at regional scales (e.g., Macpherson & Duarte 1994; Floeter et al., 2005; Navarrete et al., 2014). A limitation of regional studies is that they may be biased by local environmental and habitat conditions and may not reflect evolutionary scale biogeographic patterns. Placing these patterns in a global context will provide a stronger and more general theoretical understanding of evolution. Moreover, to understand how LDGs may be influenced by environmental variables, I describe the relationship between LDGs and environmental variables in this study. Also, this study asks: (1) Is the LDG the same across groups of fish and depth zones? (2) Is the LDG unimodal or bimodal? (3) Is the LDG correlated with temperature, salinity, primary productivity, and continental shelf area? In addition, the gradients of five taxonomic levels of marine fish along with depth are compared.

2.2. Methods

2.2.1. Data

The distribution ranges of 5619 fish species were obtained from AquaMaps (Kaschner et al., 2019) and represent about one-third of all marine fish species (Froese & Pauly, 2019). AquaMaps uses environmental niche modelling of species observations and known species ranges to predict the probabilities of occurrence of each species in a given half-degree latitude by longitude cell. The environmental ranges of each species are determined for depth, temperature, salinity, primary production, and ice concentration. These consequent species' environmental envelopes are used to predict suitable environments of each species and to visualize geographic ranges by applying further restrictions in the form of bounding boxes based on known species ranges (Kaschner et al., 2019). The probabilities of a fish species' occurrence (P_c) in a given half-degree cell were computed using the following equation:

$$P_c = P_{depth_c} \times P_{temperature_c} \times P_{salinity_c} \times P_{primary\ production_c} \times P_{ice\ concentration_c}$$

This multiplicative approach allows each environmental predictor to act as a “knock-out” criterion. Predicted relative probabilities produced by AquaMaps range from 0 to 1 for each half degree cell. This study converted AquaMaps predictions into binary presence and absence data using a probability threshold of 0.0 following the method in Kaschner et al. (2011) because species ranges would tend to overlap more and sample size would be greater within latitudes when fish groups were divided up. Thus, my choice of probability of occurrence threshold is conservative in terms of detecting variation in the LDG.

The use of predicted species’ geographic ranges is common in biogeography because it avoids the problems with spatially biased field observations (errors of omission). However, due to the very broad generic approach of AquaMaps, the suitability of the selected environmental parameters to describe a species habitat use and the quality of resulting predictions will vary across different species and taxa. Given the biases introduced by sampling heterogeneity in marine environments, standard statistical validation of predictions using, for example, independent, effort-corrected data sets is difficult, and the uncertainty of predictions is therefore difficult to quantify. However, maximum range extents predicted by AquaMaps match range extents of International Union for Conservation of Nature (IUCN) for the majority of species for which both types of maps are available (O’Hara et al., 2017), and map quality can be substantially improved through the expert review tool in AquaMaps (O’Hara et al., 2017). Nevertheless, species distribution models (SDM) in general cannot adequately capture the effects of biological interactions (such as competition or predation) or anthropogenic impacts and simpler SDM approaches, such as AquaMaps, will tend to over-predict species ranges. Data poor species will be disproportionally affected by overall quantity of available occurrence records species misidentifications. Therefore, this study has limited analysis to the one-third of all marine fish species which are more frequently reported (Costa et al., 2015). Applying a probability threshold of 0.0 as used here will therefore represent a more conservative approach with respect to commission errors that could affect the patterns of species richness.

The latitudinal distribution range (northern and southern limits) and the preferred maximum depth of marine fish were derived from the species geographic and depth ranges. The classification of marine fish as pelagic (1219 species) and demersal (4400 species) followed Froese and Pauly (2019) (Appendices Table A2.1). Also, I compared bony (Class Actinopterygii and Sarcopterygii) and cartilaginous fish (Class Elasmobranchii and Holocephali) groups. Overall, five groups including “All Fish”, “Pelagic Fish”, “Demersal Fish”, “Bony Fish”, and “Cartilaginous Fish” were analysed for LDGs in the whole water column and three depth zones (Table 2.1). These were not independent groups, with many species in multiple groups. For example, groups of “All Fish”, “Bony Fish”, and “Demersal fish” shared many species, and most of species in “Cartilaginous Fish” also belonged to “Pelagic Fish”. The calculation of taxonomic richness used 5° latitudinal bands. The four depth zones were: whole water column, surface (0 – 200 m), middle (201 – 1000 m), and deep (1001 – 6000 m), reflecting the light penetration zones of photic, mesophotic and aphotic (Costello & Breyer, 2017). Thus, a total of 100 LDGs (5 fish groups × 5 taxonomic levels × 4 depth zones) were generated and standardized to percentage. The initial number of all LDGs are in Appendices Figures A2.1 and A2.2. The calculation of five taxonomic levels along with depth among five fish groups was using the preferred distributed depth range (minimum and maximum depth limits) of fish species, in 100 m depth bands from 0 m to 3500 m. The numbers of fish species in each of the five taxonomic levels and five fish groups in the whole water column and three depth zones are in Table 2.1.

Table 2.1. The number of taxa within each of the five taxonomic levels in the depth zones.

Depth	Fish groups	Class	Order	Family	Genus	Species
Whole water column	All Fish	6	52	358	1824	5619
	Pelagic Fish	2	21	94	421	1219
	Demersal Fish	6	42	264	1403	4400
	Bony Fish	2	37	298	1654	5118
	Cartilaginous Fish	2	13	57	163	488
0 m – 200 m	All Fish	5	47	271	1342	4102
	Pelagic Fish	2	18	57	220	636
	Demersal Fish	5	38	214	1122	3466
	Bony Fish	1	32	226	1228	3821
	Cartilaginous Fish	2	13	42	109	274
201 m – 1000 m	All Fish	6	37	178	531	1184
	Pelagic Fish	2	15	51	177	420
	Demersal Fish	6	31	127	354	764
	Bony Fish	2	24	147	459	1005
	Cartilaginous Fish	2	11	29	68	175
1001 m – 6000 m	All Fish	4	25	82	198	333
	Pelagic Fish	2	11	34	102	163
	Demersal Fish	4	19	48	96	170
	Bony Fish	1	18	68	175	292
	Cartilaginous Fish	2	6	13	21	39

2.2.2. Data analysis

For determining the modality of LDGs, studies generally use visual observation to determine whether the LDG is unimodal (one peak) or bimodal (e.g., Chaudhary et al., 2016, 2017; Saeedi et al., 2017). However, there are some LDGs with ambiguous modalities. Therefore, this study used a statistical method to test the modality of LDGs. Amongst the many statistical methods available for testing modality, Hartigan's dip statistic (HDS) (Hartigan & Hartigan, 1985) is considered the most sensitive method (Freeman & Dale, 2013). Thus, this study used the HDS to test the modality of LDGs by using the R package "diptest" (Maechler, 2016). The dip statistic D and its *p*-value were generated by HDS. The *p*-value of HDS ranges from 0 to 1, and unimodality is assumed when the $p > 0.05$ (i.e., not significant) and not unimodal if the $p < 0.05$ (so it could be bi- or multi-modal) (Hartigan & Hartigan, 1985; Freeman & Dale, 2013). However, the HDS may not be able to find the distribution to be significantly different from unimodal if sample sizes are small. Therefore, the absence of non-unimodality does not mean the distribution is unimodal, and in this situation, visual assessment can complement the use of this statistical test. This study found that the HDS was sensitive to sample size (number of taxa in each fish group), with none of the LDGs with ≤ 25 taxa significantly different from unimodal. However, at larger sample sizes, the HDS determined that most LDGs were not unimodal. Thus, this study limited use of HDS to when sample sizes were > 25 (Table 2.1). Of the 100 potential LDGs, 12 classes had too few taxa ($n \leq 2$) to assess. The remaining 88 LDGs were all assessed visually, and 66 LDGs by HDS (excluding 20 classes, 12 orders, 1 family, and 1 genus).

The standard errors of taxonomic richness in each 5-degree latitude band were very low and are shown in Appendices Figures A2.3 – A2.7. They are excluded from the graphs in the main paper for clarity.

The LDGs of species richness were correlated with the long-term averages of monthly sea surface temperature (SST, °C), annual sea bottom temperature (SBT, °C) included shallow water to deep sea, sea surface salinity (practical salinity unit, PSU), and annual primary productivity (mg C m^{-2} day^{-1} $cell^{-1}$) as obtained from Global Marine Environmental Datasets (Basher et al., 2018; Basher & Costello, 2020). Raster data of each environmental variable were calculated to one mean value for each 5-degree latitude band between 75°S and 70°N. Generalised Additive Models (GAM) (Hastie & Tibshirani, 1990) were used to assess the relationship between LDGs of species richness and four environmental variables in the same 5-degree latitude bands. A GAM is a nonparametric regression method that uses smooth functions of the predictors. Also, a GAM is flexible in regard to the assumptions concerning the underlying statistical distribution of the data (Swartzman et al., 1995). The package "mgcv" (Wood, 2011) in R (R core team,

2018) was used for the GAM analysis. A GAM with Gaussian error distribution and identical link function was used for modelling. Smoothness selection (s) of thin plate regression splines was used for the model fitting process. The model was as follows:

Species richness ~ s(SST) + s(SBT) + s(Salinity) + s(Primary Productivity)

Standard diagnostics Quantile-Quantile (Q-Q) plot, minimised Generalised Cross-Validation (GCV) scores, maximised deviance explained and maximised adjusted r^2, were used to assess distributional and smoothing assumptions (Wood, 2006) (Appendices: GAM-Chapter 2). The deviance explained, adjusted r^2 and GCV scores were recorded. The relationships of each species richness to each environmental variable were plotted.

2.3. Results

2.3.1. Latitudinal gradients of environmental variables

The gradients of both mean SST and mean SBT declined from the tropics to the poles (Figures 2.1a, b), but mean SBT was less than 6°C in all latitudes because of the dominating effect of the large area of deep sea in each latitude. Both mean SST and mean SBT had a small dip at the equator visually but peaked in different latitudes (Figures 2.1a, b). Mean SST peaked at 10°N and 5°S and mean SBT peaked at 25°N and 5°S. The SST range was narrower near the equator and in the Southern Ocean reflecting the more stable temperatures (Figure 2.1a). In contrast, SBT ranges were widest in the tropics to subtropics, and narrower at high latitudes reflecting that SBT varied dramatically from shallow water to deep sea in the tropical areas (Figure 2.1b). Mean salinity varied between 28 PSU to 35 PSU with latitude, which is within the tolerance of marine organisms (Figure 2.1c). However, mean salinity was lower and more variable north of 40°N. Mean primary productivity varied greatly in all latitudes except for the Southern Ocean (Figure 2.1d). Its gradient was weakly trimodal by visual with highest mean productivity at 55°N (Figure 2.1d).

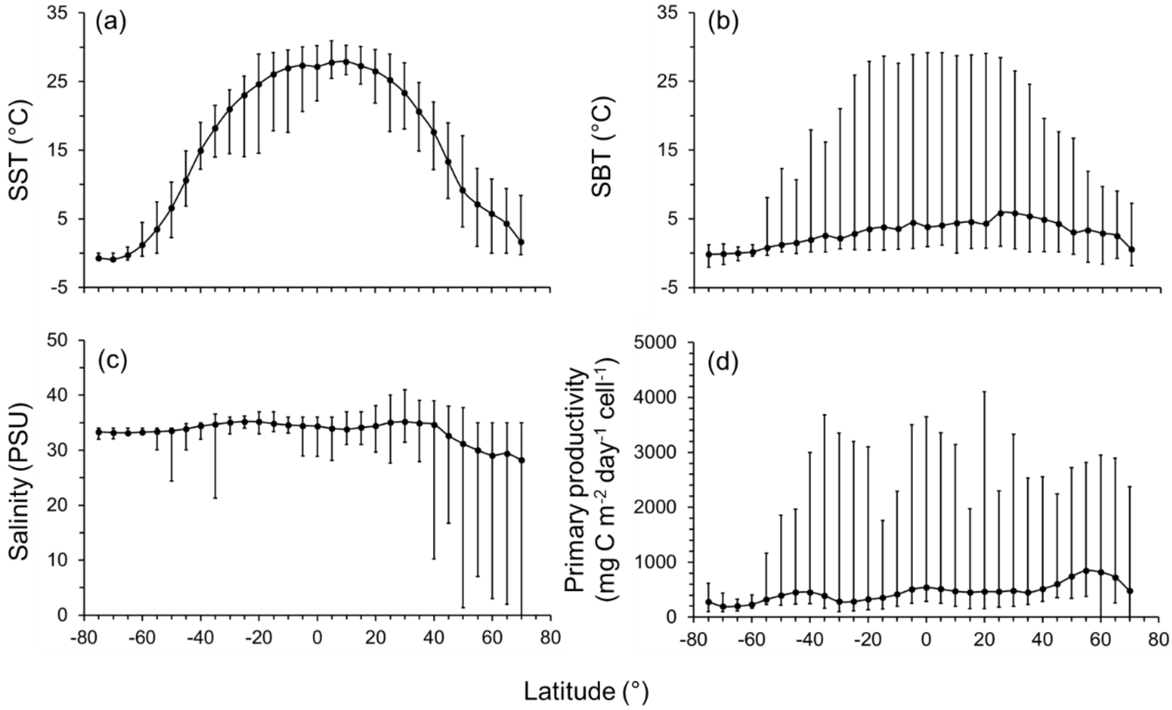


Figure 2.1. The latitudinal gradients of means (solid circle), maxima (top lines), and minima (bottom lines) of (a) sea surface temperature (SST), (b) sea bottom temperature (SBT), (c) sea surface salinity, and (d) primary productivity. PSU indicates practical salinity unit.

2.3.2. Taxonomic richness

The numbers of orders, families, genera, and species were highest in the surface zone, followed by the middle zone and deep zone (Table 2.1). Five classes occurred in the surface zone, but six in the middle zone. The surface zone contained 73% of all species, 75% of bony fish and 79% of demersal fish (Table 2.1). Over half of pelagic (52%) and cartilaginous (56%) fish occurred in the surface zone.

The taxonomic richness peak was higher in the northern than the southern hemisphere by 6% for species, 6% for genera, 2% for families, and 4% for orders (Figure 2.2a). In contrast, it was 9% higher for classes in the southern than the northern hemisphere. In addition, the peak shifted poleward with higher taxonomic level: from 25°N for species to 30°N for genera and families, 25°N to 40°N (median 33°N) for orders and 25°N to 70°N (median 48°N) for classes. In the southern hemisphere, it also shifted poleward: genera peaked at 10°S, families at 20°S, orders at 25°S to 30°S, and classes at 35°S (Figure 2.2a).

LDGs of orders, families, genera, and species were nearly the same among all, pelagic, and bony fish in all depth zones. Most LDGs for these three fish groups had peaks at both middle latitudes and a dip at or near the equator (Figures 2.2 & 2.3). Similarly, clear peaks were also at middle latitudes in most LDGs of cartilaginous fish (Figures 2.2 & 2.3). In addition, the LDGs of the whole water column were similar to the LDGs of the surface zone due to most species being in the surface zone (Figures 2.2 & 2.3). Highest species richness was at the northern middle latitudes for five fish groups and three depths, except for the LDG of cartilaginous fish in the middle depth zone (Figures 2.2 & 2.3). Although most LDGs of species richness were highest at middle latitudes, over 40% species still existed in the tropics no matter in what fish group and depth (Figures 2.2 & 2.3).

2.3.3. Modality

(a) Visual assessment

From visual assessment of the 88 LDGs, 56 were bimodal, 2 were unimodal and 30 were ambiguous (Figures 2.2 & 2.3, Table 2.2). There were 17 bimodal LDGs for families, 14 for orders, 13 for genera, 6 for species and 6 for classes, respectively. In contrast, unimodal LDGs were only visible in orders (2 of 20 LDGs). The 30 ambiguous LDGs were 14 at species, 7 at genus, 4 at order, 3 at family, and 2 at class level (Table 2.2).

Of the 22 LDGs in the whole water column, 13 were bimodal, 8 were ambiguous and 1 was unimodal. The ambiguous LDGs were families of pelagic fish, genera of five fish groups excluding the cartilaginous fish group, species of all, demersal, and bony fish (Figure 2.2, Table 2.2). The unimodal LDG had no distinct peak, with a plateau shape, and was for the orders of pelagic fish (Figure 2.2).

For the 66 LDGs in the three depth zones, I considered 43 LDGs to be bimodal, 22 LDGs to be ambiguous and 1 LDG to be unimodal. Most bimodal LDGs existed in the families (13 of 15 LDGs), followed by genera (12 of 15 LDGs), orders (10 of 15 LDGs), species (4 of 15 LDGs) and classes (4 of 6 LDGs). In contrast, only orders of cartilaginous fish in deep zone were unimodal. 22 ambiguous LDGs, for 11 species, 4 orders, 3 genera, and 2 families and 2 class were ambiguous (Figure 2.3, Table 2.2).

(b) Hartigan's dip statistic (HDS)

Overall, this test indicated that all 66 LDGs tested were not unimodal. The not unimodal LDGs were in the 8 orders, 19 families, 19 genera, and 20 species (Table 2.2). After HDS assessment, 24 of 30 ambiguous LDGs in the visual assessment were all indicated to be not unimodal. There were 6 ambiguous LDGs not assessed by HDS because of sample size ≤ 25. Therefore, for discussion of the modality of LDGs, I employed the results of visual observation for 22 LDGs with sample size ≤ 25 (including 8 classes, 12 orders in five fish groups, and 1 family, 1 genus in cartilaginous fish group), and the results of HDS for 8 orders, 19 families, 19 genera and 20 species (Table 2.2).

(c) Deep sea modality

To test whether the LDGs may appear bimodal or not unimodal because the depth range of the more species-rich shallow water species may extend into deep water, I limited analysis to the 112 species of fish only occurring in the deep sea. The LDGs of orders, families, genera, and species were visually ambiguous but the HDS test indicated they were not unimodal for families, genera, and species (Table 2.3, Figure 2.4). The richness was greater by 14% for families, 12% for genera, and 22% for species from the equator to 5°N (Figure 2.4). This was because an additional 27 species only occurred from the equator to 5°N. Therefore, I confirmed that the LDGs of taxonomic richness in the deep zone were bimodal or not unimodal and were not because of range extensions of the shallow water species.

(d) Synthesis

The synthesized results showed that 80 of the 88 LDGs were bimodal or not unimodal, 2 LDGs were unimodal, and 6 LDGs were still ambiguous (Table 2.2). For 22 LDGs in the whole water column, 21 LDGs were bimodal or not unimodal. Only the orders of pelagic fish were unimodal (Table 2.2). Of 66 LDGs in the three depth zones, 59 LDGs were bimodal or not unimodal. Only orders of cartilaginous fish in deep zone were unimodal. Due to the small sample size, 6 visually ambiguous LDGs were not assessed by HDS, so they still maintained as ambiguous (Table 2.2). Thus, most LDGs in five taxonomic levels and depth zones were bimodal or not unimodal.

Table 2.2. The modality of latitudinal diversity gradient (LDG) of taxonomic richness among five fish groups by visual assessment and Hartigan's Dip Statistic (HDS) where there were > 25 taxa. *** = $p < 0.001$, - indicates the LDG could not be analysed, Bi indicates the LDG was Bimodal, Uni indicates the LDG was Unimodal, NU indicates the LDG was Not Unimodal, and ? indicates the LDG was ambiguous.

Depth	Fish group	Class				Order				Family				Genus				Species			
		Visual	HDS		Synthesis	Visual	HDS		Synthesis	Visual	HDS		Synthesis	Visual	HDS		Synthesis	Visual	HDS		Synthesis
			D	*p*			D	*p*			D	*p*			D	*p*			D	*p*	
Whole water column	All Fish	Bi	–	–	Bi	Bi	0.02	0.003	NU	Bi	0.02	***	NU	?	0.03	***	NU	?	0.03	***	NU
	Pelagic Fish	-	–	–	-	Uni	-	-	Uni	?	0.02	***	NU	?	0.03	***	NU	Bi	0.03	***	NU
	Demersal Fish	Bi	–	–	Bi	Bi	0.02	0.003	NU	Bi	0.02	***	NU	?	0.03	***	NU	?	0.03	***	NU
	Bony Fish	-	–	–	-	Bi	0.02	0.02	NU	Bi	0.02	***	NU	?	0.03	***	NU	?	0.03	***	NU
	Cartilaginous Fish	-	–	–	-	Bi	-	-	Bi	Bi	0.03	***	NU	Bi	0.03	***	NU	Bi	0.03	***	NU
0 m - 200 m	All Fish	Bi	–	–	Bi	Bi	0.02	0.004	NU	Bi	0.03	***	NU	Bi	0.03	***	NU	?	0.04	***	NU
	Pelagic Fish	-	–	–	-	Bi	-	-	Bi	Bi	0.03	***	NU	Bi	0.03	***	NU	Bi	0.03	***	NU
	Demersal Fish	Bi	–	–	Bi	Bi	0.02	0.003	NU	Bi	0.03	***	NU	Bi	0.03	***	NU	?	0.04	***	NU
	Bony Fish	-	–	–	-	?	0.02	0.01	NU	Bi	0.03	***	NU	Bi	0.03	***	NU	?	0.04	***	NU
	Cartilaginous Fish	-	–	–	-	?	-	-	?	Bi	0.03	***	NU	Bi	0.03	***	NU	Bi	0.03	***	NU
201 m - 1000 m	All Fish	Bi	–	–	Bi	Bi	0.02	0.01	NU	Bi	0.02	***	NU	Bi	0.02	***	NU	Bi	0.03	***	NU
	Pelagic Fish	-	–	–	-	?	-	-	?	Bi	0.02	***	NU	Bi	0.02	***	NU	?	0.03	***	NU
	Demersal Fish	Bi	–	–	Bi	Bi	0.02	0.01	NU	Bi	0.02	***	NU	?	0.03	***	NU	?	0.03	***	NU
	Bony Fish	-	–	–	-	Bi	-	-	Bi	Bi	0.02	***	NU	?	0.02	***	NU	?	0.03	***	NU
	Cartilaginous Fish	-	–	–	-	Bi	-	-	Bi	Bi	0.02	0.02	NU	Bi	0.02	***	NU	Bi	0.03	***	NU
1001 m - 6000m	All Fish	?	–	–	?	Bi	-	-	Bi	Bi	0.02	***	NU	Bi	0.03	***	NU	?	0.03	***	NU
	Pelagic Fish	-	–	–	-	?	-	-	?	?	0.02	0.03	NU	?	0.02	***	NU	?	0.03	***	NU
	Demersal Fish	?	–	–	?	Bi	-	-	Bi	Bi	0.02	***	NU	Bi	0.03	***	NU	?	0.03	***	NU
	Bony Fish	-	–	–	-	Bi	-	-	Bi	Bi	0.02	***	NU	Bi	0.03	***	NU	?	0.03	***	NU
	Cartilaginous Fish	-	–	–	-	Uni	-	-	Uni	?	–	–	?	Bi	–	–	Bi	?	0.03	0.01	NU

Table 2.3. The uni- and bi-modality of latitudinal diversity gradient (LDG) of taxonomic richness for fish species that only occurred in the deep zone (below 1000 m). *** = $p < 0.001$, - indicates the LDG was not analysed.

Taxon	Number of samples	Visual	HDS		Synthesis
			D	*p*	
Class	3	-	-	-	-
Order	18	ambiguous	-	-	ambiguous
Family	42	ambiguous	0.03	0.004	Not Unimodal
Genus	85	ambiguous	0.03	***	Not Unimodal
Species	121	ambiguous	0.03	***	Not Unimodal

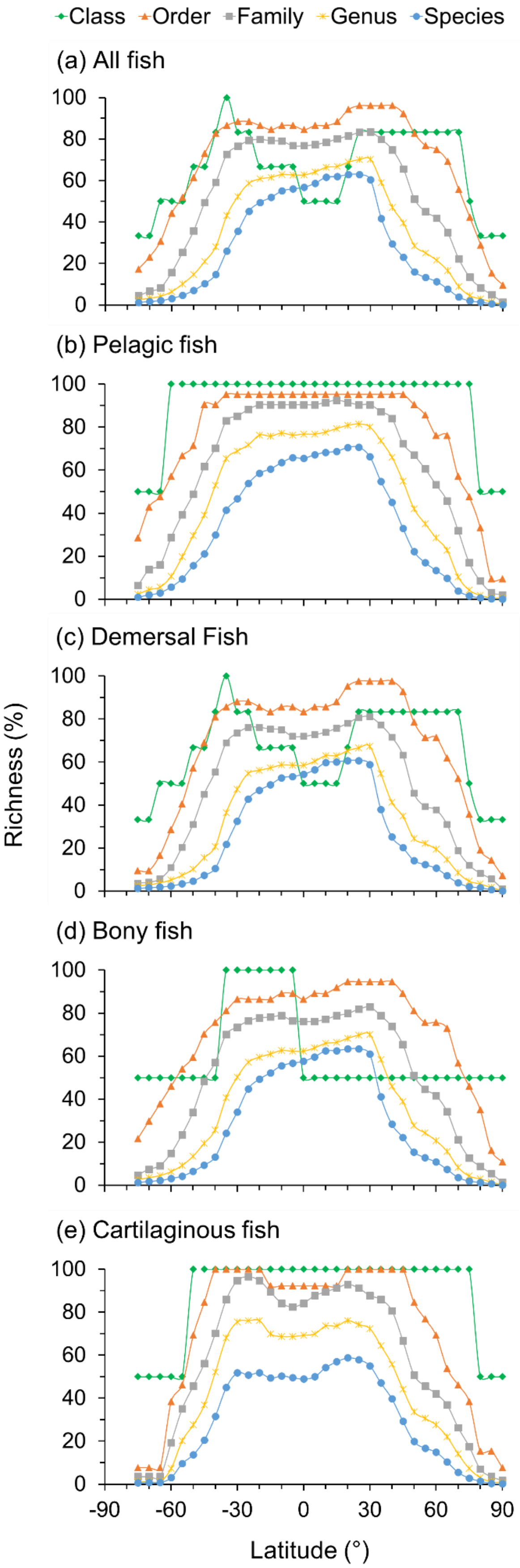


Figure 2.2. The latitudinal gradients of taxonomic richness (%) of (a) all, (b) pelagic, (c) demersal, (d) bony and (e) cartilaginous fish, from class to species level in the whole water column. Plots of the actual number of richness are in Appendices Figure A2.1.

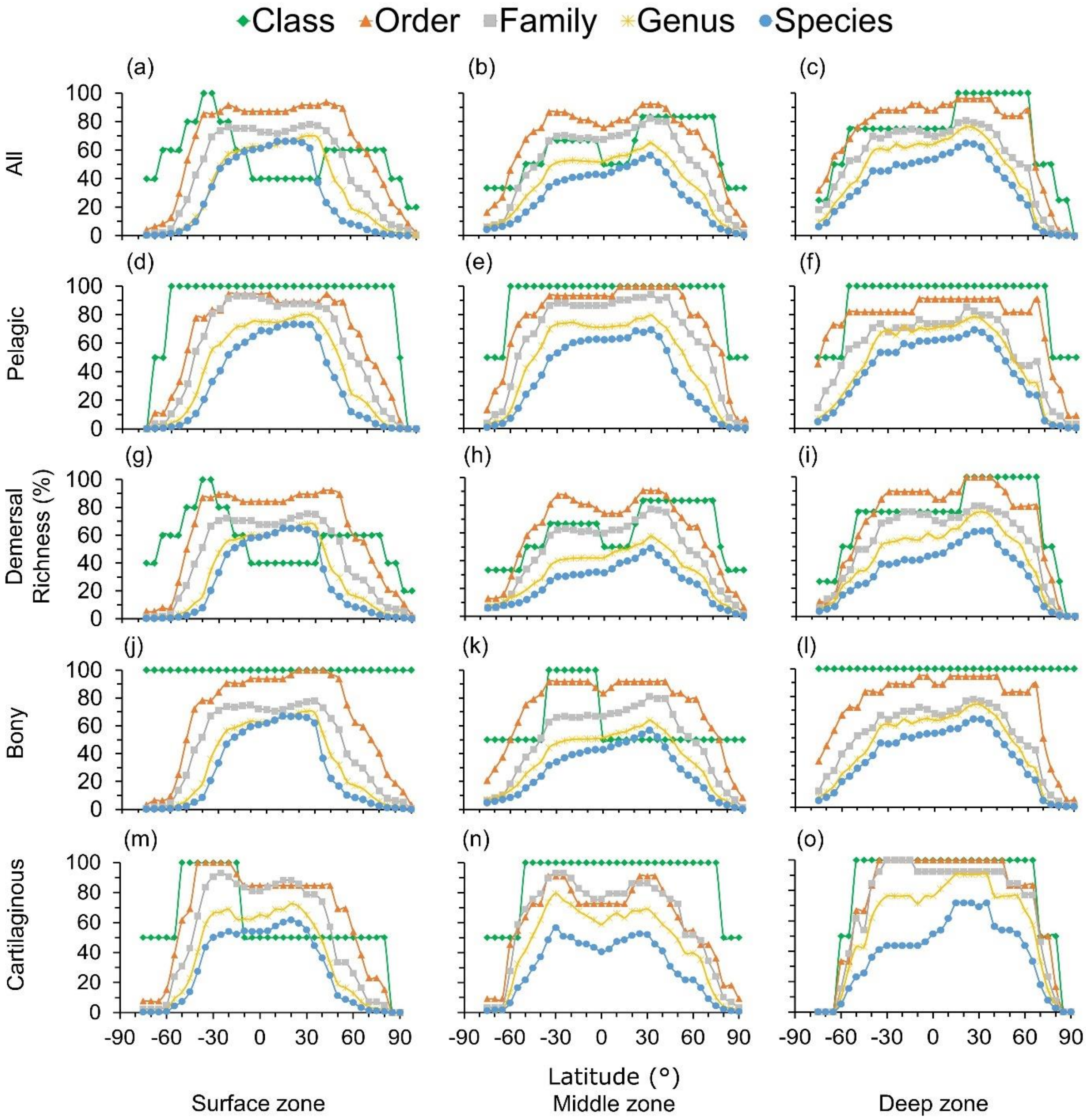


Figure 2.3. The latitudinal gradients of taxonomic richness (%) in the surface (0 – 200 m), middle (201 – 1000 m), and deep (1001 – 6000 m) zones among the five fish groups. Plots of the actual number of richness are in Appendices Figure A2.2.

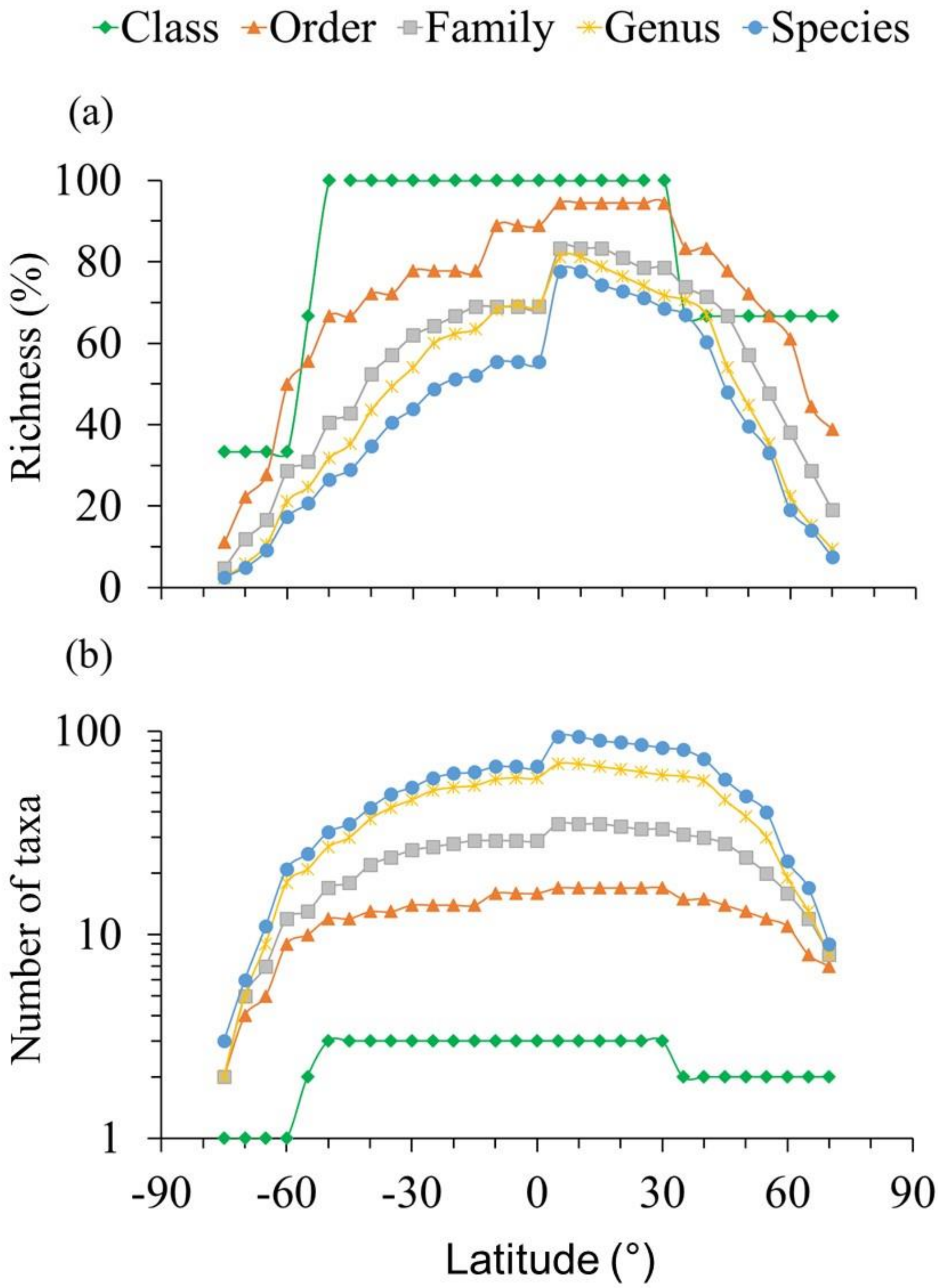


Figure 2.4. The latitudinal richness of five taxonomic levels for species that only occurred in the deep zone (below 1000 m). (a) Richness as a percentage and (b) Number of five taxonomic levels.

2.3.4. Environmental relationships

The smoothed fits model by GAM explained 98.8% to 99.8% of deviance for five fish groups (Table 2.4). The adjusted r^2 were between 0.984 and 0.996 for five fish groups (Table 2.4).

The smoothed fits model showed that all LDGs of species richness had a significantly positive correlation ($p < 0.001$) with mean SST (Table 2.4, Figure 2.5). However, the species richness of all, demersal, and bony fish decreased when mean SST was > 25°C. In contrast, species richness in pelagic fish continued to increase, and of cartilaginous fish groups did not further change, when mean SST was > 25°C (Table 2.4, Figure 2.5).

Mean SBT was significantly correlated ($p < 0.001$) with all LDGs except for the cartilaginous fish ($p > 0.05$) (Table 2.4, Figure 2.5). The model indicated that higher species richness of all, demersal, and bony fish existed at mean SBT between 3°C and 5°C. Wider 95% confidence bands at mean SBT < 3°C reflected lower species richness in this environment (Figure 2.5). In contrast, the species richness of pelagic fish increased with higher mean SBT (Table 2.4, Figure 2.5).

Mean sea surface salinity was significantly correlated with the LDGs of all, demersal, and bony fish groups, but not stronger than mean SST and mean SBT ($p < 0.05$) (Table 2.4, Figure 2.5). The highest species richness of these three fish groups existed between 34 PSU and 35 PSU. In contrast, species richness decreased when mean salinity < 34 PSU (Table 2.4, Figure 2.5). For pelagic and cartilaginous fish, there was no significant relationship between mean sea surface salinity and LDGs ($p > 0.05$) (Table 2.4).

There were no significant relationships between all LDGs and mean primary productivity ($p > 0.05$) (Table 2.4). Overall, the GAM results showed the temperature was the primary, and salinity the secondary, driver affecting the LDGs.

Table 2.4. Generalised Additive Models (GAM) results of the species richness among five fish groups and four environmental variables. Degrees of freedom (d.f.) and significance levels (p) are displayed for each of covariates. GCV indicates Generalised Cross-Validation. * p < 0.05, ** p < 0.01, *** p < 0.001.

	All		Pelagic		Demersal		Bony		Cartilaginous	
Adjusted r^2	0.996		0.996		0.995		0.996		0.984	
Deviance explained (%)	99.8		99.7		99.8		99.8		98.8	
GCV score	16771		471.2		12636		14218		232.94	
	d.f.	*p*	d.f.	*p*	d.f.	*p*	d.f.	*p*	d.f.	*p*
Sea Surface Temperature	8.49	< 0.001***	2.39	< 0.001***	8.37	< 0.001***	8.42	< 0.001***	4.07	< 0.001***
Sea Bottom Temperature	2.00	< 0.001***	1.76	< 0.001***	2.00	< 0.001***	2.00	< 0.001***	1.00	0.07
Sea Surface Salinity	4.62	< 0.05*	1.00	0.75	4.37	< 0.05*	4.34	< 0.05*	1.00	0.28
Primary Productivity	1.00	0.24	1.00	0.32	1.00	0.25	1.00	0.21	1.00	0.20

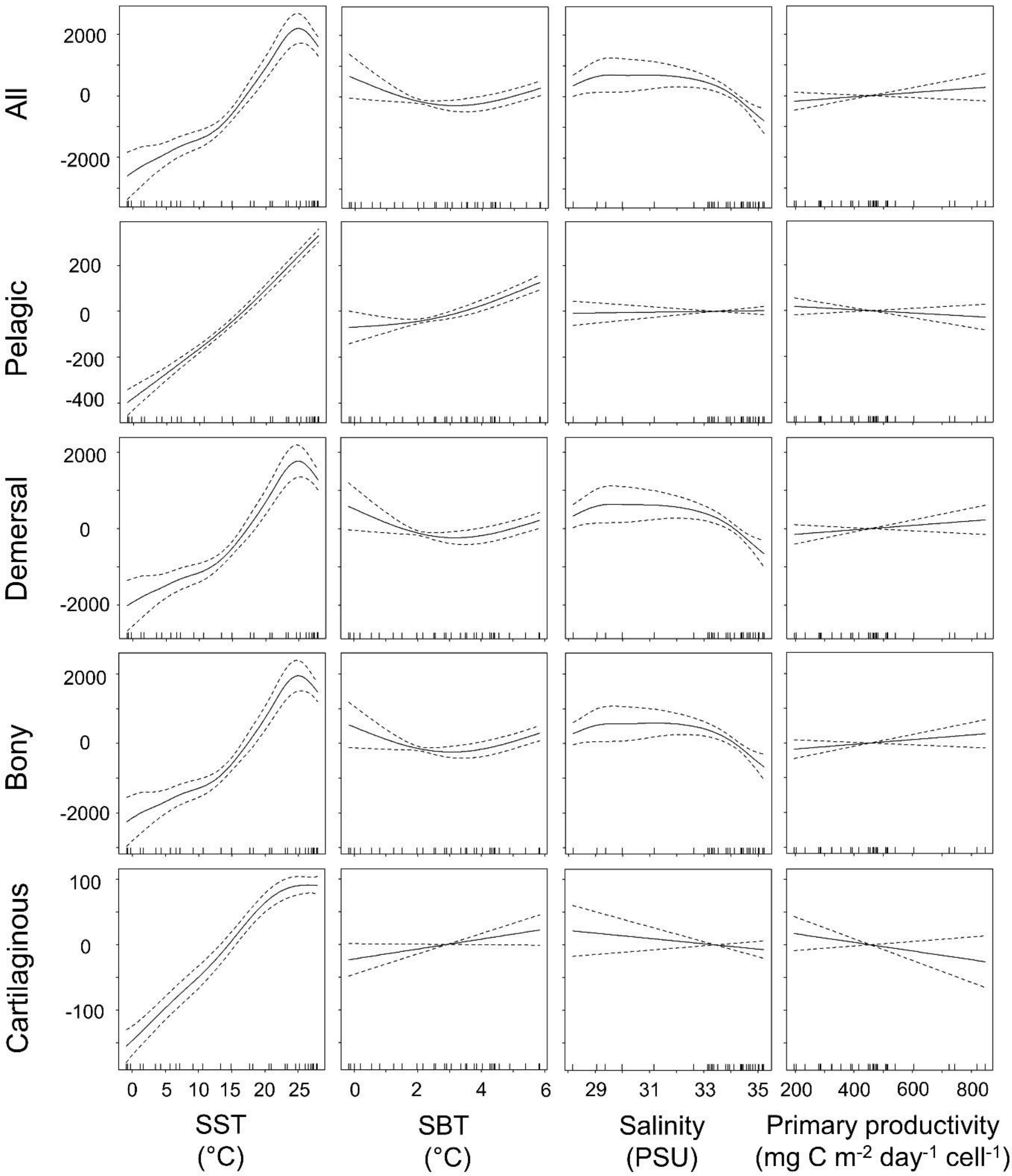


Figure 2.5. The Generalised Additive Models (solid lines) for number of species against environmental variables among the five fish groups. The dashed lines indicate the 95% confidence intervals. The tick marks of x-axis are observed data points. The y-axis represents the spline function. PSU indicates practical salinity unit.

2.3.5. Taxonomic richness along with depth

Over 60% of classes, orders, families, genera, and species among five fish groups were found in the shallow water (< 100 m), and then decreased along with depth (Figure 2.6). In depths of 101 m – 200m, all six classes of marine fish could be found (Figure 2.6a). There were fewer than 10 species deeper than 3300 m for all and bony fish, 2600 m for pelagic fish, 2500 m for demersal fish, and 1800 m for cartilaginous fish (Figure 2.6). There were no cartilaginous fish deeper than 2300 m (Figure 2.6). The actual numbers of five taxonomic levels among five fish groups are in the Appendices Figure A2.8.

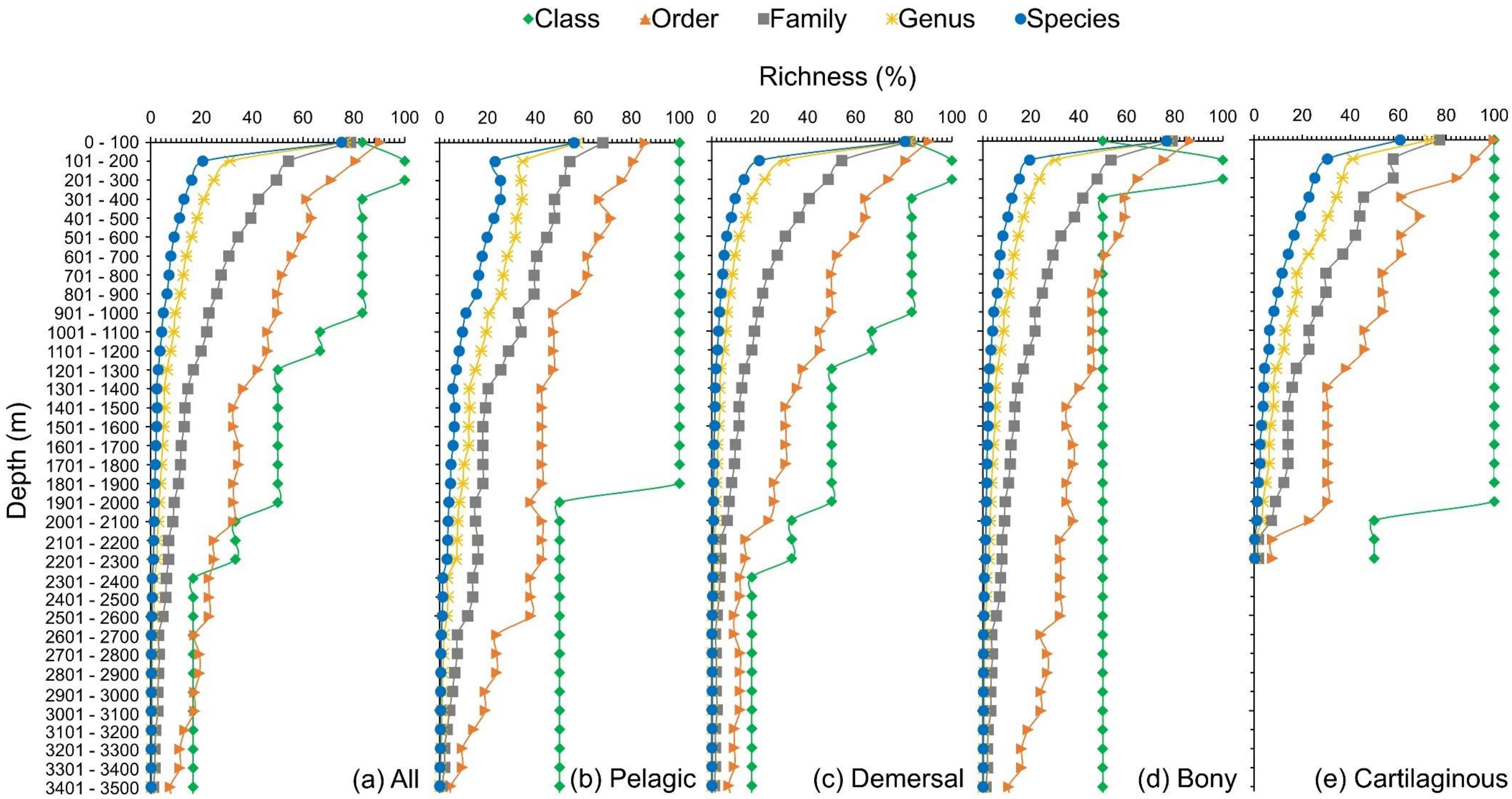


Figure 2.6. The richness of five taxonomic levels along with depth in 100 m depth bands from 0 m to 3500 m for (a) All, (b) Pelagic, (c) Demersal, (d) Bony, and (e) Cartilaginous fish.

2.4. Discussion

2.4.1. Latitudinal gradients

This is the first study encompassing global marine fish richness in five taxonomic levels, among contrasting ecological guilds (pelagic, demersal) across the whole water column and three depth zones. The overall patterns were most influenced by the surface depth zone because over 73% of species lived at < 200 m depth. Furthermore, bony and demersal fish accounted for 91% and 78% of all marine fish, respectively, so the LDGs among all, bony, and demersal were similar.

In general, this study found the most LDGs were similar across all taxonomic levels, fish groups and depth zones. Most LDGs were bimodal or not unimodal with a dip at or near the equator, and peaks in the subtropics. The northern hemisphere peak was marginally higher to that in the southern hemisphere for most taxonomic levels. The peaks of taxonomic richness shifted further away from the equator from species to class levels. Thus, the LDGs of taxonomic richness are not perfectly synchronous at species and higher taxonomic levels. This study suggests this contrast is because extinction is lower (less influence of glaciations), and speciation is higher in the tropics on evolutionary timescales. Empirical studies that analysed large datasets on several different taxa from the terrestrial to the marine environment, such as angiosperm families (Davies et al., 2004), rain forest plants (Wright et al., 2006; Gillman et al., 2010), marine foraminifera (Allen et al., 2006), and marine fish (Wright et al., 2011) also found that rates of evolution were greater in the tropics, although Rabosky et al. (2018) claimed that marine fish had higher speciation rates at both poles. Due to the effect of temperature on mutation rates, generation times, more intense ecological competition and greater habitat diversity (Costello & Chaudhary, 2017). Consequently, there are relatively more species than higher taxa at lower latitudes.

This study found most taxa occurred in northern tropical to subtropical latitudes (15°N – 30°N). However, there were some exceptions. In the whole water column, all six classes of all fish and demersal fish existed at 35°S, but only five classes of them between 25°N and 70°N. The missing class in the northern hemisphere was the class Sarcopterygii, the lobe-finned fish or coelacanths. So, the number of classes was higher in the southern than the northern hemisphere. There were also more families in the southern than the northern hemisphere because six families of cartilaginous fish, Brachaeluridae, Callorhinchidae, Centrophoridae, Gurgesiellidae, Hypnidae, and Proscylliidae, could only be found in the southern hemisphere. However, although there were more classes of all fish and families of cartilaginous fish in the south, they had relatively few species, so species richness was higher overall in the northern hemisphere.

The results in this study were similar to studies of fish species richness using point species' occurrence data (Lucifora et al., 2011; Chaudhary et al., 2016; Menegotto & Rangel, 2018). These occurrence data were also bimodal with two extremely clear peaks in species richness at 10°N – 15°N and 25°S – 30°S for 2600 fish species (Chaudhary et al., 2016), at different depth strata for 35000 species based on observation records (Menegotto & Rangel, 2018) and 30° – 40° of both hemispheres (symmetric bimodal) for 507 shark species (Lucifora et al., 2011). The wider peaks and equatorial dip in the analysis of this study reflect that the use of species ranges. The advantage of modelled range occurrence data is that it minimises bias due to spatial sampling from the point occurrence data (Graham & Hijmans, 2006; Kaschner et al., 2006, 2019). That both point occurrence and range data show a bimodal gradient with a dip at the equator, reinforces that the pattern is not an artefact of sampling bias.

2.4.2. Deep sea

The initial expectation was that the deep sea may not have clear modality in the LDGs because its temperature is consistently cold across latitudes (Figure 2.1b) and deep-sea fish have wider geographic ranges than shallow depth species (Ekman, 1953; Macpherson, 2003; Watling et al., 2013; Costello et al., 2017; Costello & Chaudhary, 2017). Indeed, I found that 93% of the 4102 shallow species, but only 63% of the 333 species in the deep zone, had a latitudinal range narrower than 90 degrees. However, the LDG of species richness in the deep zone was still not unimodal as determined by HDS (Table 2.2, Figure 2.2) as was the LDG for deep-sea brittle-stars (Ophiuroidea, Echinodermata) (Woolley et al., 2016). However, this not a unimodal LDG, and, while significant, is subtle and northern biased (Figure 2.4), and may be due to the slightly warmer deep sea in the Gulf of Mexico and Mediterranean (Costello & Breyer, 2017), and/or high endemicity of the Mediterranean.

2.4.3. Environmental relationships

Several possible explanations, including environmental variables, geographic areas, evolutionary speed, and competition, have been proposed to understand the formation of latitudinal gradients of species richness (Roy et al., 1998; Connolly et al., 2003; Valdovinos et al., 2003; Worm et al., 2005; Tittensor et al., 2010; Chaudhary, 2019). In this study, I found that temperature is one of the most important factors to influence the latitudinal gradients of marine fish, other studies also observed the same (Rutherford et al., 1999; Kaspari et al., 2004; Krug et al., 2009; Saeedi et al., 2017; Chaudhary, 2019). The LDGs of species richness among five fish groups were significantly positively related to mean SST. The mean SBT was also significantly related to species richness of all, pelagic, demersal, and bony fish groups. Apart from temperature, I found that mean salinity was correlated with the LDGs of species richness among all, demersal, and bony fish groups although not nearly as strongly as temperature (Table 2.4). However, although the gradients of richness were positively related with temperature and salinity, none of the gradients for any groups of fish or taxonomic levels peaked at the equator.

The warmer SBT in mid-northern latitudes (25°N – 35°N) is due to the warmer deep sea in the Mediterranean and Gulf of Mexico (Costello & Breyer, 2017), and may contribute to the slightly higher fish taxonomic richness in these northern compared to the equivalent southern latitudes, as well as the bimodality of the deep-sea endemic fish fauna.

The dip of LDGs at the equator may be because the tropical species cannot tolerate the raised temperature at the equator and they have moved away due to climate change (Chaudhary et al., 2016; Garciá Molinos et al., 2016). This temperature limitation is indicated by the GAM plots which show declining species richness of all, demersal, and bony fish above the mean SST of 25°C. In contrast, the species richness of pelagic fish and cartilaginous fish were highest at SST > 25°C which may be related to pelagic reef species living in the tropical coral-reef ecosystem, and wider distribution of large pelagic predators (e.g., tunas, swordfishes, sharks).

Because the dip in richness at the equator is related to temperature, and climate change is causing species to move their geographic distributions poleward (e.g., Burrows et al., 2019; Brito-Morales et al., 2020), it was hypothesized that the dip reflected warming temperature at the equator (Chaudhary et al., 2017). However, Yasuhara et al. (2020) have shown that at least for planktonic Foraminifera that the dip at the equator began in pre-industrial times. The results in this study support this because this study used species ranges which reflect biogeographic patterns over the past century. It remains possible that the equatorial dip is getting deeper and/or wider due to ocean warming, but this requires comparison of marine biodiversity over decadal timescales in the late 20th century. Yasuhara et al. (2020) suggested that extant marine species have evolved during the longer glacial than inter-glacial time periods, and the pre-industrial dip in species richness at the equator is because the fauna was not adapted for higher sea temperatures. The findings in this study for marine fish support their results for Foraminifera suggesting this hypothesis may be generalized, such that present day marine species have evolved in cooler oceans than currently exist. Thus, future ocean warming is hypothesized to further reduce species richness at the equator through the movement of species into higher latitudes and/or extinctions. However, once dramatic climate change as in the Permian-Triassic has occurred and more species extinction happened, the modern marine LDG may be flattened in the very far future (Song et al., 2020).

2.5. Conclusion

This study found that modalities of LDGs were generally bimodal or not unimodal at all taxonomic levels among pelagic, demersal, bony, and cartilaginous fish in three depth zones. In addition, from the LDGs of different taxonomic levels, this study showed that the tropics and subtropics around 15° to 35° of the northern hemisphere had the most marine fish species in all fish groups and depth zones. Nevertheless, although the species richness of the equator was less than areas of 15° to 35°, the species richness in the tropics across the equator still had 40% more species than higher latitudes. The poleward shift in the peaks of richness with higher taxonomic level is attributed to higher species formation in lower latitudes.

That the gradient of SST is highly correlated with taxonomic richness indicates temperature is a primary driver of the LDGs, whether this may be in terms of suitability for more species, and/or indirectly in influencing speciation and extinction rates. That the dip of speies richness at the equator suggests that the sea temperature may be too hot there for some species to flourish. Regardless of how long this has been the case, it provides further evidence that climate change will lead to a further loss of richness across all taxonomic levels around the equator and may reconstruct the communities in the higher latitudes. Once climate change has become more dramatic, the LDG may be reshaped.

Except for the LDGs, study on predation of pelagic fish also found a bimodal gradient that stronger predation was higher at temperate than equatorial area (Roesti et al., 2020). Therefore, latitudinal gradients on other topics, such as phylogenetic, physiological, functional traits or ecological interaction of marine fish are worth for future study.

Chapter 3

Latitudinal and Depth Gradients of Phylogenetic Indices of Marine Fish

Chapter 3: Latitudinal and depth gradients of phylogenetic indices of marine fish

3.1. Introduction

The latitudinal diversity gradient (LDG) has interested ecologists for a long time since it generalises over local and regional patterns, and thus helps us to understand where species have evolved and survived on both ecological and evolutionary time scales (Ekman, 1953; Gaston, 2000; Willig et al., 2003; Pontarp et al., 2019). Dozens of mechanisms have been proposed to explain the formation of LDG, and many of them are intercorrelated (Gaston, 2000; Jørgensen et al., 2007). Temperature directly and indirectly influences physiology, environmental conditions and ecological interactions which may affect the LDG (Rohde, 1992; Davies et al., 2004; Allen et al., 2006; Wright et al., 2006, 2011; Gillman et al., 2010; Brown, 2014). The general LDG of species richness decreasing from the equator to poles is connected to the high speciation and low extinction rates in the tropical areas, with glaciations triggering extirpations and cold temperatures slowing speciation rates in high latitudes (Brown, 2014; Costello & Chaudhary, 2017).

Until recently, the literatures presented the typical LDG to be a decrease in species richness from the equator to the poles. However, LDGs of many marine species are now bimodal with a dip at or near the equator (Powell et al., 2012; Chaudhary et al., 2016, 2021; Arfianti & Costello, 2020; Lin et al., 2021). Studies found that sea temperature is the most important factor to make the LDG be bimodal, it may be because the sea temperature is too high for some species at the equator to stay (Chaudhary, 2019; Yasuhara et al., 2020; Chaudhary et al., 2021; Lin et al., 2021). In Chapter 2, I found that species richness decreased when the temperature was greater than 25°C. It thus appears that some tropical species cannot tolerate elevated temperature at the equator, they move into subtropical latitudes due to climate change (Garciá Molinos et al., 2016; Chaudhary, 2019; Yasuhara et al., 2020; Chaudhary et al., 2021). Thus, temperature may be a critical factor to influence the evolution and distribution of species.

Species richness is the most common and simplest way to measure biodiversity. However, biodiversity is a more complex concept that is the variation within species, between species and of ecosystems (Wilson & Baird-Middleton, 1994; Purvis & Hector, 2000). Other indices, such as species evenness was also widely used on several studies (Tolimieri, 2007; Symonds & Johnson, 2008; Soininen et al., 2012). However, both species richness and species evenness treat all species as equal value for their contribution of diversity. Therefore, two species in the same family are considered as diverse as two species from different families. On the other hand, measures of phylogenetic indices are based on the phylogenetic tree and provide a view of biodiversity related to evolutionary history (Faith, 1994; Purvis & Hector, 2000; Clarke & Warwick, 2001).

Average phylogenetic diversity (AvPD) reflects the phylogenetic relationship of species within an assemblage, and has been applied to latitudinal studies on terrestrial (Fergnani & Ruggiero, 2017) and one study in the marine environment (Wu et al., 2016). A higher AvPD indicates that species in the assemblage are more phylogenetically distantly related. In contrast, a lower AvPD indicates the species are more phylogenetically closely related. Wu et al. (2016) found that AvPD for nematodes increased with latitude, showing that nematodes had closer phylogenetic relationships at lower latitudes. However, the latitudinal gradient of phylogenetic diversity has yet to be plotted for marine fish at a global scale.

In this study, two simple phylogenetic indices were created to offer an easy way to understand the higher taxonomic richness and phylogenetic relationship. One was the sum of the higher taxonomic levels (STL) that added the number from classes to genera as a measure of higher taxonomic richness. Because STL is dependent on the number of species present, this study also divided STL by the number of species present (STL/spp) in a given latitude and depth zone to standardise higher taxonomic (phylogenetic) richness for species richness. Thus, a given area with few species but lots of higher taxa will have higher STL/spp (distant phylogenetic relationship). In contrast, a given area with more species but a less or similar number of higher taxa will have lower STL/spp (closer phylogenetic relationship). The concept of STL/spp is similar to AvPD but directly using the number of taxonomic levels, so it is a simpler way to understand the phylogenetic relationship in a given area.

The species richness is related to the sea temperature. An area with warmer sea temperatures has more fish species than an area with cold sea temperatures (Chapter 2). In this chapter, I hypothesis that phylogenetic indices are highly related to the species richness, and thus the phylogenetic indices are also affected by sea temperatures. Two hypotheses were tested in this study. First, an area with high species richness would have more higher taxonomic richness (STL). Second, warmer area has higher speciation rate leading to higher species richness (Rohde, 1992; Wright et al., 2011; Brown, 2014), thus the fish assemblage has closer phylogenetic relationship.

In the marine environment, species richness is also related to depth. Generally, species richness declines with depth, although it may peak at intermediate depths for some taxa in some places (Rex, 1981; McClain & Etter, 2005; Rosa et al., 2008; Costello & Chaudhary, 2017). Depth may also influence the LDG. The environment at the sea surface is more variable than in the deep sea (Costello, Basher, et al. 2018). The variation of sea surface temperature is higher in mid-latitudes than low and polar latitudes (Basher & Costello, 2020). In contrast, the temperature in the deep sea is always low with no significant latitudinal gradient (Costello & Breyer, 2017; Sayre et al., 2017; Basher & Costello, 2020). Therefore, it might be expected that species richness varies across latitudes in the surface zone, but would be more constant in the relatively homogenous cold deep-sea environment. However, studies found that the LDG of brittle stars (Woolley et al., 2016) and marine fish (Lin et al., 2021; Chapter 2) were still bimodal in the deep sea. Therefore, it would be expected that phylogenetic indices would also have clear gradients in the surface water and deep sea with both latitude and depth.

How marine fish composition changes among latitudes in different depth zones, and along depth zones at the global scale has not been studied. A previous global-scale study showed that multiple marine taxa in 5-degree latitude bands could be divided into five assemblages: tropical (between 32.5°S and 27.5°N), two temperate groups, and two polar groups (Chaudhary, 2019). Therefore, it could be expected that latitudinal distribution of species assemblages fits the boundaries of climate zones in the surface water, but not in the deep sea because of the consistently low temperature across latitudes. Furthermore, it could be expected that species composition would change with depth because the environment in the sea surface is very different to that in the deep sea (Costello, Basher, et al., 2018). Marine species usually have distribution boundaries determined by their thermal tolerance (Somero, 2010; Sunday et al., 2011). Anderson et al. (2013) found that species turnover of demersal fish in the North-Eastern Pacific between 32.57°N and 48.52°N and between 51 m and 1200 m depth was significant at < 200 m depth but not clear when depth > 800 m, and the latitudes of species turnover were at about 43°N, 39°N, 35°N, and 31°N. For species composition along with depth, Zintzen et al. (2011) found marine fish between 0 m and 2000 m depth could be divided into five assemblages (0 – 300 m, 300 – 600 m, 600 – 900 m, 900 – 1200m, and > 1200 m) in the region of the Norfolk Ridge and Lord Howe Rise (Western Pacific). In the present context, species assemblage clustering (i.e., species turnover) may identify latitudes and depths where boundaries may separate assemblages differing in phylogenetic and/or species richness.

Here, I describe species richness, higher taxonomic richness (STL), phylogenetic relationships (AvPD and STL/spp), and species assemblages of marine fish across latitudes in the whole water column and three depth zones from 75°S to 75°N, and in depths from 0 m – 3500 m at the global scale. I also describe gradients among all, bony and cartilaginous fish to see the difference among fish groups. Furthermore, I illustrate the relationship between phylogenetic indices, species richness, and sea temperatures.

3.2. Methods

3.2.1. Data

The distribution ranges of 5619 fish species were obtained from AquaMaps (Kaschner et al., 2019) and they represent about one-third of all marine fish species (Froese & Pauly, 2019). For this analysis, I converted AquaMaps' species ranges into binary presence and absence data using a probability threshold of 0.0 following the method in Kaschner et al. (2011). By using the threshold of 0.0, species ranges would overlap and thus represent a more conservative approach concerning commission errors that could affect the patterns of species distribution (Chapter 2). Five taxonomic levels, (class, order, family, genus, and species) were used for calculation of phylogenetic indices. The number of classes, orders, families, genera, and species in the 5° latitude band were derived from the taxonomy in FishBase (Froese & Pauly, 2019) as used in Chapter 2. The Fish Tree of Life used 24 genes to generate a different phylogenetic tree for 11368 fish species than used in FishBase (Rabosky et al., 2018). However, I found the latitudinal and depth gradients had no significant change when using the taxonomy from FishBase or the Fish Tree of Life (Appendices Figures A3.1 & A3.2). Thus, I report results from the FishBase in this thesis. The list for taxonomic levels of 5619 fish species is in Appendices Table A3.1.

3.2.2. Phylogenetic indices

Average phylogenetic diversity (AvPD) is a measure of the average phylogenetic distance (branch length) between any two chosen species (Clarke & Warwick, 2001):

$$AvPD = PD / s = \sum n_i / s$$

where s is the number of observed species, and n_i is the number of i nodes within the minimum spanning path in a phylogenetic tree. When an area has species assemblage concentrated on a few branches, they will have lower AvPD compared to an area with species assemblage distributed over many branches. Therefore, a lower AvPD means species in an assemblage in an area are more phylogenetically closely related, and a high AvPD means species in an assemblage are more phylogenetically distantly related. AvPD was calculated by using PRIMER v6 software (Clarke & Gorley, 2006). Five taxonomic levels (class, order, family, genus, and species) of marine fish were used based on the taxonomic classification in Froese and Pauly (2019) (Appendices Table A3.1). Simple linear scaling was used where the maximum distance through the phylogenetic tree of our dataset was set as $\omega = 100$. Therefore, the weighting between taxonomic levels is $\omega = 20$ for different species in the same genus, $\omega = 40$ for species in the same family but different genera, $\omega = 60$ for species in the same order but different families, $\omega = 80$ when species are in the same order but different classes, and $\omega = 100$ when species are in different classes.

In addition, two simple methods of phylogenetic diversity based on the number of five taxonomic levels in a given latitude band or depth zone were created in this study. One was the sum of the higher taxonomic levels (STL):

$$\mathrm{STL} = \sum\sum_{c<g} w_{cg}$$

where c, g is the range of higher taxonomic levels. In this study, the range was from classes to genera. The w is the weighted scaling. In this study, I used the $w = 5$ for classes, $w = 4$ for orders, $w = 3$ for families, and $w = 2$ for genera. Therefore, the equation of STL for each latitude band or depth band in this study was classes × 5 + orders × 4 + families × 3 + genera × 2.

Another simple measure was the sum of the higher taxonomic levels divided by the number of species (STL/spp):

$$\mathrm{STL/spp} = \mathrm{STL} / \mathrm{s} = \sum\sum_{c<g} w_{cg} / \mathrm{s}$$

where s is the number of species, and c, g, and w are described as above. This measure is used to account for the number of species because where very few species occur then fewer higher taxa can occur.

3.2.3. Data analysis

The latitudinal distribution range (northern and southern limits) and the preferred maximum depth were derived from the species geographic and depth ranges. I compared bony (Class Actinopterygii, 5117 species) and cartilaginous (Class Elasmobranchii, 470 species) fish. Overall, three groups including "All Fish", "Bony Fish", and "Cartilaginous Fish" were analysed for species richness and three phylogenetic indices in the whole water column and three depth zones. The number of taxa in the depth zones among three fish groups are in Table 3.1.

Table 3.1. Number of taxa of all, bony, and cartilaginous fish in the whole water column, surface (0 – 200 m), middle (201 – 1000 m), and deep (1001 – 6000 m) zones.

Depth Zones	Fish groups	Class	Order	Family	Genus	Species
Whole water column	All	6	52	358	1824	5619
	Bony	1	36	297	1653	5117
	Cartilaginous	1	12	54	158	470
Surface	All	5	47	271	1342	4102
	Bony	1	32	226	1228	3821
	Cartilaginous	1	12	41	108	272
Middle	All	6	37	178	531	1184
	Bony	1	23	146	458	1004
	Cartilaginous	1	10	27	65	165
Deep	All	4	25	82	198	333
	Bony	1	18	68	175	292
	Cartilaginous	1	5	11	18	33

The calculation of the species richness and three phylogenetic indices used a 5° latitude band between 75°S and 75°N and four depth zones (whole water column, surface (0 – 200 m), middle (201 – 1000 m), and deep (1001 – 6000 m)) reflecting the photic, mesophotic and aphotic zones of light penetration (Costello & Breyer, 2017). I also calculated the species richness and three phylogenetic indices in the 100 m depth band from 0 m to 3500 m. The phylogenetic indices were only calculated when there was more than 10 species per latitude and depth band following previous study (Plazzi et al. 2010). The calculation of STL and STL/spp were based on the taxonomic richness in Chapter 2. The raw values of species richness, AvPD, STL, and STL/spp in 5° latitude bands among four depth zones and 100 m depth bands among all, bony, and cartilaginous fish are shown in Appendices Tables A3.2 – A3.5.

A polynomial regression was used for assessing the relationship between phylogenetic indices and species richness among all, bony, and cartilaginous fish in the four depth zones. In addition, the latitudinal gradients of phylogenetic indices of all fish were correlated with the long-term averages of monthly sea surface temperature (SST, °C) and sea bottom temperature (SBT, °C). The environmental variables were obtained from Global Marine Environmental Datasets (Basher & Costello, 2020). Raster data of environmental variables were calculated as the mean value in every 5-degree latitude band between 75°S and 70°N as showed in Chapter 2. Generalised Additive Models (GAM) (Hastie & Tibshirani, 1990) were used to assess the relationship between latitudinal gradients of AvPD, STL and STL/spp of all fish and environmental variables in the same 5-degree latitude bands. A GAM is a nonparametric regression method that uses smooth functions of the predictors. Also, a GAM is flexible regarding the assumptions concerning the underlying statistical distribution of the data (Swartzman et al., 1995). The package “mgcv” (Wood, 2011) in R (R core team, 2018) was used for the GAM analysis. A GAM with Gaussian error distribution and identical link function was used for modelling. Smoothness selection(s) of thin plate regression splines was used for the model fitting process. The model was as follows:

$$\text{Phylogenetic indices} \sim s(\text{Environmental variable})$$

Standard diagnostics including Quantile-Quantile (Q-Q) plot, minimised Generalised Cross-Validation (GCV) scores, maximised deviance explained and maximised adjusted r^2, were used to assess distributional and smoothing assumptions (Wood, 2006) (Appendices: GAM-Chapter 3). The deviance explained, adjusted r^2, and GCV scores were recorded. The relationships of phylogenetic indices to each environmental variable were plotted.

The Jaccard similarity index (Jaccard, 1912) is the simplest and most popular measure of species turnover (beta diversity) (Whittaker, 1975; Kreft & Jetz 2010). Jaccard similarity has been used for latitudinal patterns of species compositions of terrestrial flora (Bannister et al., 2012; Gehrke & Linder, 2014), freshwater bacteria (Romina Schiaffino et al., 2011), marine ostracods (Angel et al., 2007), and marine fish (Anderson et al., 2013; Navarrete et al., 2014). It produces the same results as alternative methods at global scales (Costello et al., 2017; Costello, Tsai, et al. 2018):

$$J_{i,j} = \frac{a}{a + b + c}$$

where *a* is the number of species that are common in samples *i* and *j*, *b* is the number of species present in sample *i* but absent in sample *j*, and *c* is the number of species present in sample *j* and absent in sample *i* (Jaccard, 1912). The index was clustered using the Unweighted Pair Group Method with Arithmetic mean (UPGMA), and the Similiarity Profile Analysis (SIMPROF) used to determine which latitude and depth bands had a significantly different species composition at the 95% level using PRIMER v6 (Clarke & Gorley, 2006).

3.3. Results

3.3.1. Latitudinal gradients of species richness

Species richness of all and bony fish had similar latitudinal gradients in each depth zone (Figures 3.1 & 3.2). The highest species richness was at 10°N –15°N in the whole water column (Figures 3.1a & 3.2a) and surface zones (Figures 3.1d & 3.2d). Highest species richness was at 30°N in the middle (Figures 3.1g & 3.2g) and deep zones (Figures 3.1j & 3.2j). Similarly, species richness of cartilaginous fish was all highest at 20°N – 25°N in each depth zone except for the middle zone. In addition, species richness of cartilaginous fish was visually bimodal in the surface (Figure 3.3d) and middle zones (Figure 3.3g). Species richness among all, bony, and cartilaginous fish all had a small dip at the equator, was higher at the tropics and subtropics, and decreased with latitude in all depth zones (Figures 3.1 – 3.3).

3.3.2. Latitudinal gradients of phylogenetic indices in the whole water column

Both species and higher taxonomic richness (STL) were low in polar latitudes and high in the tropics and subtropics in all depth zones (Figure 3.1). In contrast, when adjusted for species richness as the average phylogenetic diversity (AvPD) and the sum of the higher taxonomic levels divided by the number of species (STL/spp), then all, bony, and cartilaginous fish groups were all lower at tropical and subtropical areas (between 30°S and 30°N) but higher at high latitudes. At higher latitudes, AvPD and STL/spp increased and peaked at 55°S and 75°N, respectively (Figures 3.1b, c, 3.2b, c & 3.3b, c). However, in the Southern Ocean, the AvPD and STL/spp of all and bony fish slightly decreased indicating that species there were more phylogenetically closely related compared to species at other high latitude areas (Figures 3.1b, c & 3.2b, c).

The STL among all, bony and cartilaginous fish showed a similar gradient as species richness with a small dip at the equator (Figures 3.1c, 3.2c, & 3.3c). The STL of all and bony fish peaked at 25°N, then decreased poleward (Figures 3.1c & 3.2c). The STL of cartilaginous fish was bimodal, peaking at 30°S and 25°N, respectively (Figure 3.3c). Thus, subtropical latitudes had slightly more species from more different higher taxonomic levels than at the equator.

3.3.3. Latitudinal gradients of phylogenetic indices in the depth zones

The latitudinal gradients of AvPD, STL and STL/spp of all, bony and cartilaginous fish groups in the surface zone were similar to the gradients in the whole water column (Figures 3.1 – 3.3). This is because about 73% of all fish, 75% of bony fish, and 58% of cartilaginous fish were in the surface zone, and their distribution influenced the latitudinal gradients of the whole water column more than species in other depths. In addition, latitudinal gradients of AvPD, STL, and STL/spp for all and bony fish were also similar in different depth zones because 91% of all fish species were bony fish in this dataset. The main differences were that the gradients became less pronounced with depth and more variable when there were fewer species.

AvPD and STL/spp of all, bony and cartilaginous fish were all lower between 30°S and 30°N in the surface and middle zones and between 40°S and 40°N in the deep zone, and they all peaked at 55°S and 75°N, respectively (Figures 3.1 – 3.3). In addition, AvPD and STL/spp of all and bony fish decreased in the surface and middle zones of the Southern Ocean but increased in the deep zone of the Southern Ocean (Figures 3.1 – 3.3). There were no phylogenetic data for cartilaginous fish in the high southern latitudes because there were less than ten species present

(Figure 3.3). This result showed that species of all, bony and cartilaginous fish had closer phylogenetic relationships in the tropics and subtropics than high latitudes in all depth zones.

The STL of all and bony fish in the surface, middle and deep zones were all similar to species richness, being highest in the northern subtropical areas (between 25°N and 35°N), and they all had a small dip at the equator in the three depth zones (Figures 3.1 – 3.2). For cartilaginous fish, STL was also similar to species richness in the surface (Figure 3.3f) and middle zones (Figure 3.3i) but not in the deep zone (Figure 3.3l). In the deep zone, the species richness of cartilaginous fish was highest at 15°N – 35°N (Figure 3.3j). However, STL of cartilaginous fish was flattened across the tropics and subtropics in the deep zone. Thus, cartilaginous fish had similar higher taxonomic richness across the tropics and subtropics in the deep sea (Figure 3.3l).

Overall, I found that the species were on average more phylogenetically closely related in the tropics and subtropics (between 30°S and 30°N) in all four depth zones. In contrast, the species assemblage in the southern temperate area and Arctic Ocean were phylogenetically distantly related in all depth zones. The species in the Southern Ocean were more closely phylogenetically related in the surface and middle zones, but not in the deep zone compared to the temperate latitudes (Figures 3.1 – 3.3).

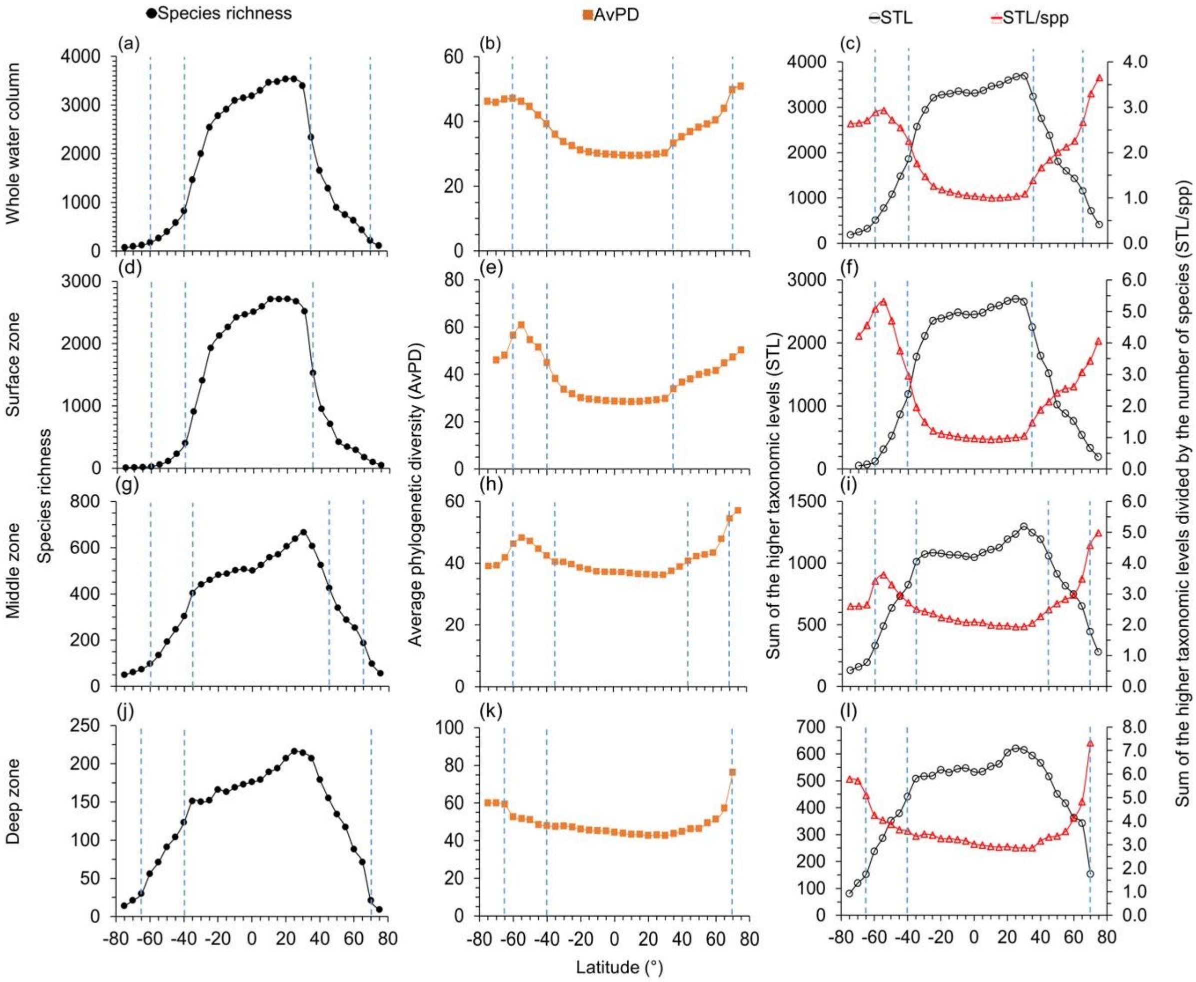


Figure 3.1. For all fish, latitudinal gradients of species richness, average phylogenetic diversity (AvPD), the sum of the higher taxonomic levels (STL) and the sum of the higher taxonomic levels divided by the number of species (STL/spp) between 75°S and 75°N in the whole water column, surface (0 m – 200 m), middle (201 m – 1000 m), and deep (1001 m – 6000 m) zone. The dashed lines on AvPD indicate the distinct fish assemblages as clustering results in Figure 3.11.

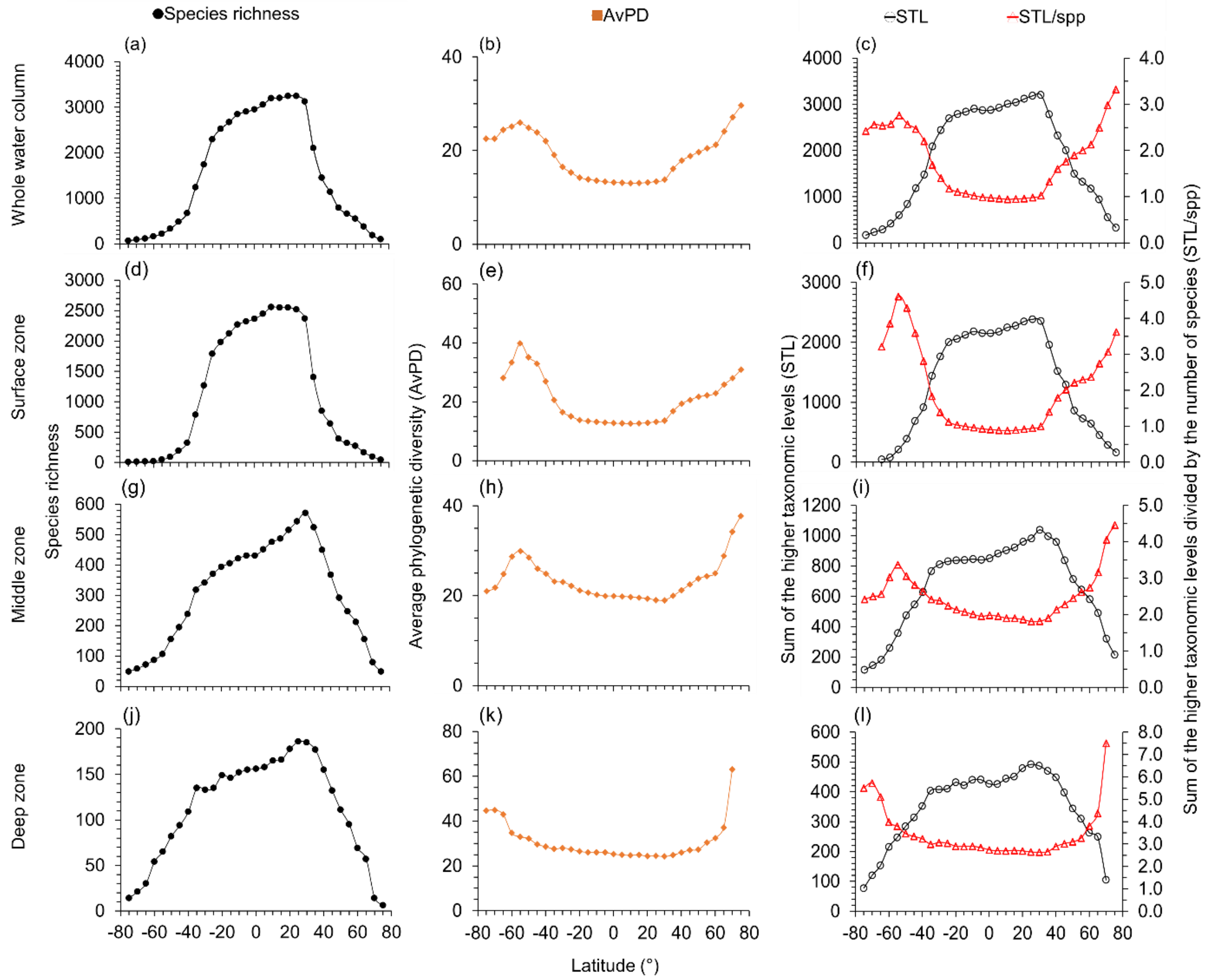


Figure 3.2. For bony fish, latitudinal gradients of species richness, average phylogenetic diversity (AvPD), the sum of the higher taxonomic levels (STL) and the sum of the higher taxonomic levels divided by the number of species (STL/spp) between 75°S and 75°N in the whole water column, surface (0 m – 200 m), middle (201 m – 1000 m), and deep (1001 m – 6000 m) zone.

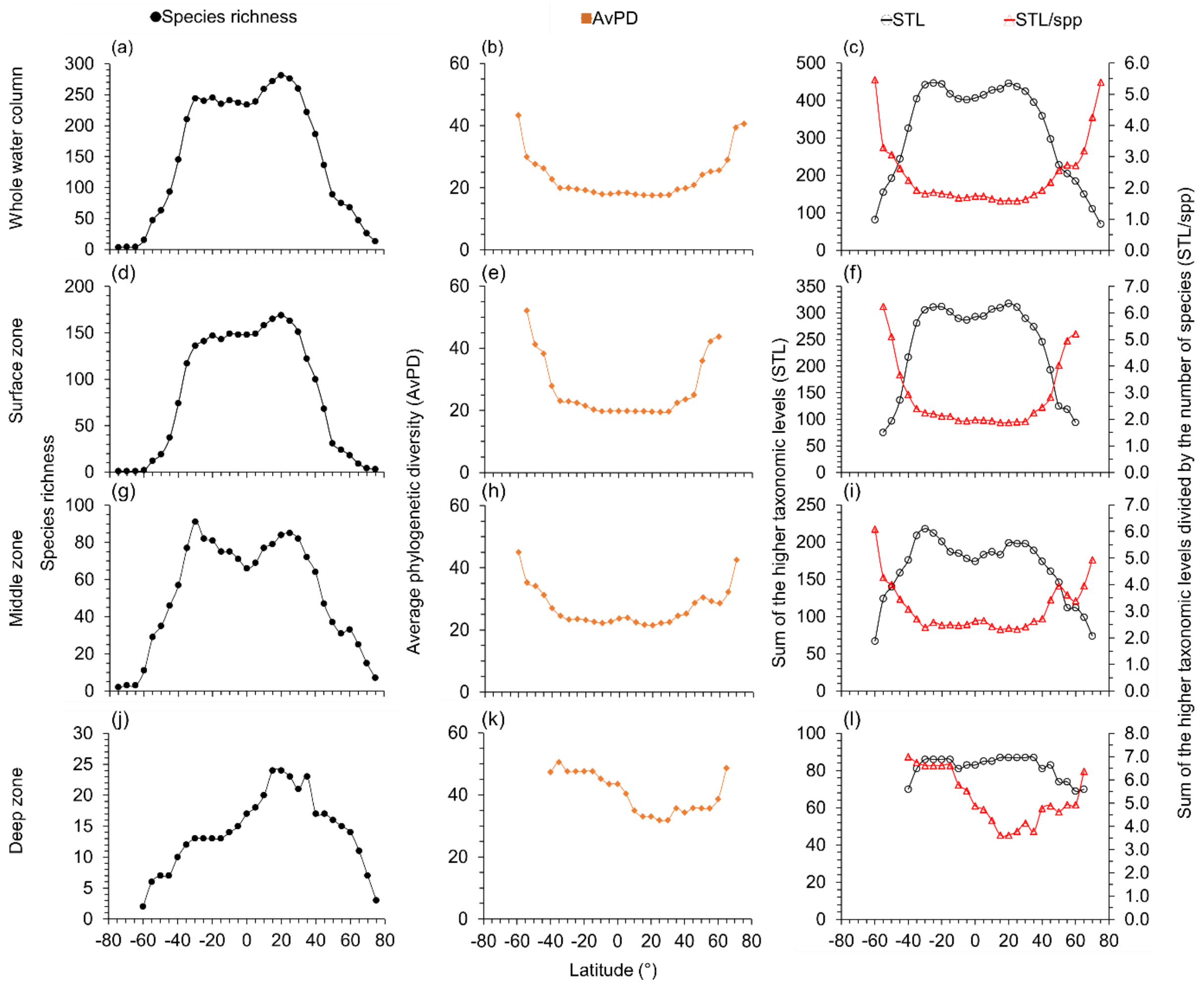


Figure 3.3. For cartilaginous fish, latitudinal gradients of species richness, average phylogenetic diversity (AvPD), the sum of the higher taxonomic levels (STL) and the sum of the higher taxonomic levels divided by the number of species (STL/spp) between 75°S and 75°N in the whole water column, surface (0 m – 200 m), middle (201 m – 1000 m), and deep (1001 m – 6000 m) zone.

3.3.4. Relationship of phylogenetic indices and species richness

AvPD, STL, and STL/spp were all significantly positively correlated to species richness among all, bony, and cartilaginous fish in the whole water column, surface, middle, and deep zones ($R^2 = 0.55 – 0.99$, p-values < 0.001) (Figures 3.4 – 3.6). These relationships were not linear. Most latitudes with more species had lower AvPD and STL/spp for all, bony and cartilaginous fish. However, both higher and lower indices of AvPD and STL/spp for all and bony fish existed in the areas where species richness was low. This was because both the Arctic Ocean and the Southern Ocean had low species richness, but species were phylogenetically more distantly related (higher AvPD and STL/spp) in the Arctic than the Southern Ocean (Figures 3.4 – 3.6).

The STL of all, bony, and cartilaginous fish raised with increased species richness among four depth zones reflected that areas with high species richness also had diverse higher taxonomic levels (Figures 3.4 – 3.6). However, one exception was cartilaginous fish in the deep zone where areas with different species richness but had similar STL reflecting that some higher taxonomic levels contained more cartilaginous fish species in the deep zone (Figure 3.6k).

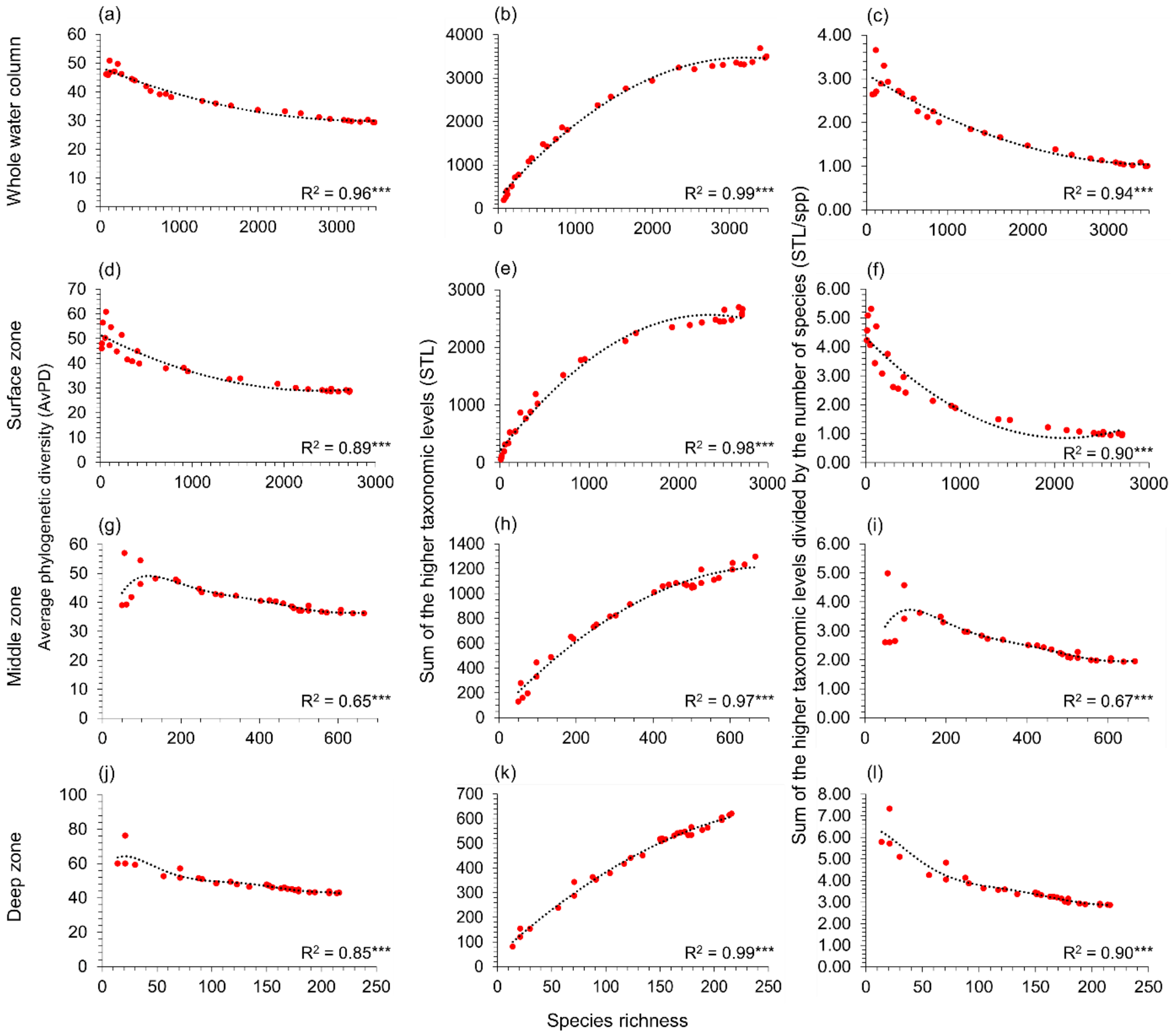


Figure 3.4. For all fish, polynomial regression of species richness, average phylogenetic diversity (AvPD, left graphs), the sum of the higher taxonomic levels (STL, centre graphs), and the sum of the higher taxonomic levels divided by the number of species (STL/spp, right graphs) in 5-degree latitude bands in the whole water column, surface (0 m – 200 m), middle (201 m – 1000 m), and deep (1001 m – 6000 m) zone. *** indicates *p*-value < 0.001.

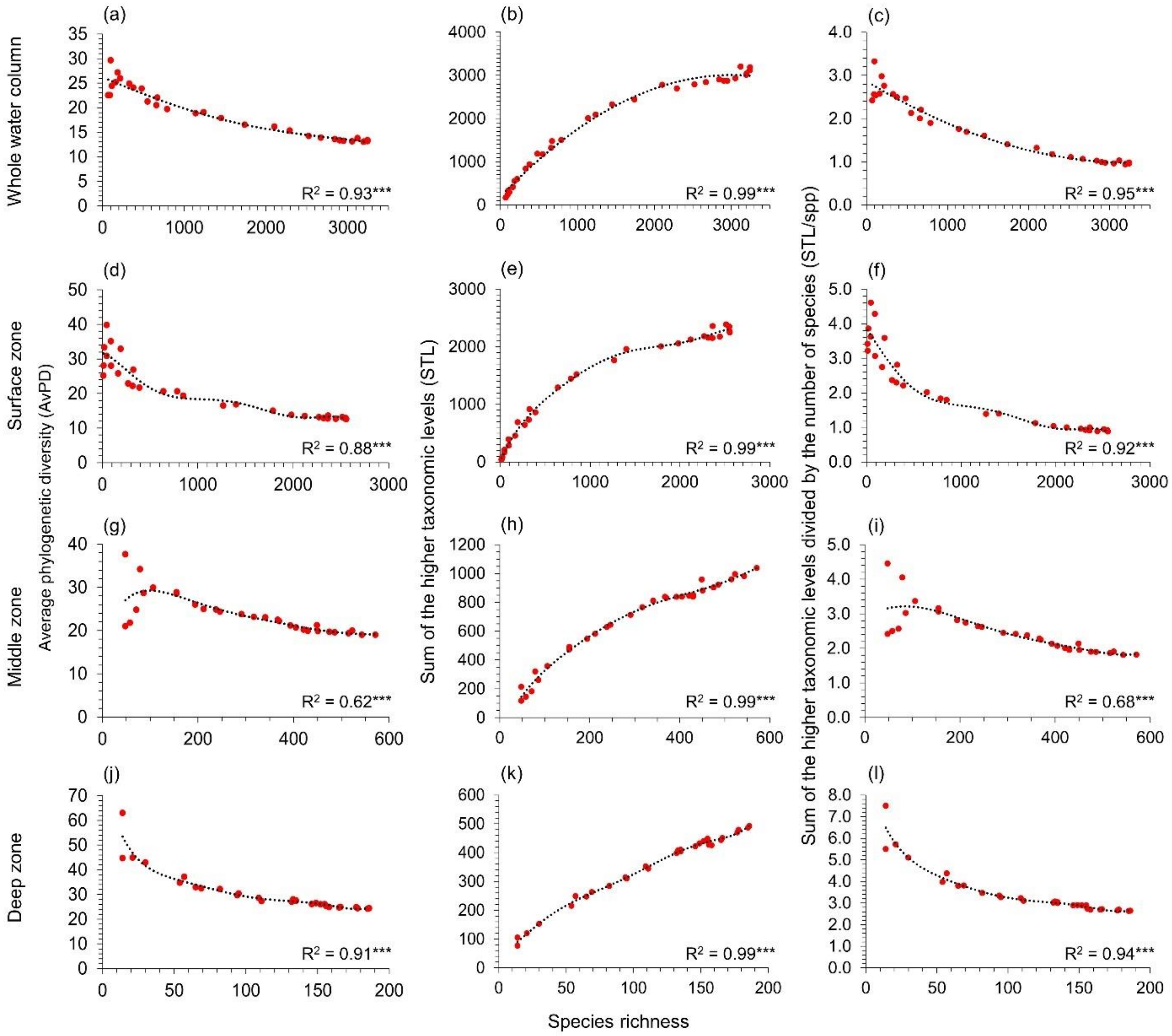


Figure 3.5. For bony fish, polynomial regression of species richness, average phylogenetic diversity (AvPD, left graphs), the sum of the higher taxonomic levels (STL, centre graphs), and the sum of the higher taxonomic levels divided by the number of species (STL/spp, right graphs) in 5-degree latitude bands in the whole water column, surface (0 m – 200 m), middle (201 m – 1000 m), and deep (1001 m – 6000 m) zone. *** indicates p-value < 0.001.

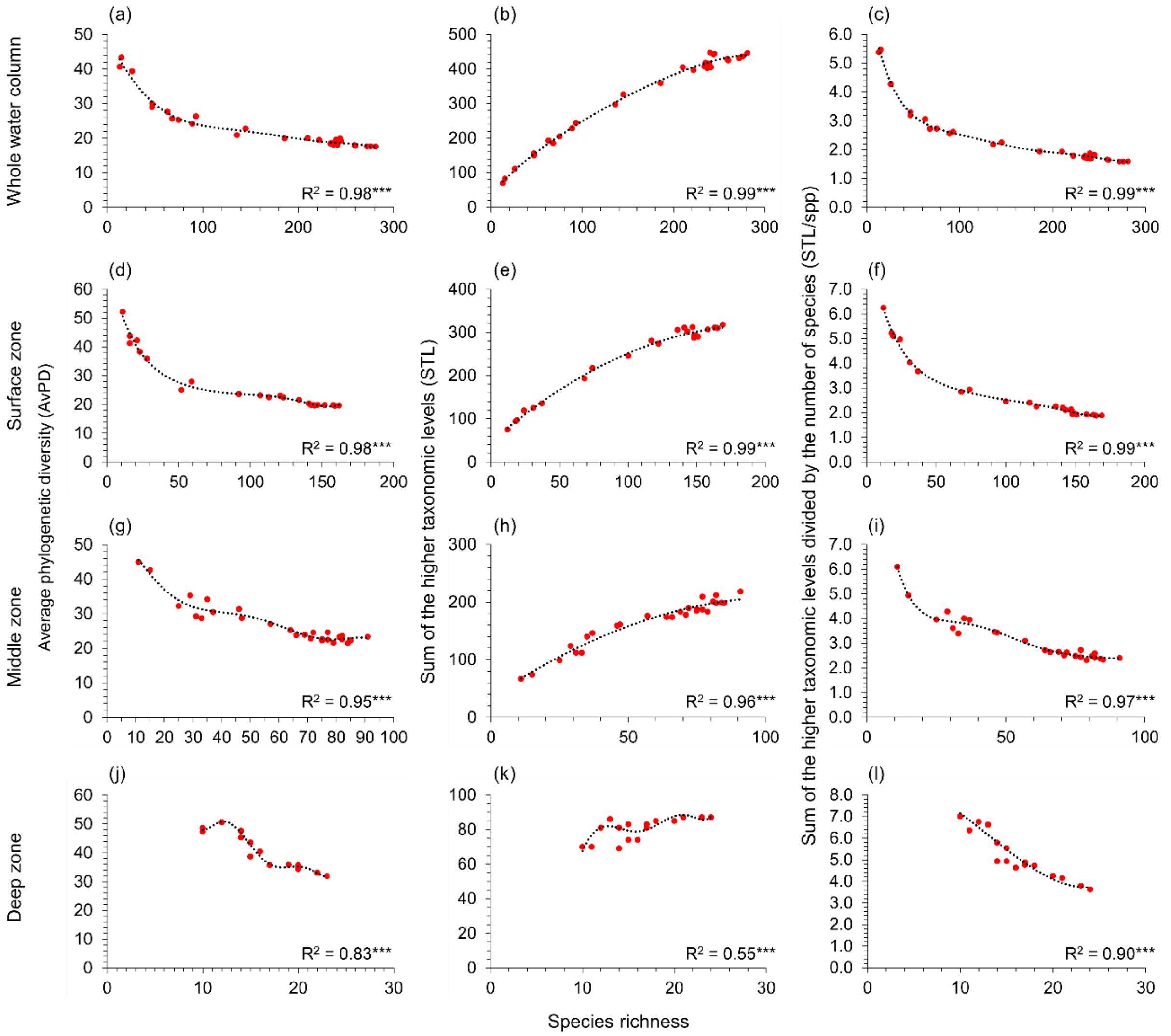


Figure 3.6. For cartilaginous fish, polynomial regression of species richness, average phylogenetic diversity (AvPD, left graphs), the sum of the higher taxonomic levels (STL, centre graphs), and the sum of the higher taxonomic levels divided by the number of species (STL/spp, right graphs) in 5-degree latitude bands in the whole water column, surface (0 m – 200 m), middle (201 m – 1000 m), and deep (1001 m – 6000 m) zone. *** indicates *p*-value < 0.001.

3.3.5. Environmental relationships

All phylogenetic indices were significantly correlated with latitudinal gradients of sea surface (SST) and bottom temperatures (SBT) (Table 3.2). Mean SST was the primary factor that affected the latitudinal gradients of AvPD, STL, and STL/spp of all fish. AvPD and STL/spp decreased with warmer SST (Figure 3.7). It implied that fish assemblages with closer phylogenetic relationships were in the tropical latitudes when mean SST > 25°C (Figure 3.7). In contrast, the STL increased with warmer SST, and it peaked at around 23 °C (Figure 3.7). This indicated that warmer latitudes had more higher taxonomic richness (Figure 3.7). Three phylogenetic indices had similar trends as SST when against SBT, but the gradients more fluctuated (Figure 3.7) because the SBT was averaged by different depths in different latitudinal bands.

Together, these results suggest that sea temperature is one of the factors influencing the distribution of species richness and higher taxonomic richness.

Table 3.2. For all fish, the Generalised Additive Model results for the latitudinal gradients of average phylogenetic diversity (AvPD), the sum of the higher taxonomic levels (STL) and the sum of the higher taxonomic levels divided by the number of species (STL/spp) against sea surface and bottom temperatures, ranked by deviance explained. *** *P*-value < 0.001.

Environmental variable	**Adjusted r^2**	**Deviance explained (%)**	**Generalised cross-validation score**	**Degrees of freedom**	***P*-value**
Sea surface temperature					
STL	0.97	97.7	47556	4.20	***
AvPD	0.95	95.0	2.59	1.00	***
STL/spp	0.92	92.2	0.05	1.10	***
Sea bottom temperature					
AvPD	0.80	83.3	11.5	4.73	***
STL/spp	0.78	82.4	0.16	5.65	***
STL	0.80	80.9	328000	1.69	***

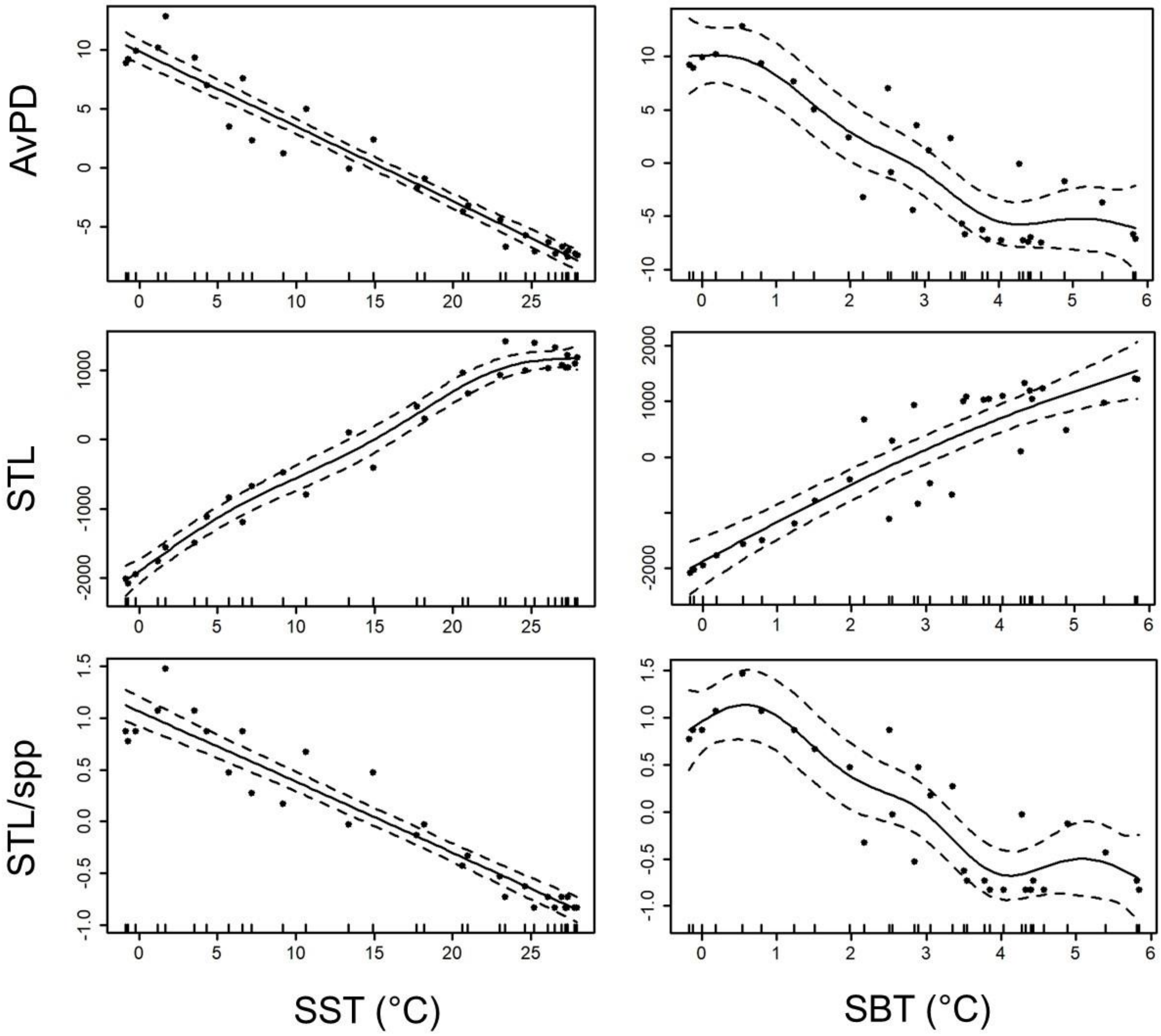


Figure 3.7. For all fish, the Generalised Additive Models (solid lines) for average phylogenetic diversity (AvPD), the sum of the higher taxonomic levels (STL) and the sum of the higher taxonomic levels divided by the number of species (STL/spp) against sea surface (SST) and bottom temperatures (SBT). The dashed lines indicate the 95% confidence intervals. The tick marks of x-axis are observed data points. The y-axis represents the spline function.

3.3.6. Depth gradients

Species richness and STL among all, bony and cartilaginous fish groups were all highest in the shallow water (< 100 m), then decreased with depth (Figures 3.8 – 3.10). There were fewer than 10 species deeper than 3300 m for all and bony fish, and deeper than 1800 m for cartilaginous fish (Figures 3.8 – 3.10). In this dataset, there were no cartilaginous fish deeper than 2300 m (Figure 3.10a).

The AvPD and STL/spp were all lowest shallower than 100 m and they increased with depth among all, bony and cartilaginous fish (Figures 3.8 – 3.10). AvPD and STL/spp peaked at around 2700 m for all and bony fish (Figures 3.8b, d & 3.9b, d), and at around 1700 m for cartilaginous fish (Figures 3.10b, d). Thus, both species and higher taxonomic richness (STL) decreased with depth, and with increased depth, the phylogenetic relationships (AvPD, STL/spp) of species became more distant.

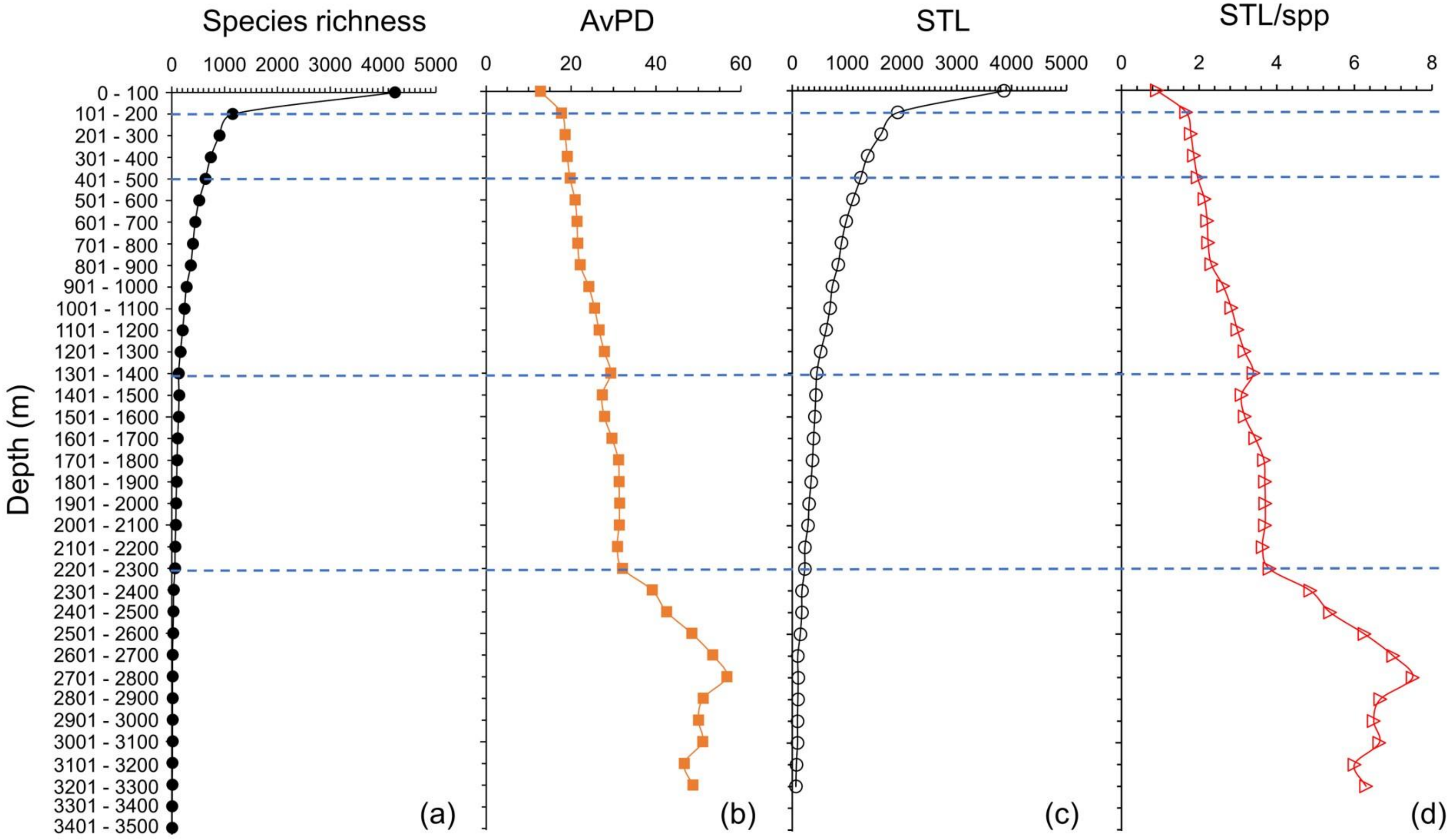


Figure 3.8. For all fish, gradients of (a) species richness, (b) average phylogenetic diversity (AvPD), (c) the sum of the higher taxonomic levels (STL), and (d) the sum of the higher taxonomic levels divided by the number of species (STL/spp) in 100 m depth bands from 0 m to 3500 m. The dashed lines indicate the distinct fish assemblages as clustering results in Figure 3.12a.

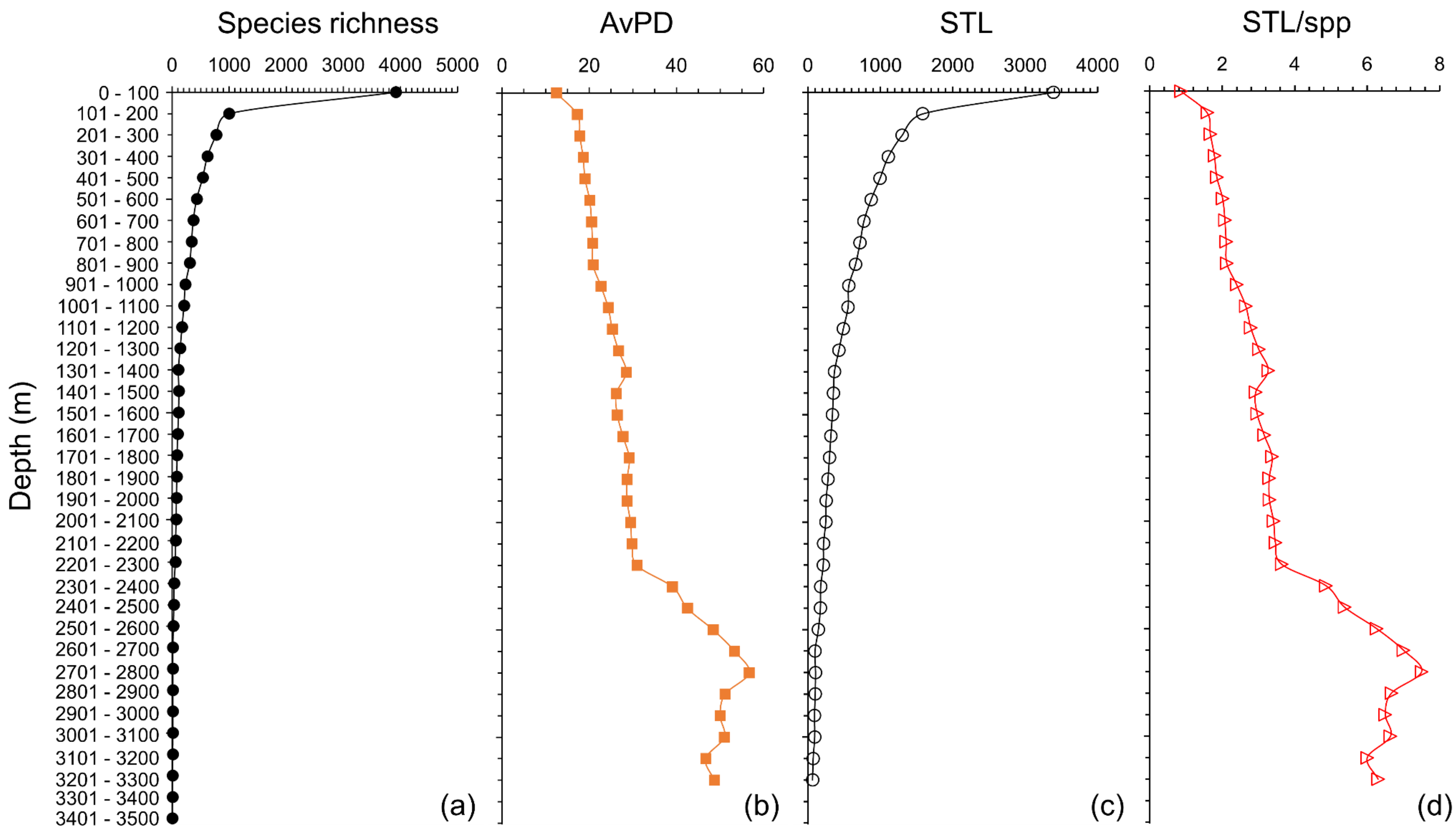


Figure 3.9. For bony fish, gradients of (a) species richness, (b) average phylogenetic diversity (AvPD), (c) the sum of the higher taxonomic levels (STL), and (d) the sum of the higher taxonomic levels divided by the number of species (STL/spp) in 100 m depth bands from 0 m to 3500 m.

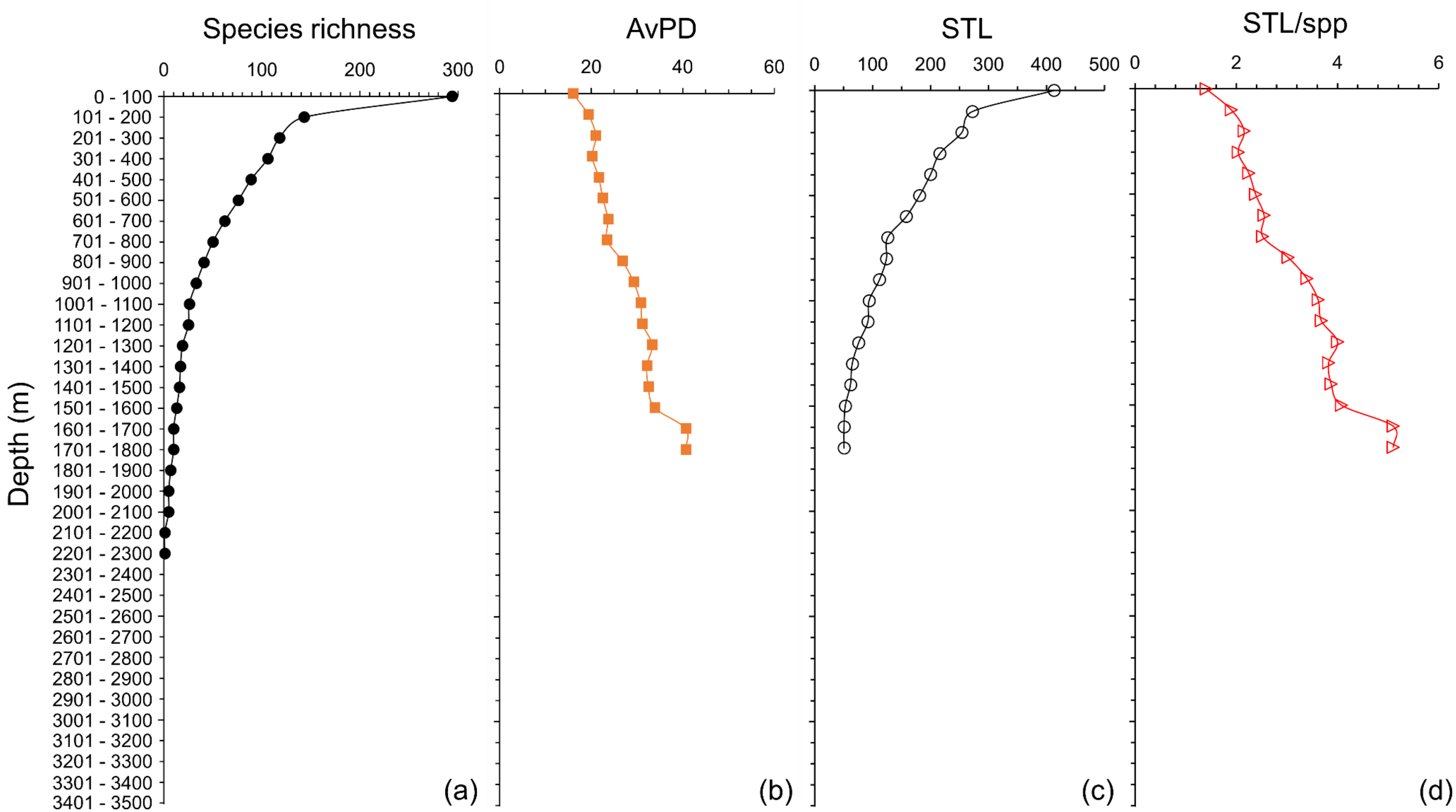


Figure 3.10. For cartilaginous fish, gradients of (a) species richness, (b) average phylogenetic diversity (AvPD), (c) the sum of the higher taxonomic levels (STL), and (d) the sum of the higher taxonomic levels divided by the number of species (STL/spp) in 100 m depth bands from 0 m to 3500 m.

3.3.7. Species assemblages by latitude

Fish species assemblages were clustered by latitudinal bands (Figure 3.11). The SIMPROF test showed no significant difference between same pairs of latitudinal bands ($P < 0.05$), but otherwise significant differences over scales of 15° latitude. Overall depths and shallower than 200 m, there were distinct tropical and subtropical (± 30° latitude), and southern and northern hemispheres groups (Figures 3.11a, b). Within these groups, there were five assemblages: Arctic Ocean (> 70°N), northern temperate (35°N – 65°N), southern temperate (40°S – 55°S), Southern Ocean (60°S – 75°S), and tropical and subtropical assemblages (Figure 3.11a).

The fish assemblages in the surface zone (Figure 3.11b) were similar to the fish assemblages in the whole water column (Figure 3.11a) and middle zone (Figure 3.11c), except for there were no distinct northern temperate and Arctic Ocean assemblages in the surface zone (Figure 3.11b).

In contrast to the surface zone, below 200 m depth, the first division in the dendrogram separated out the Southern Ocean, indicate its fish fauna is dissimilar from all the rest latitudes (Figures 11c, d). The second most distinct assemblage below 200 m was the Arctic Ocean. Thus, when depth below 200 m, the polar assemblages are the least similar to the fish fauna in the rest of the world. In the middle zone, there were a distinct tropical and subtropical group between 30°S and 40°N, and northern and southern temperate groups. These results show the different latitudinal biogeographic distribution for the shallow and deep-sea fish assemblages, with the polar assemblages being most distinct below 200 m depth.

When depth deeper than 1000 m, the fish assemblages were no difference between southern subtropics and northern temperate. There were distinct fish assemblages in the southern temperate, Arctic Ocean and Southern Ocean (Figure 3.11d).

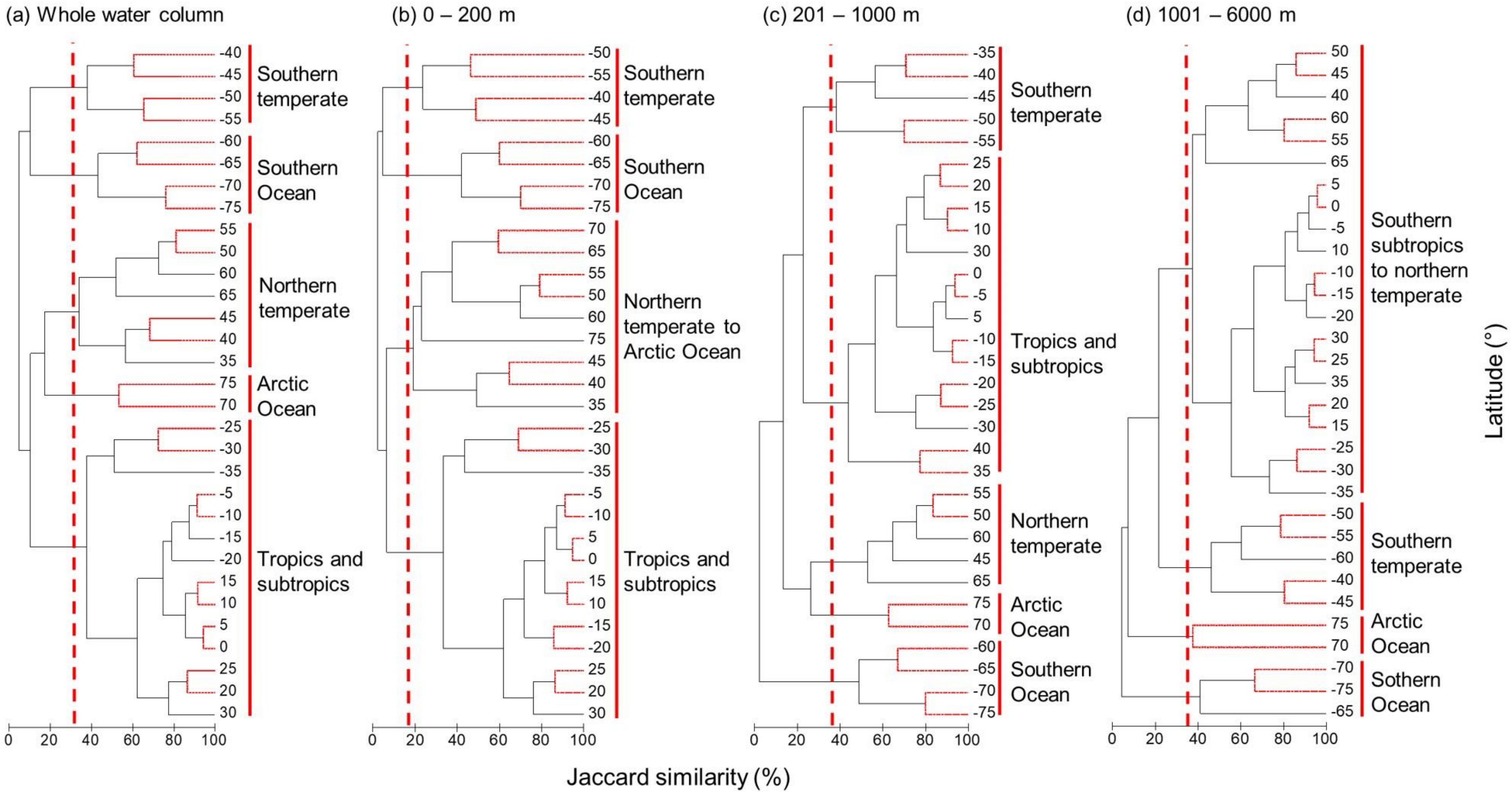


Figure 3.11. Clustering of species assemblages in 5-degree latitude bands from 75° S to 75° N in the (a) Whole water column, (b) Surface zone (0 m – 200 m), (c) Middle zone (201 m – 1000 m), and (d) Deep zone (1001 m – 6000 m). The dashed lines show the cut-offs, and the solid lines indicate the species assemblages.

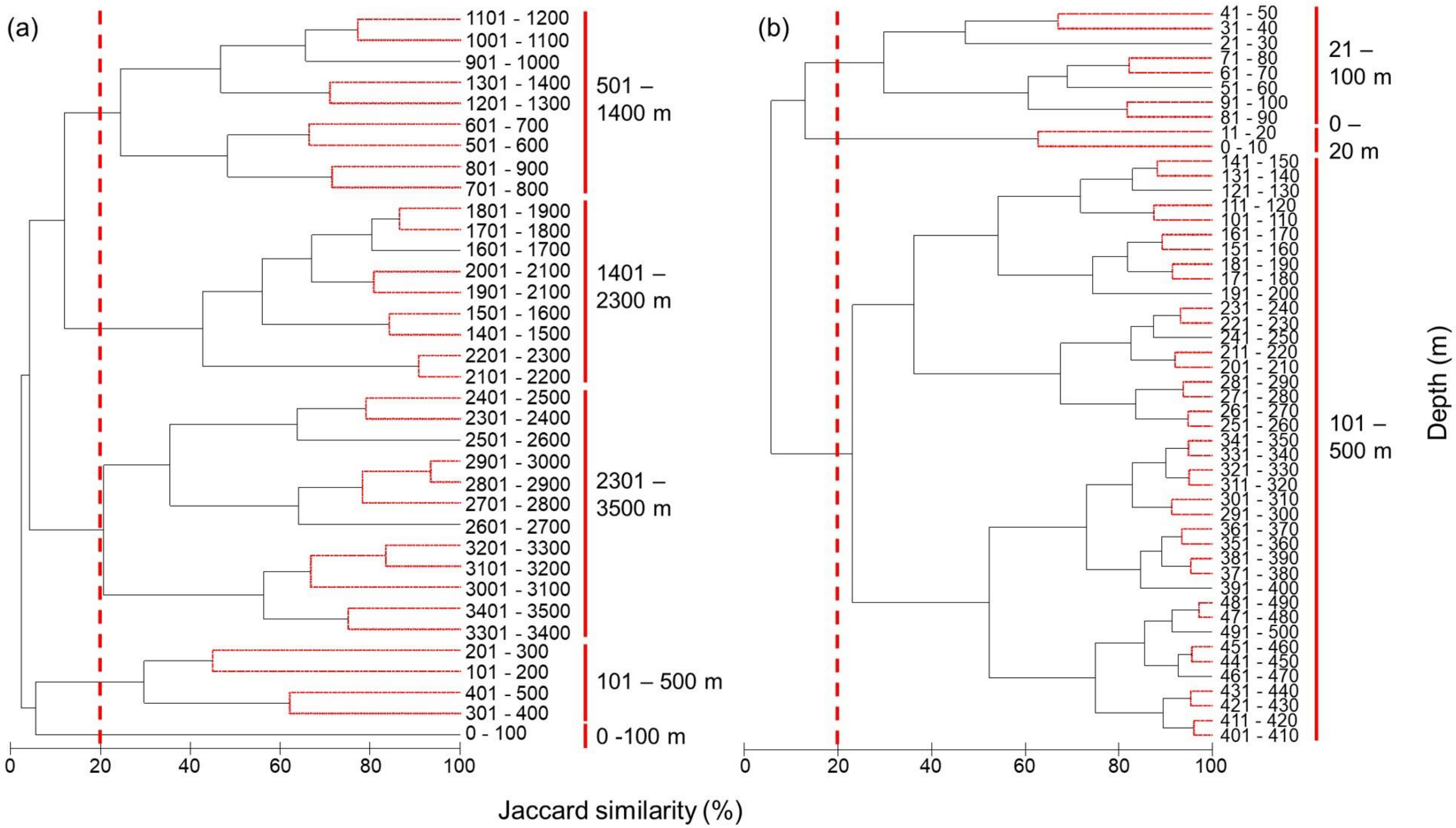


Figure 3.12. Clustering of species assemblages along with depth in the (a) 100 m depth bands from 0 m to 3500 m and (b) 10 m depth bands from 0 m to 500 m. The dashed lines show the cut-offs, and the solid lines indicate the species assemblages.

3.3.8. Fish assemblages by depth

The most distinct fish assemblages separated at 500 m, closely followed by a shallower than 100 m, 101 – 500 m, 501 – 1400 m, 1401 – 2300 m, and deeper than 2301 m (Figure 3.12a). Because most species live in the surface zone, I also clustered the species in 10 m depth bands from 0 m to 500 m. Three fish assemblages, 0 – 20 m, 21 – 100 m, 101 – 500 m, were grouped at the same similarity level as in the 100 m band analysis (Figure 3.12b). Therefore, there is increasing similarity and homogeneity in fish assemblages with depth.

3.4. Discussion

3.4.1. Latitudinal gradients

This is the first study to compare species richness and phylogenetic indices among all, bony and cartilaginous marine fish groups across latitudes in the whole water column and three depth zones, and depths on a global scale. The surface zone most influenced the overall patterns due to over 73% of fish species living at < 200 m depth. Furthermore, bony fish accounted for 91% of all fish, so gradients between all and bony fish were similar.

In general, I found gradients of STL were similar to gradients of species richness among fish groups and depth zones. The only difference was that the species richness of cartilaginous fish in the deep zone peaked at 15°N – 35°N (Figure 3.3j), but the latitudinal gradient of STL was flattened across the tropics and subtropics (Figure 3.3l). This was because there were only 21 – 24 cartilaginous fish in the deep zone at 15°N – 35°N, and four genera (i.e., *Apristurus*, *Bathyraja*, *Galeus*, *Rajella*) of cartilaginous fish contained more species than other genera.

3.4.2. Equatorial dip

Species richness and STL of all, bony, and cartilaginous fish all peaked in the northern subtropics with a small dip near the equator. The small dip of species richness and STL at the equator may be because the temperature is too high for some species. In Chapter 2, I found that species richness decreased when the temperature was greater than 25°C. It thus appears that some tropical species cannot tolerate elevated temperature at the equator, and they move into subtropical latitudes due to climate change (Garciá Molinos et al., 2016; Chaudhary, 2019; Yasuhara et al., 2020; Chaudhary et al., 2021). The results in this study showed that not only species from the same genus, but also species from different higher taxonomic levels escaped the warmer equator.

3.4.3. Phylogenetic gradients with latitude

The results showed that the latitudinal gradients in species richness of all, bony and cartilaginous fish were significantly correlated with three phylogenetic indices among all depth zones. Areas with more species, such as the tropics and subtropics (between 30°S and 30°N) had lower AvPD and STL/spp but higher STL. That is, the tropics and subtropics not only had more species with a closer phylogenetic relationship, but also had more diverse higher taxonomic levels. This result support my first hypothesis that an area with more species richness would have more higher taxonomic richness. In contrast, areas with low species richness, such as temperate areas, had higher AvPD and STL/spp but lower STL reflecting that species within assemblages at high latitudes were less phylogenetically related and from fewer higher taxonomic levels. In addition, the results showed that AvPD and STL/spp were all lower in the tropics and subtropics, but all higher at 55°S and 75°N, respectively, from the surface to the deep depth zone. These results confirmed the initial expectation that phylogenetic indices would have clear latitudinal gradients because the species richness also had clear latitudinal gradients in all depth zones (Woolley et al., 2016; Lin et al., 2021; Chapter 2).

Here, I suggest three reasons which may explain the findings that species and higher taxonomic richness were more diverse and species assemblage was more phylogenetically closely related in the tropics and subtropics than temperate latitudes. First, the warmer temperature in the tropics, resulting in shorter generation times, higher rates of metabolism, faster rates of mutation, and faster selection, which generate and maintain higher biodiversity (Rohde, 1992; Wright et al., 2011; Brown, 2014). Empirical studies that analysed large datasets on several different taxa from the terrestrial to the marine environment, such as angiosperm families (Davies et al., 2004), rain forest plants (Wright et al., 2006; Gillman et al., 2010), marine foraminifera (Allen et al., 2006), and marine fish (Wright et al., 2011) also found that rates of evolution were greater in the tropics, although Rabosky et al. (2018) claimed that marine fish had higher speciation rates at both poles. In addition, warmer temperature shortened the duration of planktonic larvae in the tropics (O'Connor et al., 2007), with the shortest dispersal distance in the subtropics (Álvarez-Noriega et al., 2020), resulting in reduced gene flow and higher rates of diversfication and speciation in the tropics and subtropics (O'Connor et al., 2007). In this study, the GAM results showed that in the warmer latitudes, there were more higher taxonomic richness and fish assemblages were more phylogenetically closer related (Figure 3.7) supporting this hypothesis. Second, the tropics and subtropics have higher habitat complexity, notably coral reefs which contain 27% of marine fish species (Costello, 2015; Froese & Pauly, 2019), that provide more ecological niches leading to higher species diversity (Rocha et al., 2005; Grosberg et al., 2012; Kovalenko et al., 2012). Third, the absence of glaciations (that would have extirpated polar fauna during ice ages) has allowed more time for speciation and lower extinction rates in the tropics (Pellissier et al., 2014; Leprieur et al., 2016; Miller et al., 2018). Together these reasons allow phylogenetic diversity and species to originate and accumulate, even in the deep sea of the tropics and subtropics because some species extend from the shallow water to the deep sea. In contrast, the colder and seasonal environment at high latitudes limits growth and slows generations times (Meseguer & Condamine, 2020; Yasuhara et al., 2020). Therefore, fish assemblages at high latitudes are more phylogenetically distantly related than they are at low latitudes, reflecting the higher tropical and subtropical speciation rates.

3.4.4. Southern Ocean

Species richness, AvPD, STL and STL/spp of all and bony fish decreased in the Southern Ocean in the whole water column, surface, and middle zones. The Southern Ocean has been a relatively enclosed environment compared to other high latitudinal areas after the opening of Drake Passage 23 – 25 million years ago, the formation of Antarctic Circumpolar Current, and the following ocean cooling, resulting in the evolution of a unique fish fauna with a high rate of endemism (McGonigal & Woodworth, 2003; Duhamel et al., 2014), and over 45% of all its marine species are endemic (Costello, Coll, et al., 2010). The fish assemblage is basically dominated by the Notothenioidei (notothenioids) which accounts for over 35% of fish species in the Southern Ocean (Eastman, 1997). Other major fish groups are the Zoarcidae (eelpouts) and the Scorpaeniform family Liparidae (snailfish) (Eastman & McCune, 2000). The adaptive radiation of Antarctic notothenioids is characterized by the presence of antifreeze glycoproteins, originating near the Oligocene-Miocene transition (mean 23.9 million years ago) during a major period of global cooling and ice-sheet extension. This allowed notothenioids to live and evolve in the cold environment (McGonigal & Woodworth, 2003; Duhamel et al., 2014).

3.4.5. Depth gradients

Species and phylogenetic richness not only declined into higher, colder latitude but also with depth in the ocean. The results showed that species richness and STL among all, bony and cartilaginous fish groups were all highest in the shallowest waters and decreased with depth. In contrast, AvPD and STL/spp increased with depth. These results indicated that species were more phylogenetically closely related in shallower depths. With shallower depths, phylogenetic relationships between species were closer reflecting higher rates of speciation due to greater productivity, generally warmer temperatures, and habitat complexity. Shallow water has the highest species richness and STL, and thus it may be an engine of speciation for marine fish (Eme et al., 2020) as it is for marine species overall (Costello & Chaudhary, 2017).

Deeper than 2300 m, there was only one class (i.e., Actinopterygii) and most of the species were from different families. At a depth of 2701 – 2800 m, 3 of 14 species were from the family Macrouridae, and the other 11 species were all from different families. Therefore, the fish at 2700 – 2800 m were far less phylogenetically related than in shallower depths.

I found that the biogeography of species assemblages declined with depth. There were three distinct assemblages shallower than 500m (Figure 3.12b), and only three assemblages deeper than 500 m (Figure 3.12a). This confirms the hypothesis that species richness declines with depth because of decreasing environmental heterogeneity, productivity and temperature (Costello & Chaudhary, 2017; Costello, Basher, et al., 2018).

3.5. Conclusion

The analyses in this study found that species richness and higher taxonomic richness (STL) were higher in the tropics and subtopics than in high latitudes, with a small dip at the equator in all fish groups and depth zones. In addition, species assemblages had closer phylogenetic relationships (lower AvPD and STL/spp) in warmer (low latitudes and shallow water) than colder environments (high latitudes and deep sea). This result is significantly related to the species richness and different fish groups among latitudes and depth zones. The results in this study support the hypothesis that a warmer temperature environment fosters speciation and thus generates higher biodiversity and a closer phylogenetic relationship. However, the cold environment in the Southern Ocean was dominated by endemic notothenioids, so it had a relatively closer phylogenetic relationship than other temperate latitudes because of its unique isolated environment.

Chapter 4

Latitudinal and Depth Gradients for Body Size and Trophic Level of Marine Fish

Chapter 4: Latitudinal and depth gradients for body size and trophic level of marine fish

4.1. Introduction

Latitudinal diversity gradients (LDGs) integrate over local and regional patterns where species have evolved and survived on both ecological and evolutionary time scales (Ekman, 1953; Gaston, 2000; Willig et al., 2003; Pontarp et al., 2019). In contrast to expectations that species richness decreased from the equator to the poles, recent studies have shown that the LDG of marine taxa are now bimodal with a dip at or near the equator (Powell et al., 2012; Chaudhary et al., 2016; 2017; Arfianti & Costello, 2020; Lin et al., 2021). These findings indicate that the LDG in terms of species richness is related to the warmer sea temperature (Yasuhara et al., 2020; Chaudhary et al., 2021; Lin et al., 2021). However, how biological traits of marine fish vary with global latitudes have not been studied.

Functional traits characterize an organism's phenotype, indicating how it may interact with the physical, chemical, and biological environments (Hooper et al., 2005). Over 25 functional traits (e.g., body size, trophic levels, depth distribution, metabolism, food consumption, spawning) are recorded in FishBase (Froese & Pauly, 2019). These functional traits can be numerical, continuous traits, or categorical data. However, numerical or continuous data can be converted into categorical (concept-based) data, so they are preferable (Costello et al., 2015). Body size, trophic level, and depth distribution are the most widely used numerical functional traits and have relatively complete records for most fish species (Costello et al., 2015; Froese & Pauly, 2019). Thus, in this study, the latitudinal and depth gradients of body size and trophic level of marine fish were studied.

A positive relationship between body size and latitude has been demonstrated in freshwater and marine ectotherms (Lindsey, 1966; Fisher et al., 2010; Bartels et al., 2020). The phenomenon where species have a smaller size in the low latitudes (warm environment) and a larger size in the high latitudes (cold environment) is known as the temperature-size rule (TSR) (Atkinson, 1994). In the marine environment, dissolved oxygen is another factor that limits marine organisms' body size (Forster et al., 2012; Hoefnagel & Verberk, 2015). This phenomenon for fish was explained by the gill-oxygen limitation theory (GOLT) that indicates the oxygen supply depends on the gill surface area related to the body mass (Pauly & Cheung, 2018). The ratio of gill surface area to body mass decreases when individuals grow. Therefore, an organism's body size is limited by the oxygen needed for maintaining its metabolic demands (Pauly & Cheung, 2018).

More marine herbivorous or omnivorous fish exist in the lower than higher latitudes (Floeter et al., 2005; Behrens & Lafferty, 2007; González-Bergonzoni et al., 2012; Dantas et al., 2019). This biogeographic pattern is explained by the temperature constraint hypothesis (TCH) which states that low temperatures constrain the efficiency of digestion for marine ectothermic herbivores (Gaines & Lubchenco, 1982). Therefore, the TSR and TCH hypotheses suggest that temperature is the primary driver constraining the body size and trophic level of fish. In this study, I correlated functional traits with the environmental variables (temperature, dissolved oxygen, and salinity), and assessed whether the results support the TSR, GOLT, and TCH hypotheses.

Another environmental gradient of interest to biodiversity patterns is depth. The deep sea is a dark, cold, and low-dissolved-oxygen environment across the latitudes (Costello & Breyer, 2017; Sayre et al., 2017; Basher & Costello, 2020). Therefore, it would be expected that the LDG may vary with latitude in the surface depth zone but be relatively constant in the deep sea. Previous studies found that relatively more species of fish with larger body size and higher trophic level occurred with greater depth (Smith & Brown, 2002; Lamprakis et al., 2008; Mindel et al., 2016). However, these studies focused on specific fish groups and study areas. Placing these patterns on a global scale will provide a more robust and more general theoretical understanding of variation. Besides, how the body size and trophic levels of marine fish change among latitudes and with depth at the global scale have not been studied previously.

This study describes the gradients of body size and trophic level of marine fish among latitudes in different depth zones and along depth globally. The relationship between functional traits of marine fish and environmental variables is also presented. The hypothesis is that fish with smaller body size and lower trophic levels dominate in the warmer waters (low latitudes, shallow depths), and less occur in the cooler waters (high latitudes, deep depths).

In chapter 2, I found that diversity of species was higher in the warmer water (tropics and subtropics and shallow depths). In chapter 3, I found that species richness is positively correlated with higher taxonomic richness. That is, the higher taxonomic levels were more diverse in the warmer water. Hence, in this chapter, I hypothesis that diversity of fish's body sizes and trophic levels are higher in the warmer water.

4.2. Methods

4.2.1. Data

The geographic distribution ranges, including latitude and depth, of 5619 fish species were obtained from AquaMaps (Kaschner et al., 2019) and represent about one-third of all marine fish species (Froese & Pauly, 2019). AquaMaps models field observations with environmental variables to predict the environmental niche and thus geographic ranges of species (Kaschner et al., 2019). A species will only occur within its range where local environmental and ecological conditions are suitable, and its abundance will vary within its range in space and time. Thus, a species may not occur everywhere within its mapped range, and if its range changes over time, such as due to climate change, it may no longer occur within part of its mapped range. To prevent a species range extending into areas that are environmentally suitable but where it does not occur for evolutionary reasons (e.g., in a different ocean), AquaMaps limits species ranges to their known occurrence in FAO regions. The probability threshold of 0.0 was used in this study as a conservative approach to ensure some species occurrences in most geographic cells (Chapter 2).

Two functional traits, maximum body size (cm) and trophic level, were collected from FishBase for each of the marine fish species (Froese & Pauly, 2019). Species of body size smaller than 30 cm (49% of species) and between 30 cm and 100 cm (40% of species) dominated this dataset. Only 11% of species had a body size larger than 100 cm in this dataset (Table 4.1, Appendices Figure A4.1). These body size groups were only used for the purpose of illustrating patterns and were not used in the calculation of means. As the number of species of all marine fish from FishBase (n = 15195) in these size categories was 62%, 32% and 6% respectively, data used in this thesis were more inclusive of larger fish species (Appendices Table A4.1).

The trophic level index is < 2.20 for herbivores and detritivores; 2.20 – 2.80 for omnivores with a preference for vegetable matter but also feeding on other prey (e.g., sponges, isopods, amphipods.) (low-trophic-level omnivores); 2.81 – 3.70 for omnivores with a preference for animals but feeding on diverse prey (e.g., algae, bivalves, isopods, fish larvae) (high-trophic-level omnivores); and > 3.70 for piscivores and carnivores with a preference for large decapods, cephalopods and fish (carnivores) (Stergiou & Karpouzi, 2002; Froese & Pauly, 2019). The proportions of the four trophic levels of all marine fish from FishBase (3%, 4%, 67%, 26%) were very similar to those in AquaMaps (4%, 5%, 58%, 33%), and thus the dataset used in this study is representative of trophic levels of all marine fish species (Appendices Table A4.1).

Table 4.1. Number of species in the three body sizes and four trophic levels in the depth zones.

	Depth zone			
Fish group	**Whole water column**	**0 – 200 m**	**201 – 1000 m**	**1001 – 6000 m**
All fish	5619	4102	1184	333
Body size				
< 30 cm	2743	2066	523	154
30 - 100 cm	2260	1618	497	145
> 100 cm	616	418	164	34
Trophic level				
Herbivores and detritivores	242	241	1	0
Low-trophic-level omnivores	286	283	3	0
High-trophic-level omnivores	3234	2374	649	211
Carnivores	1857	1204	531	122

4.2.2. Data analysis

The mean and standard error of body size and trophic level for all fish was calculated in 5° latitude bands between 75°S and 75°N and four depth zones: whole water column, surface (0 – 200 m), middle (201 – 1000 m), and deep (1001 – 6000 m); reflecting the photic, mesophotic and aphotic zones of light penetration (Costello & Breyer, 2017). This study also calculated the mean and standard error of body size and trophic level for all fish in 100 m depth bands from 0 m to 3500 m. Numbers of species, means and standard errors for traits groups in latitude and depth bands are shown as Appendices Table A4.2 – A4.8.

The mean body size and trophic level were correlated with the long-term averages of monthly salinity (practical salinity unit, psu), and sea surface and bottom temperature (SST, SBT, °C) and dissolved oxygen (SDO, BDO, ml/l) in 5-degree latitude bands. The environmental variables were obtained from Global Marine Environmental Datasets (Basher & Costello, 2020). Raster data of environmental variables were calculated as the mean value in every 5-degree latitude band between 75°S and 70°N. Generalised Additive Models (GAM) (Hastie & Tibshirani, 1990) were used to assess the relationship between latitudinal mean body size, trophic level, and environmental variables in the same 5-degree latitude bands. A GAM is a nonparametric regression method that uses smooth functions of the predictors. Also, a GAM is flexible regarding the assumptions concerning the underlying statistical distribution of the data (Swartzman et al., 1995). The package “mgcv” (Wood, 2011) in R (R core team, 2018) was used for the GAM analysis. A GAM with Gaussian error distribution and identical link function was used for modelling. Smoothness selection(s) of thin plate regression splines was used for the model fitting process. The model was as follows:

Body size or Trophic level ~ s(Environmental variable)

Standard diagnostics including Quantile-Quantile (Q-Q) plot, minimised Generalised Cross-Validation (GCV) scores, maximised deviance explained and maximised adjusted r^2, were used to assess distributional and smoothing assumptions (Wood, 2006) (Appendices: GAM-Chapter 4). The deviance explained, adjusted r^2, and GCV scores were recorded. The relationships of mean body size and mean trophic level to each environmental variable were plotted.

4.3. Results

4.3.1. Latitudinal gradients

4.3.1.1. Whole water column

Mean maximum body size of fish species was lower in the Southern Ocean, tropics and subtropics (30°S and 30°N) (Figure 4.1). Thus, there were relatively more large fish species in the temperate latitudes and Arctic, with the highest values at 50°S and 70°N (Figure 4.1).

High-trophic-level omnivores and carnivores occurred across all latitudes (Figure 4.2a). In contrast, herbivores and detritivores and low-trophic-level omnivores were absent in both poles, except for a few low-trophic-level omnivores distributed in the Arctic Ocean (Figure 4.2a). Therefore, the mean trophic level and the difference from the mean trophic level of all fish were lower in the tropics and subtropics (30°S and 30°N) and the Southern Ocean (Figure 4.2).

Overall, I found that the diversity of body sizes and trophic levels was highest in the tropics and subtropics (between 30°S and 30°N), but the mean body sizes and trophic levels in this area were smaller and lower (Figures 4.1 & 4.2). This is because there were more small, herbivorous and detritivorous fish species between 30°S and 30°N (Figures 4.1 & 4.2).

4.3.1.2. In the depth zones

The distribution of body size and trophic groups in the surface zone were similar to the pattern described in the whole water column because over 73% of marine fish occurred in < 200m depth (Figures 4.3 & 4.4). Compared to this near surface depth zone, fish were generally larger in the middle zone, and below average size in the deepest zone (Figure 4.3). However, in all depth zones, the fish of the Southern Ocean were below average in body size and trophic level (Figures 4.3 & 4.4). In contrast, Arctic fish were above average in body size and trophic level in all depth zones (Figures 4.3 & 4.4).

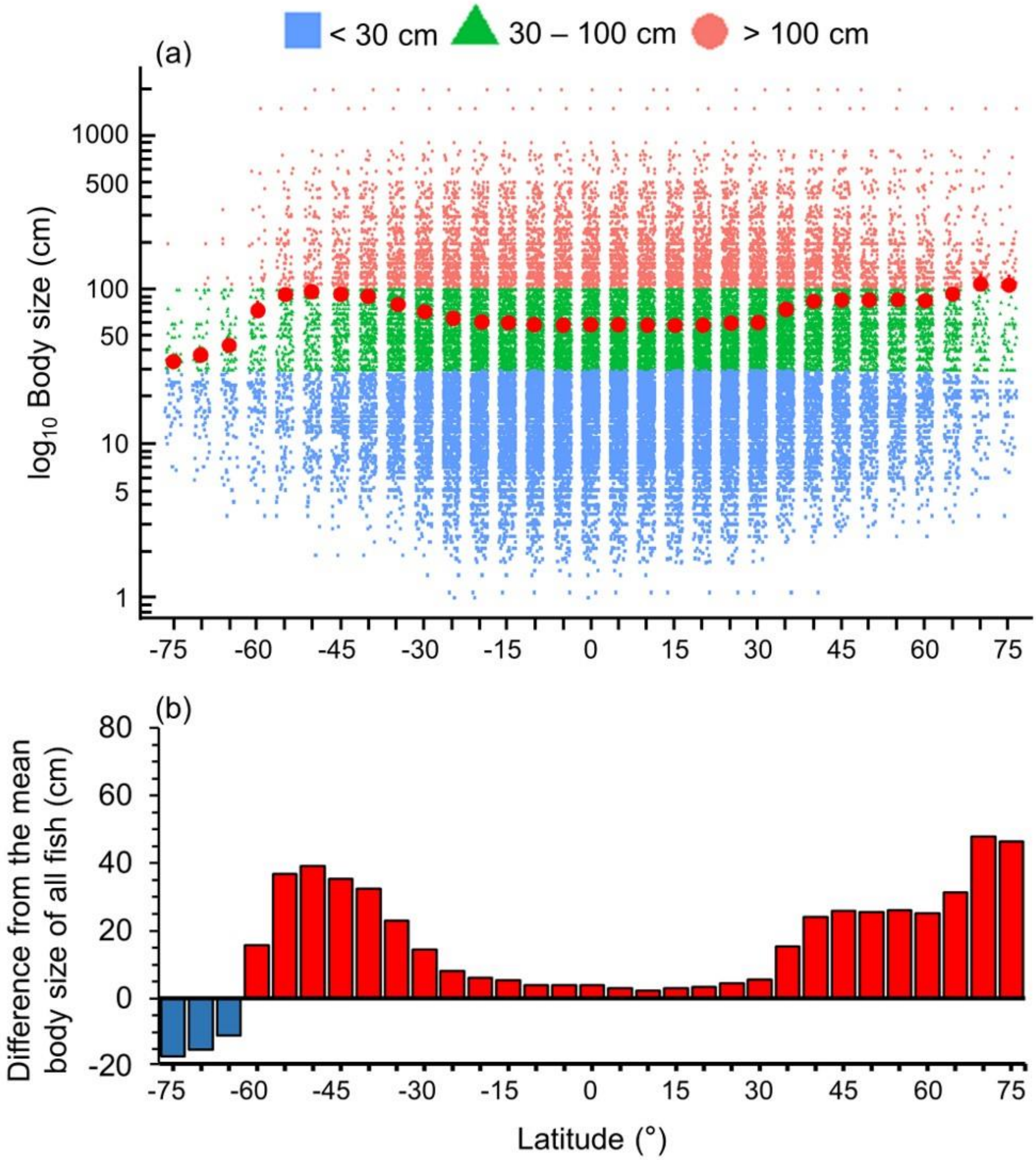


Figure 4.1. Gradients of (a) mean body size (red dot), standard error (red bar), and dot-plot of $\log_{10}$ maximum body size for < 30 cm (blue squares), 30 – 100 cm (green triangles), and > 100 cm (orange circles), and (b) difference from the mean body size of all fish in this dataset (50.7 cm) in 5-degree latitude bands in the whole water column. Each dot indicates one species.

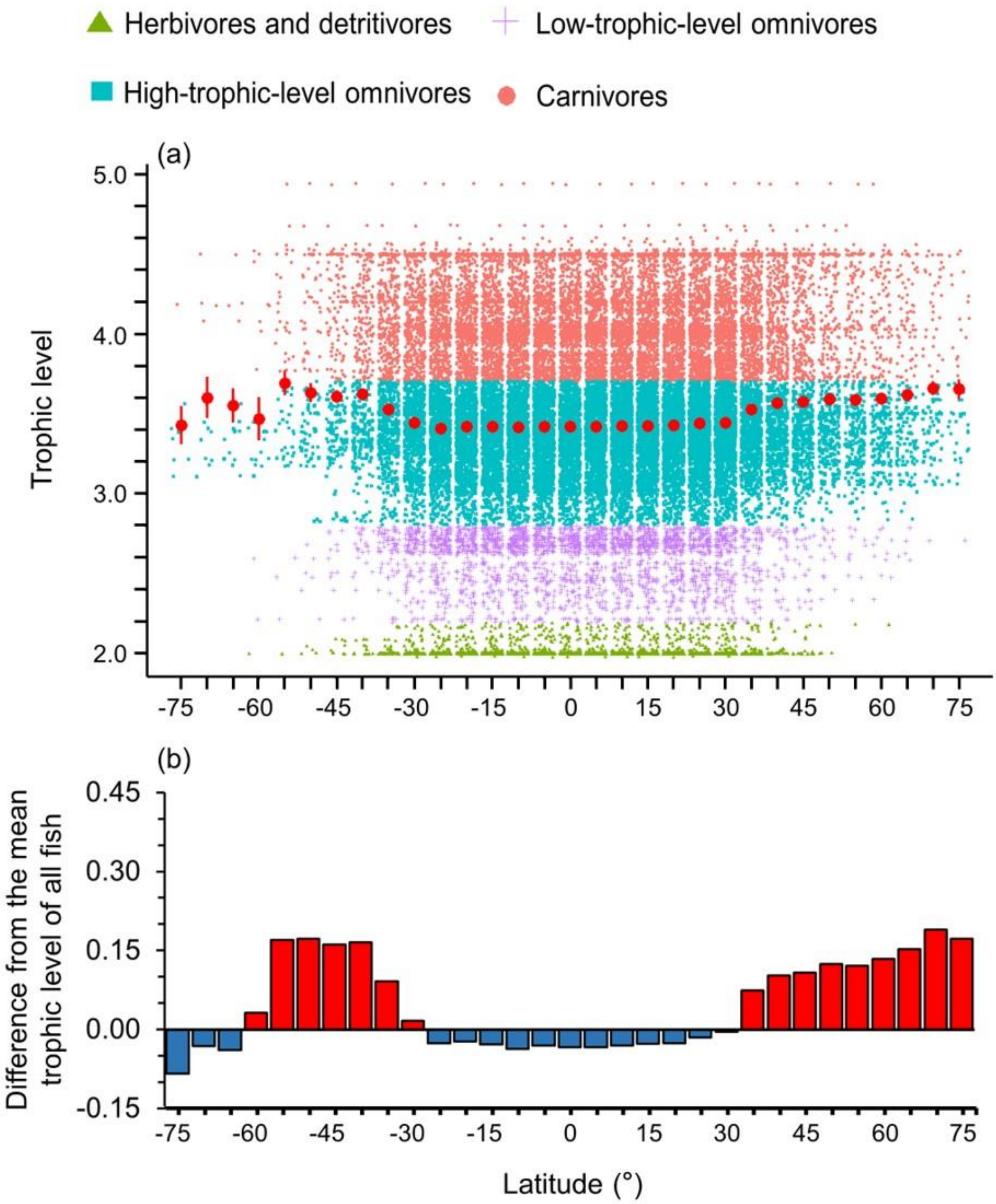


Figure 4.2. Gradients of (a) mean trophic level (red dot), standard error (red bar), and dot-plot of trophic levels among herbivores and detritivores (green triangles), low-trophic-level omnivores (purple cross), high-trophic-level omnivores (teal squares), and carnivores (red circle), and (b) difference from the mean trophic level of all fish in this dataset (3.50) in 5-degree latitude bands in the whole water column. Each dot indicates one species.

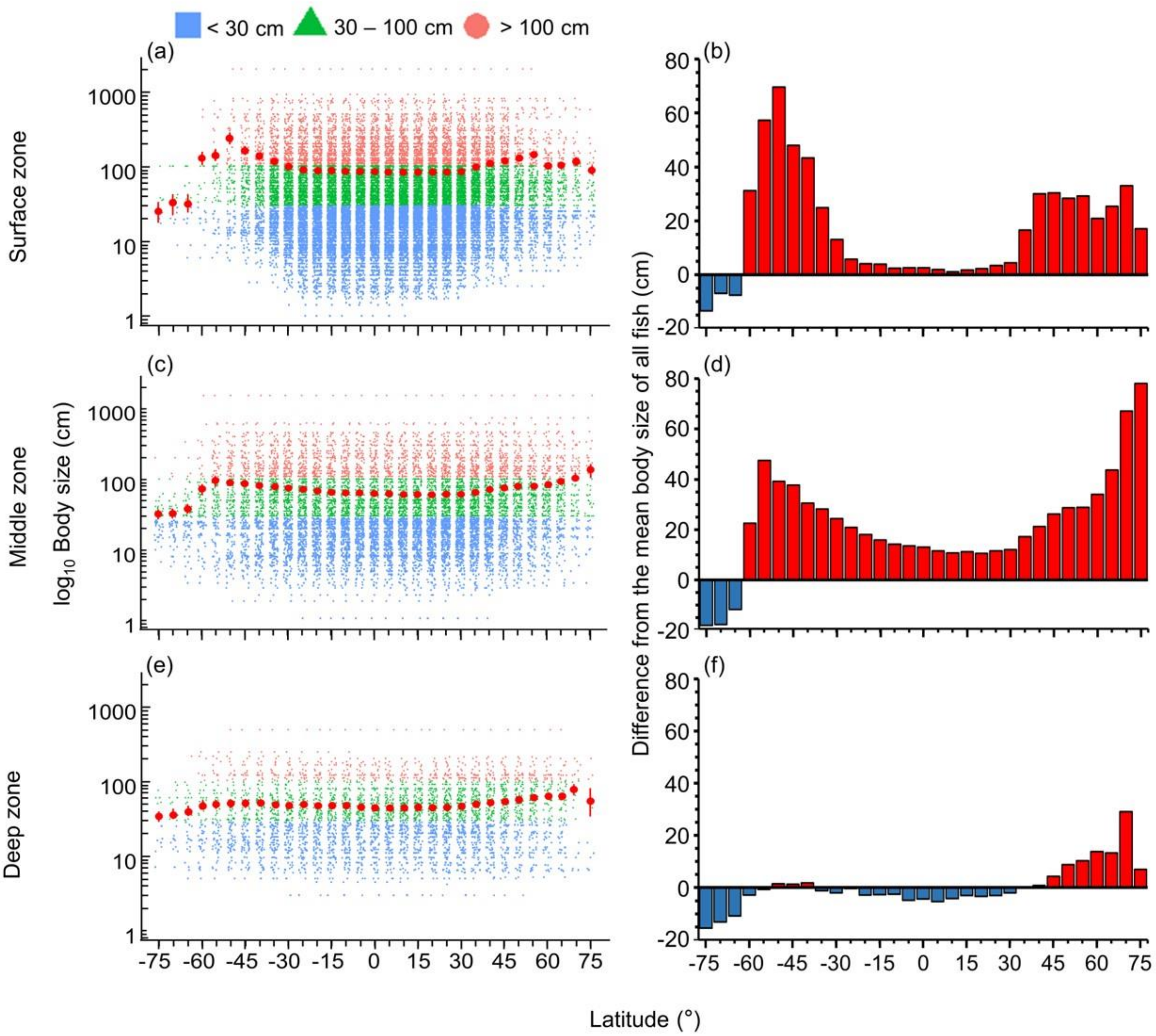


Figure 4.3. Gradients of (a, c, and e) mean body size (red dot), standard error (red bar), and dot-plot of $\log_{10}$ maximum body size for < 30 cm (blue squares), 30 – 100 cm (green triangles), and > 100 cm (orange circles), and (b, d, and f) difference from the mean body size of all fish in this dataset (50.7 cm) in 5-degree latitude bands in the surface (0 – 200 m), middle (201 – 1000 m), and deep (1001 – 6000 m) zone. Each dot indicates one species.

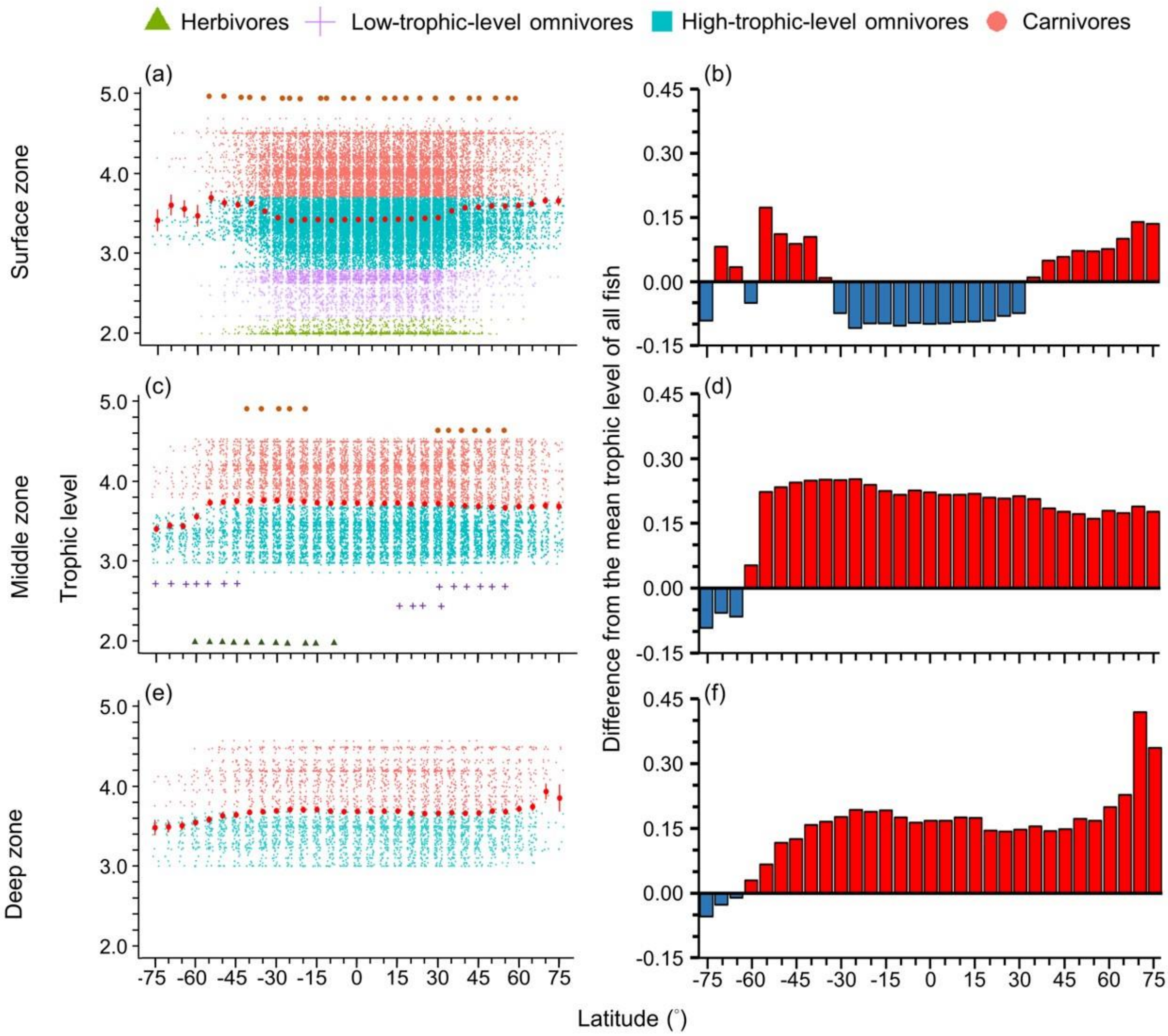


Figure 4.4. Gradients of (a, c, and e) mean trophic level (red dot), standard error (red bar), and dot-plot of trophic level among herbivores and detritivores (green triangles), low-trophic-level omnivores (purple cross), high-trophic-level omnivores (teal squares), and carnivores (orange circle), and (b, d, and f) difference from the mean trophic level of all fish in this dataset (3.50) in 5-degree latitude bands in the surface (0 – 200 m), middle (201 – 1000 m), and deep (1001 – 6000 m) zone. Each dot indicates one species.

4.3.2. Across 100 m depth bands

Mean maximum body size of marine fish decreased with depth, and fish species were below average size when water depth > 1200 m (Figure 4.5). However, the smallest and largest fish species occurred near the sea surface (< 100 m), and they did not exist in the water depth > 500 m and > 900 m, respectively (Figure 4.5a). Thus, with greater depth, fish’s body sizes converged closer to the average size (Figure 4.5a).

The ranges of almost all, 99% of herbivores and detritivores, and 98% of low-trophic-level omnivores, were in the surface zone (Figure 4.6a). Only one species of herbivore and detritivore and three species of low-trophic-level omnivores could be found between 101 m and 600 m (Figure 4.6a). Deeper than 200 m, trophic level decreased with depth and the standard errors got wider (Figure 4.6).

There were several subtle change points in depth trends of species’ maximum body size and trophic level at 100 m, 500 m, 1400 m, 2300 m, and 3000 m, respectively (Figures 4.5b & 4.6b). These changes in fish’s body size and trophic level may be because the distinct fish assemblages exist in different depths.

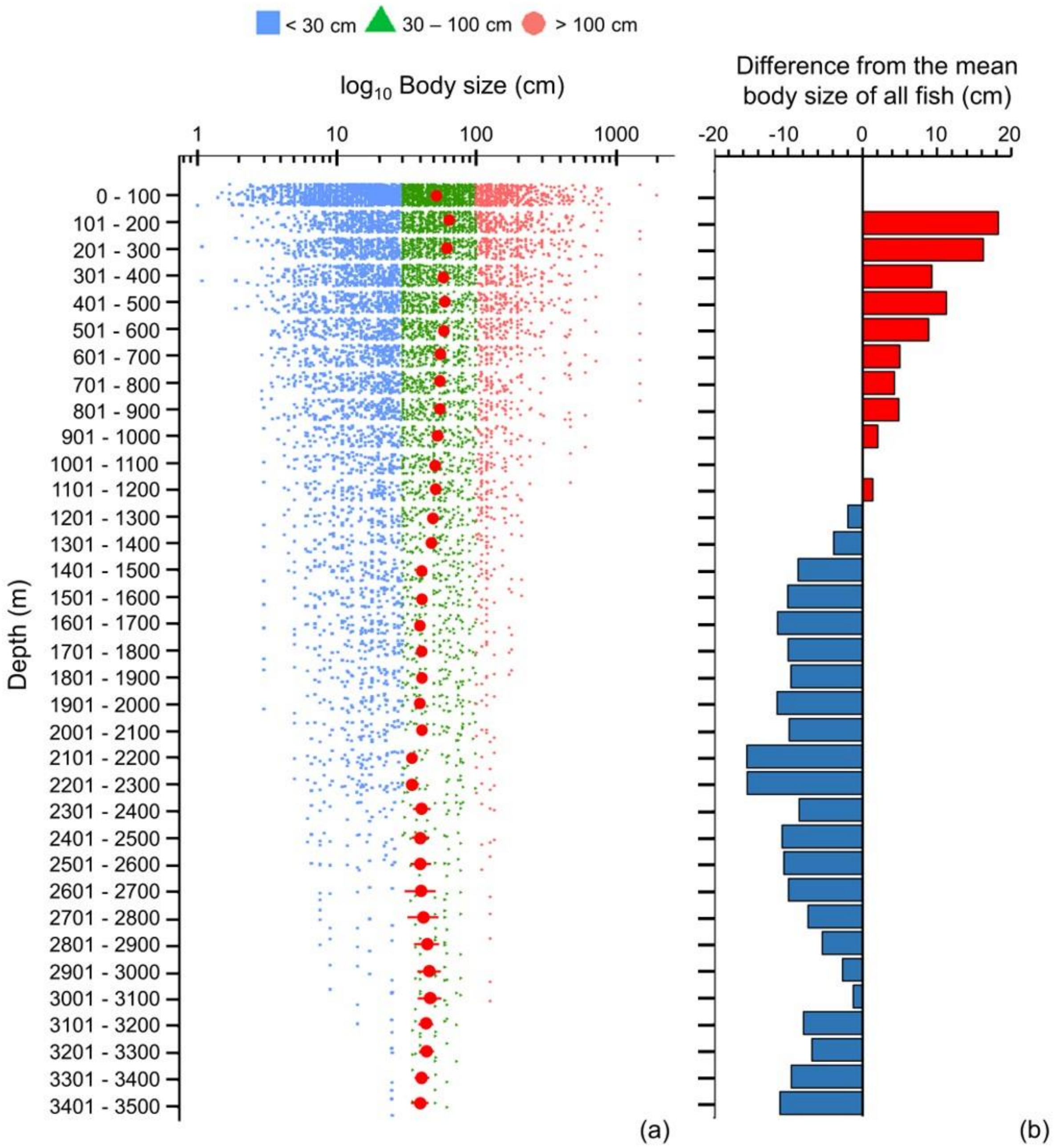


Figure 4.5. Gradients of (a) mean body size (red dot), standard error (red bar), and dot-plot of $\log_{10}$ maximum body size for < 30 cm (blue squares), 30 – 100 cm (green triangles), and > 100 cm (orange circles), and (b) difference from the mean body size (50.7 cm) of all fish in this dataset along 100 m depth bands. Each dot indicates one species.

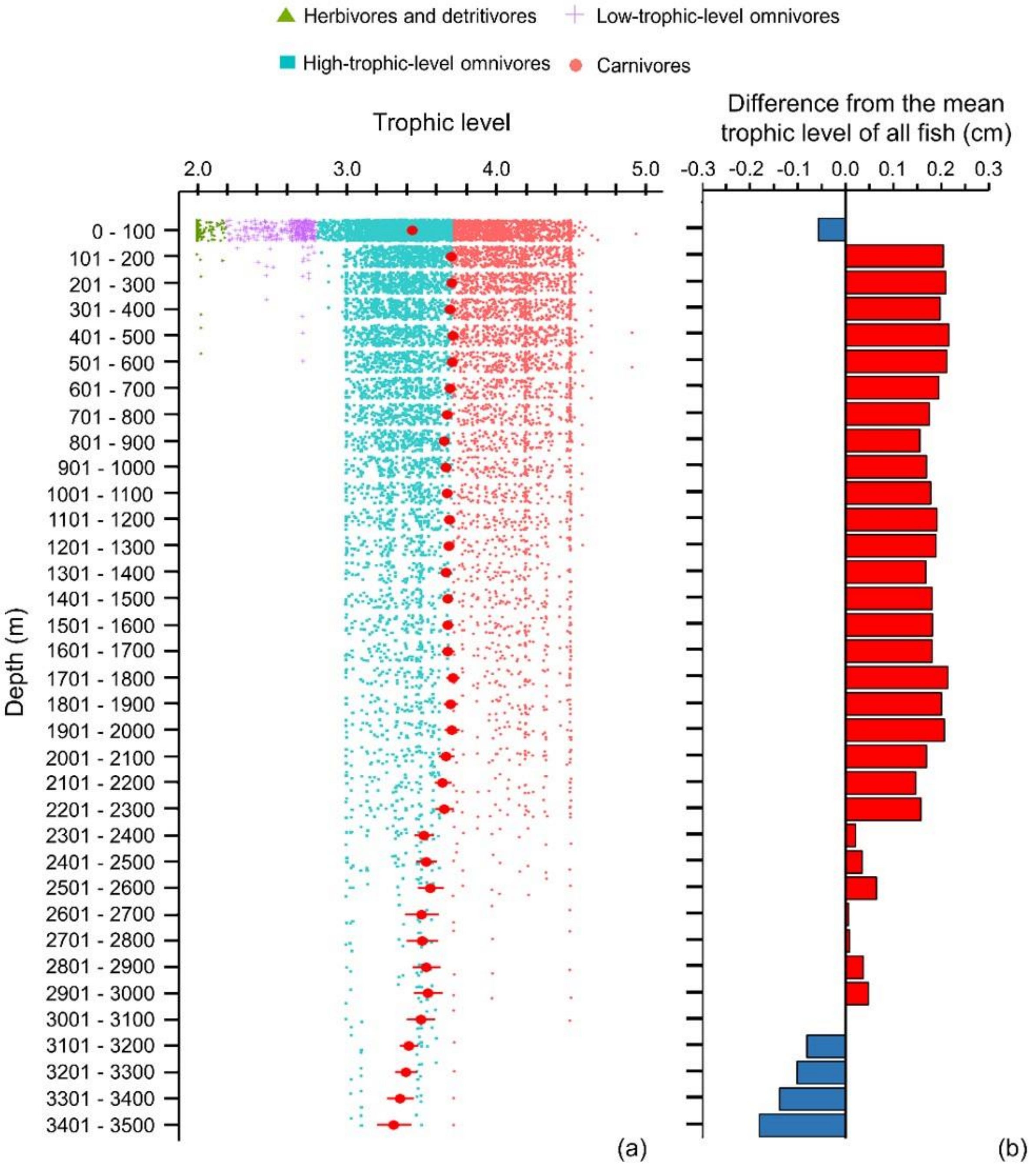


Figure 4.6. Gradients of (a) mean trophic level (red dot), standard error (red bar), and dot-plot of trophic level among herbivores and detritivores (green triangles), low-trophic-level omnivores (purple cross), high-trophic-level omnivores (teal squares), and carnivores (orange circle), and (b) difference from the mean trophic level of all fish in this dataset (3.50) along 100 m depth bands. Each dot indicates one species.

4.3.3. Environmental relationships

4.3.3.1. Environmental gradients

Mean sea surface temperature (SST) declined from the tropics to the poles at 10°N and 5°S (Figure 4.7a). The narrower SST range near the equator and in the Southern Ocean indicated the more stable temperatures (Figure 4.7a).

The latitudinal gradient of mean sea bottom temperature (SBT) was similar to SST, but mean SBT was less than 6°C in all latitudes because of the dominating effect of the large area of deep sea in each latitude. SBT ranges were widest in the tropics to subtropics, and narrower at high latitudes because SBT varied more from shallow to deep sea in the tropical areas (Figure 4.7b).

Mean sea surface dissolved oxygen (SDO) decreased from the poles to the tropics (Figure 4.7c), being lowest between 25°N and 25°S. The range of SDO was widest in the Arctic Ocean (Figure 4.7c).

Mean sea bottom dissolved oxygen (BDO) was lowest at 10°N, then increased with southern and northern latitudes. The range of BDO was wide in every latitude, especially in the northern temperate and Arctic Ocean (Figure 4.7d).

Mean sea surface salinity varied between 28 PSU to 35 PSU with latitude, which is within the tolerance of marine organisms (Figure 4.7e). However, mean sea surface salinity was lower and more variable north of 40° N (Figure 4.7e). Thus, all variables studied here, SST, SBT, SDO, BDO and salinity, were more several times more variable in the Arctic than Antarctic seas (Figure 4.7).

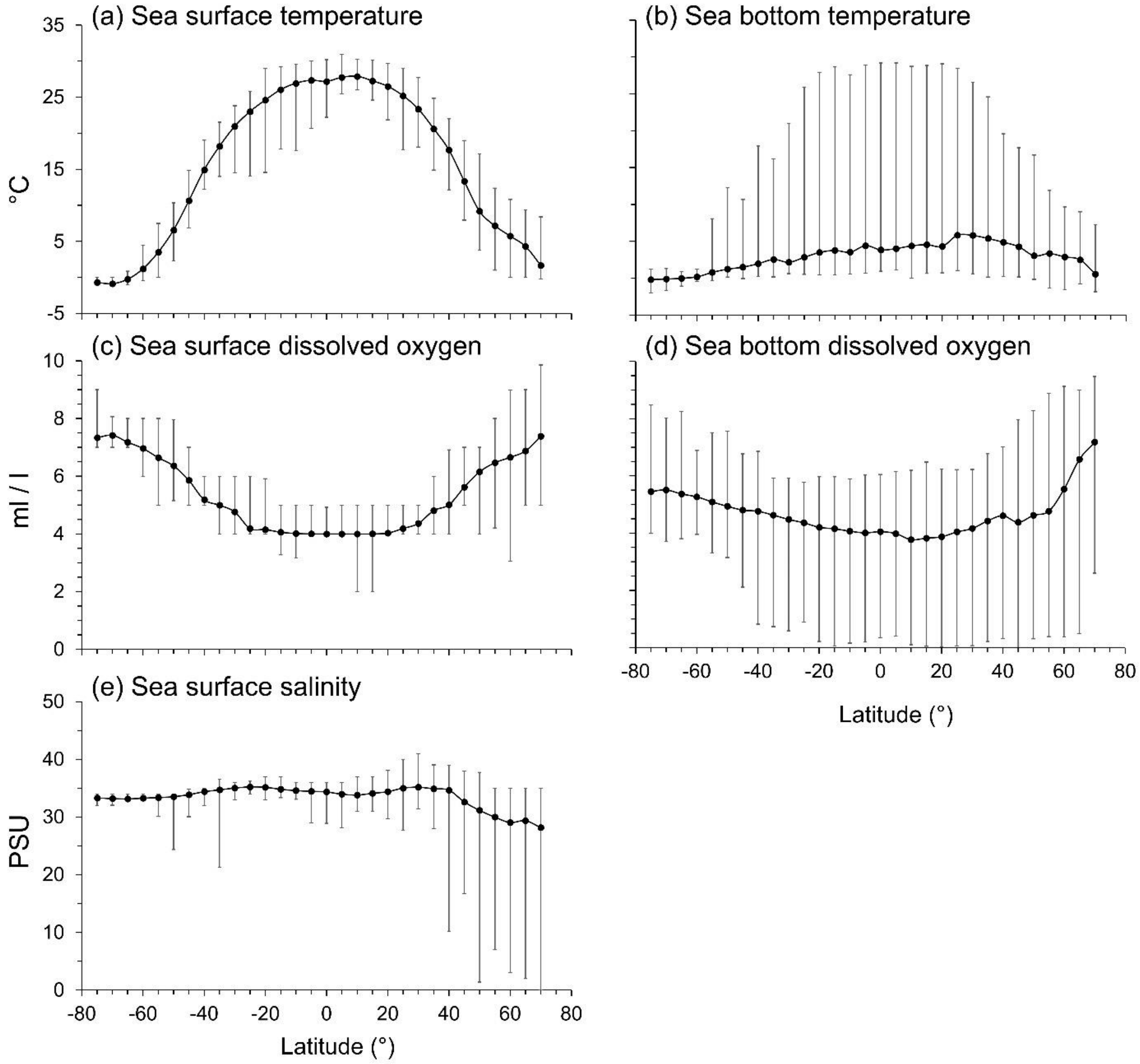


Figure 4.7. The latitudinal gradients of means (solid circle), maxima (top lines), and minima (bottom lines) of (a) sea surface temperature (°C), (b) sea bottom temperature (°C), (c) sea surface dissolved oxygen (ml/l), (d) sea bottom dissolved oxygen (ml/l), and (e) sea surface salinity (practical salinity unit, PSU).

4.3.3.2. Correlations

All environmental variables were significantly correlated with gradients in maximum body size and trophic level (Table 4.2). Mean SST was the primary factor that influenced the latitudinal gradients of both mean body size and trophic level (Table 4.2). Fish with smaller body size and lower trophic levels were in the tropical latitudes with mean SST > 25°C (Figures 4.8a, f). Similarly, mean body size and mean trophic level decreased with warmer mean SBT (Figures 4.8d, i).

When mean SDO was at 6 ml/l and mean BDO was at 5 ml/l, mean maximum body size of marine fish was largest (Figures 4.8b, e). As with body size, mean trophic levels increased in the latitudes with higher mean SDO and mean BDO. When mean SDO was at 6.5 ml/l and BDO was at 5 ml/l, mean trophic levels was highest (Figures 4.8g, j).

Mean sea surface salinity was the least influential factor compared to temperature and dissolved oxygen. Most species, regardless of body size and trophic level, were living in salinities between 33 PSU and 35 PSU. Only a few species with larger body size and higher trophic level live in lower salinity water (Figures 4.8c, h).

Together, these results suggest that temperature may be the primary and DO a secondary factor to influence the distribution of body size and trophic level of marine fish.

Table 4.2. Generalised Additive Model results for the latitudinal gradients of mean body size and trophic level of all fish against five environmental variables, ranked by deviance explained. * P-value < 0.05, ** P-value < 0.01, *** P-value < 0.001.

Environmental variable	Adjusted r^2	Deviance explained (%)	Generalised cross-validation score	Degrees of freedom	*P*-value
Body size					
Sea surface temperature	0.88	91	46.71	7.86	***
Sea bottom temperature	0.74	80	94.77	6.71	***
Sea bottom dissolved oxygen	0.72	80	104.76	7.84	***
Sea surface dissolved oxygen	0.45	50	165.93	2.60	***
Sea surface salinity	0.19	22	230.22	1.00	**
Trophic level					
Sea surface temperature	0.76	79	0.002	4.07	***
Sea bottom dissolved oxygen	0.69	75	0.003	5.69	***
Sea surface dissolved oxygen	0.70	73	0.002	2.48	***
Sea bottom temperature	0.36	45	0.006	4.18	*
Sea surface salinity	0.36	39	0.005	1.39	**

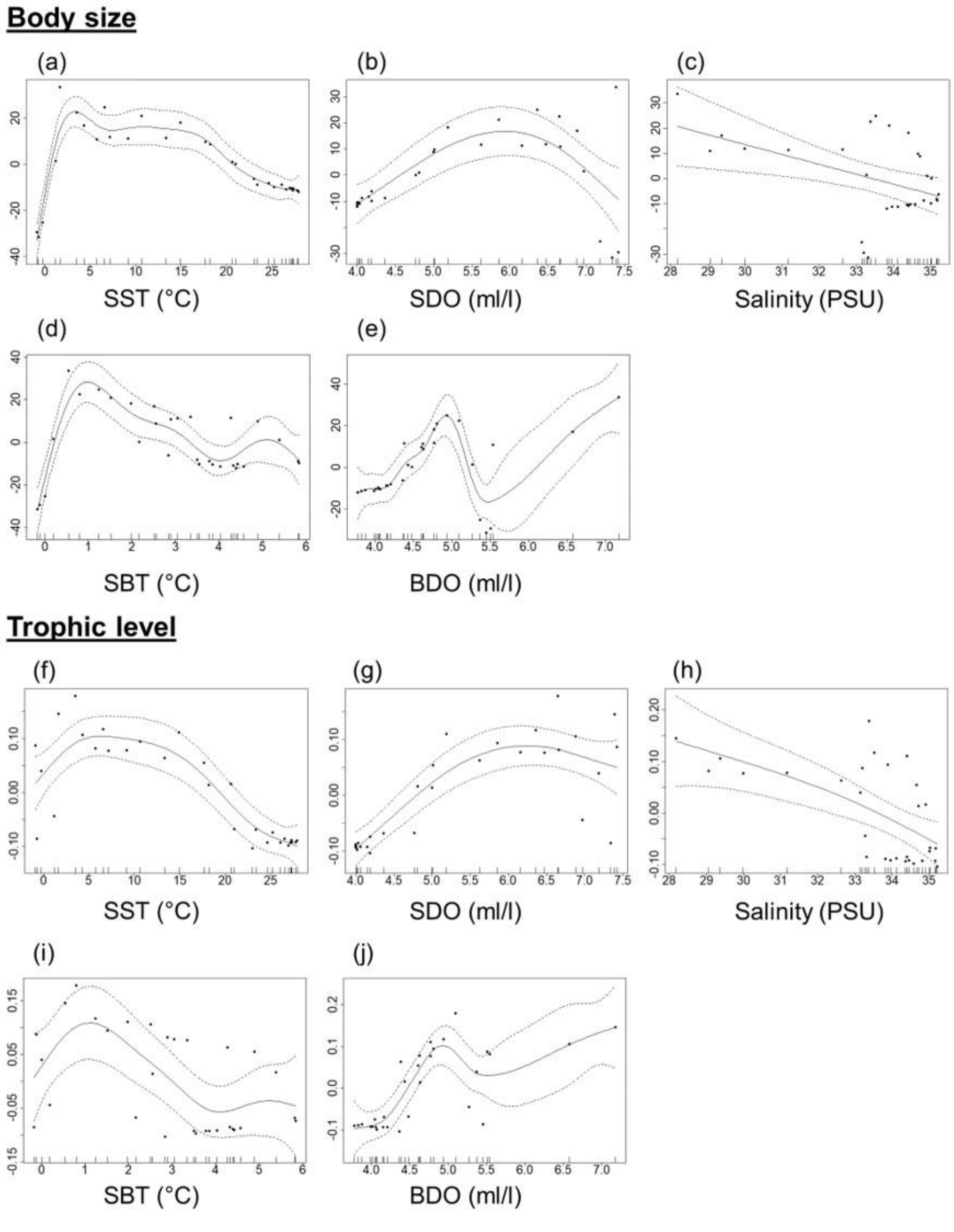


Figure 4.8. The smoothed GAM (solid lines) for (a – e) mean body size and (f – j) mean trophic level of all fish against sea surface temperature (SST), dissolved oxygen (SDO), salinity, and sea bottom temperature (SBT) and dissolved oxygen (BDO) in 5-degree latitude bands. The dashed lines indicate the 95% confidence intervals. The black dots and tick marks on the x-axis are observed data points. The y-axis represents the spline function. PSU is practical salinity units.

4.4. Discussion

4.4.1. Latitudinal gradients

4.4.1.1. Whole water column

In this study, I found that the diversity of marine fish's body size and trophic level were highest in the tropics and subtropics (between 30°S and 30°N) which support my initial hypothesis. This may be because the tropics and subtropics also have a high diversity of associated predator, prey and competitor richness and habitats (Costello et al., 2015; Costello & Chaudhary, 2017). The warm temperature in the tropics, results in shorter generation times, higher rates of metabolism, faster rates of mutation, and faster selection, which generate and maintain higher biodiversity (Rohde, 1992; Wright et al., 2011; Brown, 2014). In addition, the tropics and subtropics have higher habitat complexity, notably coral reefs which may contain 27% of marine fish species (Costello, 2015; Froese & Pauly, 2019), that provide more ecological niches leading to higher species diversity (Rocha et al., 2005; Grosberg et al., 2012; Kovalenko et al., 2012), and thus leading to higher traits diversity. Also, the long-term climatic stability in the tropics allowed more time for speciation and lower extinction rates (Pellissier et al., 2014; Leprieur et al., 2016; Miller et al., 2018). Together these reasons allow species and trait diversity to originate and accumulate in the tropics and subtropics.

The absence of herbivores outside the tropics and subtropics supports the TCH that posits that the efficiency of digestion for plant materials is compromised in cooler environments (Gaines & Lubchenco, 1982).

4.4.1.2. In the depth zones

In the surface zone, the latitudinal mean body size and mean trophic level of marine fish were all lower in the tropics and subtropics but higher in the high latitudes except for the Southern Ocean. In contrast, neither varied significantly with latitude in the deep zone (Figures 4.3 & 4.4). This was because there were more small (< 30 cm) and low trophic level (< 2.80) fish species in the tropics and subtropics than in high latitudes and deep sea. Also, the diversity of fish's body size and trophic level was similar across latitudes in the deep sea. These results support the initial expectation that latitudinal gradients of traits changed with latitude in the shallow depth zone but not in the deep sea because the deep sea has a consistent environment of no light, low temperature, and low dissolved oxygen across latitudes (Costello & Breyer, 2017; Sayre et al., 2017; Basher & Costello, 2020).

4.4.2. Across 100 m depth bands

The initial expectation was that marine fish's body size will be larger and the trophic level will be higher in the deep sea because the temperature is lower in the deep than shallow depths and food supply largely dependent on secondary production in shallower waters. However, the results showed that deeper than 200 m, mean body size decreased and mean trophic level stayed at near 3.70 to 2300 m depth, and then decreased deeper than 2300 m. Thus, the depth gradient of mean body size did not follow the temperature-size rule (TSR) but did follow the gill-oxygen limitation theory (GOLT) because the dissolved oxygen decreased with depth (Costello, Basher, et al., 2018).

Fewer than 40 species in this dataset occur deeper than 2300 m, and most of them were high-trophic-level omnivores, with less than 10 of these species being carnivorous (Figure 4.6). Without photosynthesis, deep-sea species mostly rely on detritus from the surface waters (known as marine snow), consisting of dead or dying animals and phytoplankton and faecal matter produced by zooplankton, as their primary source of food (Higgs et al., 2014). Only 5% of food can fall into the bathypelagic zone, so bathypelagic fish prey on anything that comes their way (Ryan, 2006). Thus, fish assemblages in the deep sea have a more similar environmental and dietary niche than those in shallower depths.

Although the primary trend for mean body size decreased with depth and mean trophic level stayed stable at 3.70 untill 2300 m, there were some depths where values rose or fell. These depths were at 100 m, 500 m, 1400 m, 2300 m, and 3000 m, respectively (Figures 4.5b & 4.6b), and they fit the points of turnover in species assemblages from clustering analysis in Chapter 3. Thus, these changes reflect the modelled depth zonation of fish species assemblages with different ranges of body size and trophic level.

4.4.3. Environmental relationships

The GAM results showed that marine fish's body size and trophic level were smaller and lower in the warmer and low DO latitudes (tropics and subtropics) but larger and higher in the cooler and high DO latitudes (temperate areas and Arctic Ocean but the Southern Ocean). These results may support hypotheses of temperature-size rule, gill-oxygen limitation theory, and temperature constraint hypotheses. As warmer temperature decreases aerobic capacity, fish with larger body size may be limited by oxygen supply (Pauly, 2010), and thus there are more small fish in the warmer latitudes. Also, body size has a positive relationship with trophic level, so small fish usually have a lower trophic level because of the limitation of gape size (Romanuk et al., 2011), and this relationship is more significant when excluding the lower trophic level fish because some species are large (Keppeler et al., 2020). For most vertebrate ectotherms, the metabolic rate and gut passage rate increases with raised temperature (Zachariassen et al., 1989; Zimmerman & Tracy, 1989; Horn & Gibson, 1990; Van Marken Lichtenbelt et al., 1997; Gillooly et al., 2001). However, the gut passage rate decreases more rapidly than metabolic rate when temperature declines, so herbivorous fish may not be able to digest enough food material to meet their metabolic demands at cooler temperatures (Floeter et al., 2005). Except for the physical variables, biogenic habitats may also provide niches for more fish species in the tropics, notably coral reefs which harbour about 27% of all fish species (Costello, 2015).

Both the Arctic and Antarctic are polar environments with near freezing temperatures but high DO (Figure 4.7), and relatively low species richness compared to other latitudes (Chapter 2; Lin et al., 2021). However, the environmental result show the Arctic has far more variable environmental conditions than the Antarctic (Figure 4.7). The biogeography of their fish fauna also contrasts. The fish fauna in the Arctic Ocean is an extension of that of boreal and temperate regions (Loeng et al., 2005) because of the active northward colonization from the Atlantic and Pacific over the last 6000 – 14000 years (Dayton et al., 1994; Eastman, 1997). Of the Arctic fauna, 58% of species comprise six groups of fish, zoarcoids, gadiformes, cottids, salmonids, pleuronectiforms, and chondrichthyans (Eastman, 1997), and only around 20% the fish are endemic species (Eastman, 1997; Reshetnikov, 2004; Mecklenburg et al., 2011). In contrast, Antarctica is isolated by the Antarctic Circumpolar Current and deep-sea. 88% of Antarctic fish (Eastman, 1997; McGonigal & Woodworth, 2003; Duhamel et al., 2014), and over 45% of all Antarctic marine taxa (Costello, Coll, et al., 2010) are endemic. Five fish groups, namely notothenioids, myctophids, lipids, zoarcids, and gadiforms, account for 74% of the Antarctic fish fauna, while notothenioids comprise 35% (Eastman, 1997). Therefore, the Antarctic fish fauna has a closer phylogenetic relationship than that of the Arctic (Chapter 3). The Antarctic ecosystem also has a simpler food web compared to other latitudes (Richardson, 1975; Targett, 1981; La Mesa et al., 2004; Hill et al., 2006). However, these differences in phylo-biogeography do not necessarily explain the smaller body size and lower trophic level of Antarctic than Arctic fish fauna (Figures 4.1 – 4.4). Here, I suggest that these differences are due to the greater spatial environmental heterogeneity in the Arctic providing more niches for larger and higher trophic level species than available in the more homogenous seas around Antarctica.

4.5. Conclusion

This study found that mean body sizes and mean trophic levels of marine fish were less in the tropics and subtropics, between 30°S and 30°N, than high latitudes, and less in the deep sea and Antarctica. The flatter latitudinal gradients of these traits in the deep sea reflect its more homogenous environment. While mean body size generally increases at colder temperatures, the reverse was the case with depth. Body size and trophic level decreased with depth not because of temperature, but because of the low dissolved oxygen and scarce food source in the deep sea. Thus, in the surface zone, the latitudinal gradients of marine fish's body size and trophic level support the temperature-size rule, gill-oxygen limitation theory (GOLT) and temperature constraint hypothesis. However, the depth gradient of marine fish's body size only supports GOLT. Therefore, in the surface zone, temperature is the primary and dissolved oxygen is the second factor influencing the biogeography of marine fish's body size and trophic level, whereas oxygen and food supply limit these traits in the deep sea and Antarctic species.

Chapter 5

General Discussion

Chapter 5: General discussion

In this thesis, I employed modelled range data of 5619 marine fish to show the gradients of richness of five taxonomic levels, higher taxonomic richness (STL), phylogenetic relationships (AvPD and STL/spp), functional traits of mean body sizes and trophic levels across latitudes and depths at a global scale. Also, I used the GAMs to understand the relationships of species richness, phylogenetic indices, functional traits, and environment variables. Finally, from these results, I tested whether these gradients supported the species-energy hypothesis, out-of-the-tropics hypothesis (OTT), temperature-size rule (TSR), gill-oxygen limitation theory (GOLT), and temperature constraint hypothesis (TCH).

5.1. Primary importance of temperature

For species richness, the bimodal LDGs presented in this thesis were similar to those of previous studies using point species occurrence data, and species richness was higher in the subtropics with a dip at or near the equator (Lucifora et al., 2011; Chaudhary et al., 2016; Menegotto & Rangel, 2018). The LDGs in some other studies had wider peaks and a greater equatorial dip because they used reported occurrences and thus would have accounted for spatial gaps in some species ranges, such as at the equator (Graham & Hijmans, 2006; Kaschner et al., 2006; Kaschner et al., 2019). That both point and modelled range data show a bimodal gradient with a dip at the equator, reinforces that the pattern is not an artefact of sampling bias.

The reults in this thesis suggest that the LDGs of species richness and higher taxonomic richness (STL) were all higher in the subtropics with a dip near the equator because the temperature is too high for some species. In Chapter 2, the GAMs found that species richness decreased when the mean latitudinal sea surface temperature was greater than 25°C. Therefore, some tropical species may not be able to tolerate the increasing temperature at the equator, and thus move into subtropical latitudes due to climate change (Garciá Molinos et al., 2016; Chaudhary, 2019; Yasuhara et al., 2020; Chaudhary et al., 2021). The same bimodal LDGs in the higher taxonomic richness showed that species from the same genus and species from different higher taxonomic levels all escaped the warmer equator. The peak of richness increasingly shifted poleward with higher taxonomic levels: from 25°N for species to 48°N for classes in the northern hemisphere, and from 10°S for genera to 35°S for classes in the southern hemisphere. These results may support the out-of-the-tropics hypothesis that suggests marine taxa originate in the tropics and expand to higher latitudes without losing their tropical presence (Jablonski et al., 2006) (Table 5.1). The tropics may be both a “cradle” and a “museum” of biodiversity (Chown & Gaston, 2000; Jablonski et al., 2006; Fine, 2015). While there were relatively more species than higher taxa in low latitudes, this may be because the tropical area had lower extinction rate, less influence of glaciations, and higher speciation rate on evolutionary time scales (Pellissier et al., 2014; Leprieur et al. 2016; Costello & Chaudhary, 2017; Miller et al., 2018), and those missing classes of species moved from the warming tropical area into temperate areas.

Although the equator's species richness was less than the subtropics, the species richness in the tropics across the equator still had 40% more species than high latitudes. Besides, over 60% of classes, orders, families, genera, and species lived in the warmer water depths (< 100 m). These results support the predictions of the species-energy hypothesis, which suggests that warmer temperatures increase the rates of metabolism and mutation, shorten the generation time due to increasing competition for resources, and can thus generate and maintain higher biodiversity (Rohde, 1992; Davies et al., 2004; Allen et al., 2006; Wright et al., 2006, 2011; Gillman et al., 2010; Brown, 2014) (Table 5.1, Figure 5.1). Warmer temperature also shortens planktonic larval duration time in the tropics (O'Connor et al., 2007), potentially resulting in lower spatial gene flow and may provide suitable conditions for higher diversification and speciation rates (O'Connor et al., 2007). The long-term climatic stability in the tropics has allowed more time for speciation and lower extinction rates (Pellissier et al., 2014; Leprieur et al., 2016; Miller et al., 2018). In addition, there is evidence of more intense ecological competition, and greater habitat diversity in the tropics (Costello & Chaudhary, 2017). Together these reasons allow species with closer phylogenetic relationships (lower AvPD and STL/spp) to originate and accumulate in the warmer environments (tropics, subtropics, shallow depths). In contrast, the cooler temperatures had the opposite mechanisms of warmer temperatures, with a high extirpation during the glacial period (Meseguer & Condamine, 2020; Yasuhara et al., 2020). Thus, there were fewer species with more distant phylogenetic relationships (higher AvPD and STL/spp) in the cooler environments (high latitudes, deep sea) (Figure 5.1).

Temperature also affected the latitudinal gradients of mean body sizes and mean trophic levels. In Chapter 4, the GAMs showed that fish, on average, with smaller body sizes and lower trophic levels were more common in the latitudes with mean SST > 25°C. In contrast, fish with larger body sizes and higher trophic levels were in the high latitudes. These results support the temperature-size rule (TSR), gill-oxygen limitation theory (GOLT), and temperature constraint hypothesis (TCH) (Table 5.1). The warming temperature reduced the oxygen solubility, thus an organism with relatively smaller gill to body size would be limited by the oxygen needed for maintaining its metabolic demands. In contrast, the cooler temperatures in high latitudes had higher oxygen solubility combined with lower energetic demands, thus an organism can have a larger body size (Pauly & Cheung, 2018) (Figure 5.1). That the results in this thesis showed smaller mean body sizes in the cold deep depths does not support the TSR but does support the GOLT because dissolved oxygen decreases with depth (Costello, Basher, et al., 2018). Most herbivorous and detritivorous, and low-trophic-level omnivorous fish were in the tropics and subtropics, and they were all absent in the polar areas and deep depths. Therefore, these results support the TCH that suggests the efficiency of digestion for plant materials is lower in cooler environments (Gaines & Lubchenco, 1982). The lower mean trophic levels in the depths > 2300 m may be because the food source is scarce. Those bathypelagic fish could only feed on anything that comes to them (Ryan, 2006). Thus, they may possess a similar niche and develop a similar low trophic position.

Overall, the analyses presented in this thesis showed that temperature is the primary factor influencing the gradients of taxonomic richness, phylogenetic relationships, body sizes and trophic levels of marine fish. Thus, it would be expected that different climatic zones have different fish compositions and the clustering results in Chapter 3 support this expectation. The clustering results suggested the turnover areas of species composition were at around 60°S, 40°S, 35°N, and 70°N in the surface and middle zones that approximate the boundaries of recognised climatic zones. The species assemblages in the deep sea did not fit climate zone boundaries, which is expected because the temperature is consistently low across latitudes (Costello & Breyer, 2017; Sayre et al., 2017; Basher & Costello, 2020). However, there were still distinct fish assemblages in the Arctic Ocean and the Southern Ocean because of their unique environment (Figure 3.11). The turnover depths for species composition separated at 500 m, closely followed by a shallower than 100 m, 101 – 500 m, 501 – 1400 m, 1401 – 2300 m, and deeper than 2301 m (Figure 3.12a). These results showed distinct assemblages of species at different depths, and implied that deeper sea species are not simply a subset of shallow assemblages. These distinct fish assemblages reflected the difference in phylogenetic relationship, mean body size, and mean trophic level over latitude and depth.

Table 5.1. Validation for whether the gradients in latitude and depth in this thesis support the hypotheses.

Hypothesis	References	Concept	Results in this study	Support	
				Latitude	Depth
Species-energy hypothesis	Rohde, 1992; Davies et al., 2004; Allen et al., 2006; Wright et al., 2006, 2011; Gillman et al., 2010; Brown, 2014	Warmer temperatures resulting in shorter generation times, higher metabolism rates, faster rates of mutation, and more rapid selection due to increasing competition for resources, can generate and maintain higher biodiversity.	Higher species richness was in the tropics and subtropics and shallow depths where sea temperature was warmer than high latitudes and deep sea.	Yes	Yes
Out-of-the-tropics hypothesis	Jablonski et al., 2006	Marine taxa originate in the tropics and expand to higher latitudes without losing their tropical presence	The peak shifted poleward with higher taxonomic level: from 25°N for species to 48°N for classes in the northern hemisphere, and from 10°S for genera to 35°S for classes.	Maybe	Not applicable
Temperature-size rule	Atkinson, 1994	Smaller size in the warm environment and a larger size in the cold environment	Mean body sizes were smaller in the tropics and subtropics where temperature was warmer and dissolved oxygen was lower than in high latitudes. Mean body size decreased with depth. Mean body sizes were smaller in the deep sea where the temperature and dissolved oxygen were low.	Yes	No
Gill-oxygen limitation theory	Pauly & Cheung, 2018	The ratio of gill surface area to body mass decreases when individuals grow. Therefore, an organism's body size is limited by the oxygen needed for maintaining its metabolic demands which is influenced by increased oxygen demand and decreased oxygen solubility at warmer temperatures		Yes	Yes
Temperature constraint hypothesis	Gaines & Lubchenco, 1982	Low temperatures constrain the efficiency of digestion for plant materials	Most herbivorous fishes were in the tropics, subtropics, and shallow depths, but were absent in the polar areas and deep sea.	Yes	Yes

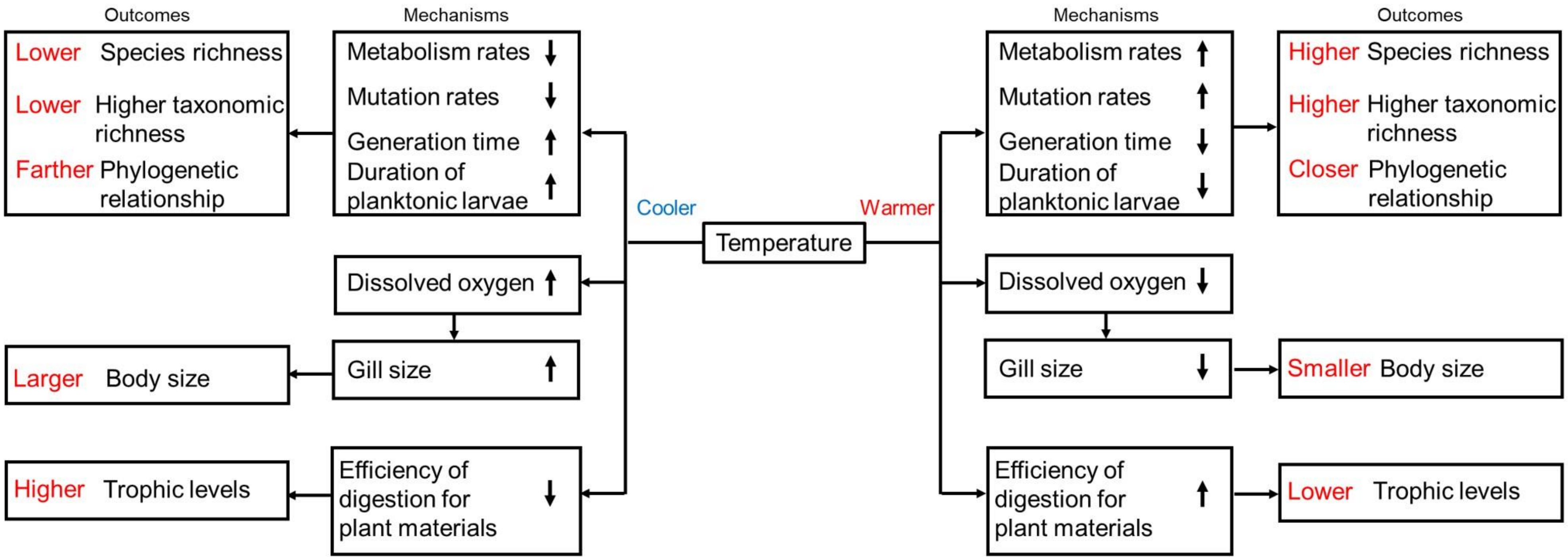


Figure 5.1. Proposed relationships between changing temperatures, physiological mechanisms and their outcomes on latitudinal species richness, higher taxonomic richness, phylogenetic relationship, body size, and trophic level for marine fish.

5.2. Arctic and Antarctic

Both the Arctic and Southern Oceans belong to the polar environment, with extremely cold temperature and low species richness. However, the analyses in this thesis showed that fish composition, phylogenetic relationship, mean body size and mean trophic level were all different between the Arctic and Antarctic fish. These differences may be related to the distinct physical and biological characteristics of each pole.

The Arctic Ocean is a frozen ocean surrounded by continental landmasses and open seas, while the Southern Ocean surrounds the continental landmass of Antarctica (Table 5.2, Figure 5.2). The Arctic Ocean is mixed by warm (North Atlantic Current) and cold (Transpolar Current) currents (Figure 5.2a) and influenced strongly by seasonal atmospheric transport and river inflow from surrounding continents (McBride et al., 2014). Thus, it has lower (and more variable) salinity around 30 – 32‰ (Figure 2.1c, Table 5.2). Most fish taxa found in the Arctic Ocean also live in the northern boreal and even in the temperate regions (Loeng et al., 2005) because of the active northward colonization over the last 6000 – 14000 years (Dayton et al., 1994; Eastman, 1997). Thus, only around 20% of marine fish are endemic in the Arctic Ocean (Eastman, 1997; Reshetnikov, 2004; Mecklenburg et al., 2011). Consequently, the fish assemblage has a greater average phylogenetic diversity (farther phylogenetic relationship) than in Antarctica (Table 5.2). The fish assemblage is dominated by zoarcoids, gadiform, cottids, salmonids, pleuronectiforms, and chondrichthyans, accounting for 58% of Arctic fish fauna (Eastman, 1997).

The Southern Ocean is an enclosed environment compared to high latitudinal areas after the opening of Drake Passage around 23 – 25 million years ago, the formation of the Antarctic Circumpolar Current, and the subsequent ocean cooling, resulting in the evolution of a unique fish fauna with 88% endemic (Eastman, 1997; McGonigal & Woodworth, 2003; Duhamel et al., 2014) (Table 5.2), and over 45% of all its marine species are endemic (Costello, Coll, et al., 2010). Five dominant fish groups, namely notothenioids, myctophids, lipids, zoarcids, and gadiforms, account for 74% of the Antarctic fish fauna (Eastman, 1997). With 35% of the species, notothenioids are the most dominant benthic or demersal fish group in the Southern Ocean (Eastman, 1997). Thus, Antarctic fish fauna had a lower average phylogenetic diversity (closer phylogenetic relationship). The evolution of Antifreeze Glycoproteins (AFGPs), originating near the Oligocene-Miocene transition (mean 23.9 million years ago) during a major period of global cooling and ice-sheet extension, allowed notothenioids to invade the newly developing, ice-associated niches or to replace other clades which became extinct in or retreated from the Southern Ocean (Matschiner et al., 2011; Duhamel et al., 2014). Only zoarcids and liparids are common to both the Arctic and Southern Oceans (Eastman, 1997).

It is clear that there are differences in species composition, phylogenetic diversity, mean body sizes, and mean trophic levels between the Arctic and Antarctic fish. In part these may reflect the long geographic isolation of Antarctica. However, one might still expect the species to have evolved similar body size and trophic diversity in both polar regions where the environments are the same. When 23 physical and biological characteristics are compared between the Arctic and Southern Oceans, the differences in temperatures and oxygen stand out as likely to be biologically significant (Table 5.2). With a colder and less variable temperature in Antarctica than the Arctic, it may expect larger and higher trophic level fish. However, this is not the case, arguing against the temperature-size rule (TSR) and the temperature constraint hypothesis (TCH). Rather, the mean sea bottom oxygen is lower in the Southern than the Arctic Ocean, so the mean body size of Antarctic fish being smaller than the Arctic fish may be related to the gill-oxygen limitation theory (GOLT) (Table 5.2). However, the temperature and DO in the Southern Ocean are all lower and higher than southern temperate area, but the Antarctic fish mean body size and trophic level are smaller and lower than southern temperate area. Thus, these results suggest the Antarctic fish cannot fully support the hypotheses of TSR, TCH, and GOLT, so it may relate to other factors in the Southern Ocean. For example, the food web in the Southern Ocean is simpler compared to other latitudes (Everson, 1977; Hill et al., 2006), Antarctic krill is the main prey for fish (Richardson, 1975; Targett, 1981; La Mesa et al., 2004; Hill et al., 2006), other prey for fish include phytoplankton and zooplankton, and Antarctic fish prey on each other (La Mesa et al., 2004). Together, the relatively enclosed environment, the high endemic fish species that have a closer phylogenetic relationship, and the simpler food web in the Southern Ocean may lead Antarctic fish to possess a similar niche, thus developing similar traits. As a result, unlike fish fauna in the neighbouring latitudes having a wider range of body size and trophic level because of more complex food webs and niches, the body size and trophic level of Antarctic fish are similarly small and low.

Table 5.2. Comparison of physical and biological characteristics of the polar oceans (Integrated results from Eastman, 1997 and this thesis).

Feature	Arctic Ocean	Southern Ocean
Geographic disposition	Enclosed by land between 60 and 90°N	Surrounds Antarctica between 60 and 75°S
Area	14.6×10^6 km^2	$35 – 38 \times 10^6$ km^2
Extent of continental shelf	Broad, extensive archipelagos	Narrow, few islands
Depth of continental shelf	100 – 500 m	400 – 600 m
Shelf continuity with ocean	Open to the south at Fram and Bering Straits	Open to oceans to the north
Direction of currents	Transpolar	Circumpolar
Upwelling and vertical mixing	Little	Extensive
Nutrient availability	Seasonally depleted	Continuously high
Seasonality of solar illumination	Strong	Weak
Primary productivity	Moderate	Moderate to high
Fluvial input to ocean	Extensive	None
Salinity at 100–150 m	30 – 32‰	34.5 – 34.7‰
Seasonality of pack ice	Low	High
Physical disturbance of benthos by large predators	Extensive	Low
Physical disturbance of benthos by ice scour	Low	High
Sea surface temperature, mean and range (min – max)	Mean: 3.9 °C Range: -0.2 – 10 °C	Mean: -0.2 °C Range: -0.4 – 4 °C
Sea bottom temperature, mean and range (min – max)	Mean: 2 °C Range: -1.8 – 10 °C	Mean: 0 °C Range: -2.0 – 1.3 °C
Sea surface dissolved oxygen, mean and range (min – max)	Mean: 7.0 ml/l Range: 3.1 – 9.9 ml/l	Mean: 7.2 ml/l Range: 6.0 – 9.0 ml/l
Sea bottom dissolved oxygen, mean and range (min – max)	Mean: 6.4 ml/l Range: 0.4 – 9.5 ml/l	Mean: 5.4 ml/l Range: 3.7 – 8.5 ml/l
Phylogenetic relationship of marine fish	Farther	Closer
Endemism of marine fish	20 – 25%	88%
Mean body size of marine fish	88.4 cm	43.8 cm
Mean trophic level of marine fish	3.7	3.5

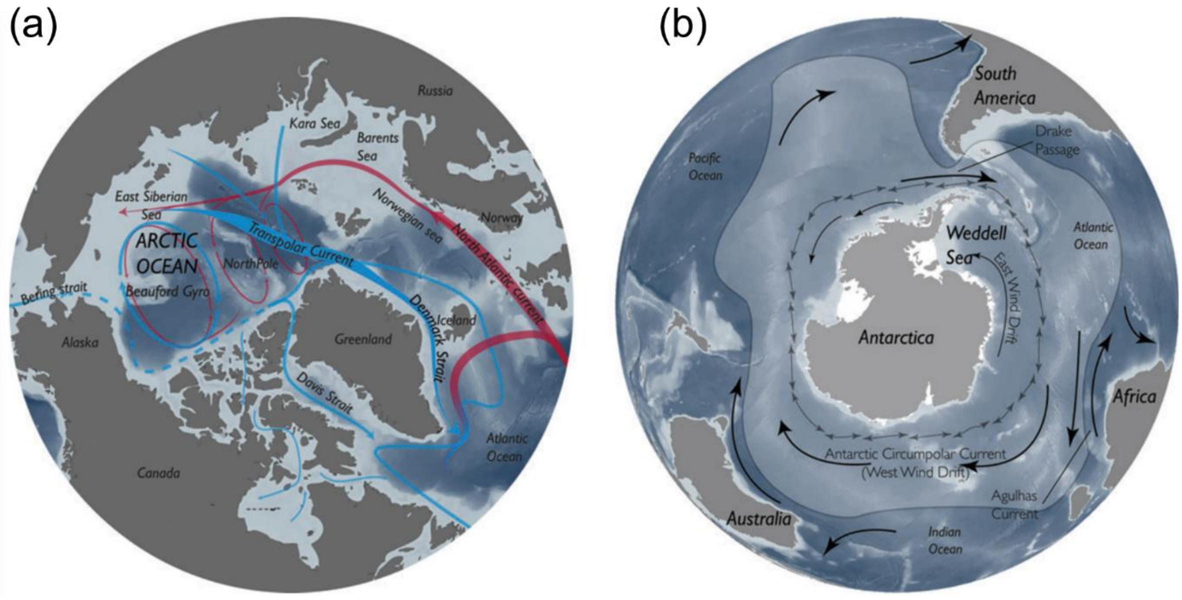


Figure 5.2. The geographic disposition and current system of (a) Arctic Ocean and (b) Southern Ocean. The North Atlantic Current is a warm current (red lines), the Transpolar Current is a cold current (blue lines), and the Antarctic Circumpolar Current continuously flows around Antarctica in a clockwise direction (light blue area) (Modified from McBride et al., 2014).

5.3. Climate change and conservation

Climate change has influenced the marine taxa in several aspects, notably affected by ocean acidification (Pandolfi et al., 2011; Wisshak et al., 2013), the poleward shifts of marine taxa (Richardson & Schoeman, 2004; Cheung et al., 2009, 2010; Beaugrand et al., 2013; Poloczanska et al., 2013; Wernberg et al., 2013; Garciá Molinos et al., 2016; Chaudhary et al., 2021), and changes in food webs and trophic positions (Durant et al., 2019; Lotze et al., 2019). If sea temperature continues to increase, more species will move away from or become extinct at the equator (Yasuhara et al., 2020). Thus, it would be expected that the dip of current marine LDG would become deeper and wider. As with the dramatic climate change of the Permian-Triassic which led to mass species extinctions, the current bimodal marine LDG may widen such that species richness may be equally low over latitude in the very far future (Song et al., 2020). Studies also found that warming sea temperature may result in shrinkage of mean body size of fish due to the increasing limitation of oxygen supply (Forster et al., 2012; Cheung et al., 2013; Rubalcaba et al., 2020), and the forecast suggests a 15 – 30% decrease in body size due to warming temperature by 2050 (Cheung et al., 2013; Pauly & Cheung, 2018).

Overfishing is another crucial factor affecting species diversity, body size and trophic position of marine fish (Pauly et al., 2002; Pauly & Palomares, 2005; Audzijonyte et al., 2015). Thus, to decrease the effects of climate change and overfishing, efficient strategies for conservation and management are needed. For example, one study identified areas on continental coasts, island arcs, oceanic islands, the southwest Indian Ridge, the northern Mid-Atlantic Ridge, the Coral Triangle, the Caribbean Sea, and the Arctic Archipelago that covered 30% of ecosystems and more than 80% of biomes, and thus should be a priority for protection (Zhao et al., 2020). Although these areas only occupy 30% of the ocean, they cover 94% of coral reefs and mangrove forests, 86% of kelp forests and seagrass meadows, and 68% of marine species (Zhao et al., 2020).

The results of this thesis show that there are assemblages of fish species distinct in species richness, phylogenetic diversity, endemicity, and function traits of body sizes and trophic across latitudes and depth zones, and they could be influenced by climate change and overfishing. Thus, the management of fisheries and selection of locations for Marine Protected Areas (MPA) need to be stratified within each of these fish assemblages in each ocean. To decrease the impacts of climate change, reducing the emission of greenhouse gas is the priority, but some new marine management and conservation methods need to be proposed because the concentration of greenhouse gas is still high (Rau et al., 2012). The MPA network proposed by Zhao et al. (2020) would help in reducing impacts on fish biodiversity by reducing fishing impacts across species ranges, thereby mitigating against changes in body size and trophic interactions due to climate change and overfishing.

Appendices

Appendices

Table A2.1. The classification of families of fish as pelagic and demersal.

Pelagic				
Aetobatidae	Cetorhinidae	Howellidae	Nomeidae	Scombrolabracidae
Alepisauridae	Chiasmodontidae	Isonidae	Notosudidae	Scopelarchidae
Alepocephalidae	Chirocentridae	Istiophoridae	Omosudidae	Sphyraenidae
Alopiidae	Clupeidae	Lactariidae	Oneirodidae	Sphyrnidae
Amarsipidae	Coryphaenidae	Lamnidae	Opisthoproctidae	Stephanoberycidae
Arripidae	Dalatiidae	Lampridae	Osmeridae	Sternoptychidae
Atherinidae	Dichistiidae	Leptochilichthyidae	Paralepididae	Stomiidae
Atherinopsidae	Dussumieriidae	Linophrynidae	Phosichthyidae	Stromateidae
Bathylagidae	Echeneidae	Lophotidae	Platytroctidae	Stylephoridae
Belonidae	Elopidae	Luvaridae	Pomatomidae	Symphysanodontidae
Bramidae	Engraulidae	Megachasmidae	Pristigasteridae	Tetragonuridae
Bregmacerotidae	Evermannellidae	Megalopidae	Pseudocarchariidae	Trachipteridae
Caesionidae	Exocoetidae	Melamphaidae	Pseudomugilidae	Trichiuridae
Carangidae	Gempylidae	Melanocetidae	Radiicephalidae	Xiphiidae
Carcharhinidae	Gibberichthyidae	Microstomatidae	Regalecidae	
Caristiidae	Gigantactinidae	Molidae	Rhincodontidae	
Centrolophidae	Giganturidae	Monodactylidae	Rondeletiidae	
Centrophrynidae	Gonostomatidae	Myctophidae	Saccopharyngidae	
Ceratiidae	Hemigaleidae	Myliobatidae	Scomberesocidae	
Cetomimidae	Hemiramphidae	Neoscopelidae	Scombridae	
Demersal				
Acanthuridae	Chanidae	Haemulidae	Neosebastidae	Rhinobatidae
Achiridae	Channichthyidae	Halosauridae	Nettastomatidae	Rhinochimaeridae
Achiropsettidae	Chaunacidae	Harpagiferidae	Normanichthyidae	Salmonidae
Acipenseridae	Cheilodactylidae	Hemiscylliidae	Notacanthidae	Samaridae
Acropomatidae	Chimaeridae	Hemitripteridae	Nototheniidae	Scaridae
Agonidae	Chironemidae	Heterodontidae	Odacidae	Scatophagidae
Albulidae	Chlamydoselachidae	Hexagrammidae	Odontaspididae	Sciaenidae
Ambassidae	Chlopsidae	Hexanchidae	Ogcocephalidae	Scombropidae
Ammodytidae	Chlorophthalmidae	Hexatrygonidae	Ophichthidae	Scophthalmidae
Anacanthobatidae	Cichlidae	Holocentridae	Ophidiidae	Scorpaenidae
Anarhichadidae	Cirrhitidae	Hypnidae	Opistognathidae	Scyliorhinidae
Anguillidae	Citharidae	Hypoptychidae	Orectolobidae	Sebastidae
Anomalopidae	Clinidae	Icosteidae	Oreosomatidae	Serranidae
Anoplogastridae	Colocongridae	Ipnopidae	Ostraciidae	Serrivomeridae
Anoplopomatidae	Congiopodidae	Kraemeriidae	Oxynotidae	Setarchidae
Anotopteridae	Congridae	Kuhliidae	Parabembridae	Siganidae
Antennariidae	Cottidae	Kyphosidae	Paralichthyidae	Sillaginidae
Aphyonidae	Creediidae	Labridae	Parascylliidae	Soleidae
Aploactinidae	Cryptacanthodidae	Labrisomidae	Pataecidae	Somniosidae
Aplodactylidae	Cyclopteridae	Lateolabracidae	Pegasidae	Sparidae
Apogonidae	Cynoglossidae	Latidae	Pempheridae	Squalidae
Argentinidae	Cyprinodontidae	Latimeriidae	Pentacerotidae	Squatinidae
Arhynchobatidae	Dactylopteridae	Latridae	Percophidae	Stegostomatidae

Ariidae	Dactyloscopidae	Leiognathidae	Peristediidae	Stichaeidae
Ariommatidae	Dasyatidae	Leptochariidae	Petromyzontidae	Synanceiidae
Artedidraconidae	Dinopercidae	Lethrinidae	Pholidae	Synaphobranchidae
Ateleopodidae	Diodontidae	Liparidae	Pholidichthyidae	Syngnathidae
Aulopidae	Diretmidae	Lobotidae	Phycidae	Synodontidae
Aulorhynchidae	Drepaneidae	Lophiidae	Pinguipedidae	Terapontidae
Aulostomidae	Echinorhinidae	Lotidae	Platycephalidae	Tetraodontidae
Balistidae	Eleginopsidae	Lutjanidae	Platyrhinidae	Tetrarogidae
Bathydraconidae	Eleotridae	Macrouridae	Plecoglossidae	Torpedinidae
Bathymasteridae	Embiotocidae	Malacanthidae	Plesiobatidae	Trachichthyidae
Bathysauridae	Emmelichthyidae	Melanonidae	Plesiopidae	Trachinidae
Batrachoididae	Enoplosidae	Menidae	Pleuronectidae	Triacanthidae
Berycidae	Ephippidae	Merlucciidae	Plotosidae	Triacanthodidae
Blenniidae	Epigonidae	Microdesmidae	Polymixiidae	Triakidae
Bothidae	Etmopteridae	Mitsukurinidae	Polynemidae	Trichodontidae
Bovichtidae	Fistulariidae	Monacanthidae	Polyprionidae	Triglidae
Brachaeluridae	Fundulidae	Monocentridae	Pomacanthidae	Tripterygiidae
Brachionichthyidae	Gadidae	Mordaciidae	Pomacentridae	Uranoscopidae
Bythitidae	Galaxiidae	Moridae	Priacanthidae	Urolophidae
Callanthiidae	Gasterosteidae	Moringuidae	Pristidae	Urotrygonidae
Callionymidae	Gerreidae	Moronidae	Pristiophoridae	Zanclidae
Callorhinchidae	Ginglymostomatidae	Mugilidae	Proscylliidae	Zaproridae
Caproidae	Glaucosomatidae	Mullidae	Psettodidae	Zeidae
Carapidae	Glaucostegidae	Muraenesocidae	Pseudochromidae	Zeniontidae
Centriscidae	Gobiesocidae	Muraenidae	Pseudotriakidae	Zoarcidae
Centrophoridae	Gobiidae	Muraenolepididae	Psychrolutidae	
Centropomidae	Gonorynchidae	Myxinidae	Ptilichthyidae	
Cepolidae	Grammatidae	Narcinidae	Rachycentridae	
Chaenopsidae	Grammicolepididae	Nematistiidae	Rajidae	
Chaetodontidae	Gurgesiellidae	Nemichthyidae	Rhamphocottidae	
Champsodontidae	Gymnuridae	Nemipteridae	Rhinidae	

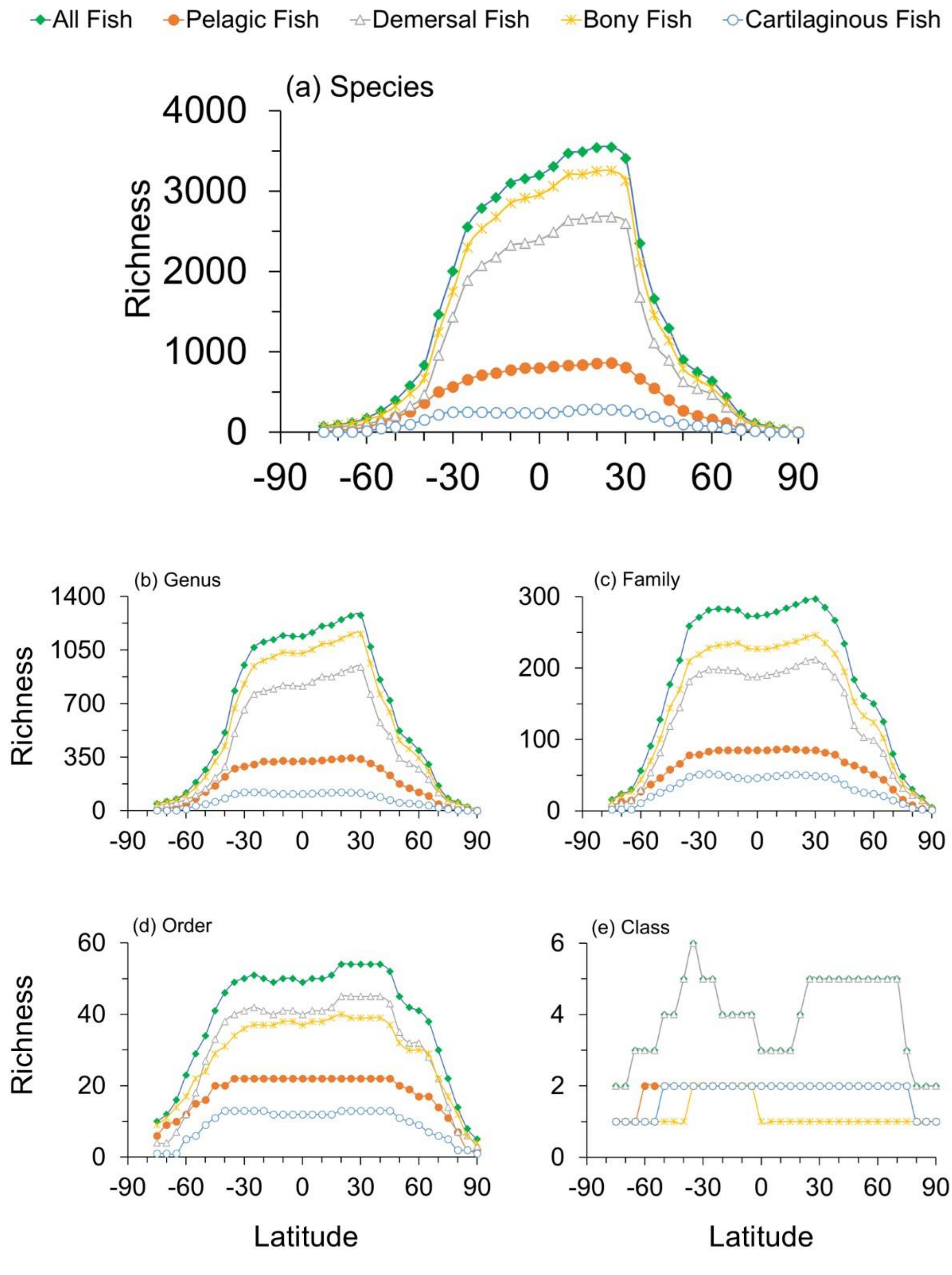


Figure A2.1. The number of taxa against latitude for the five taxonomic levels and five fish groups.

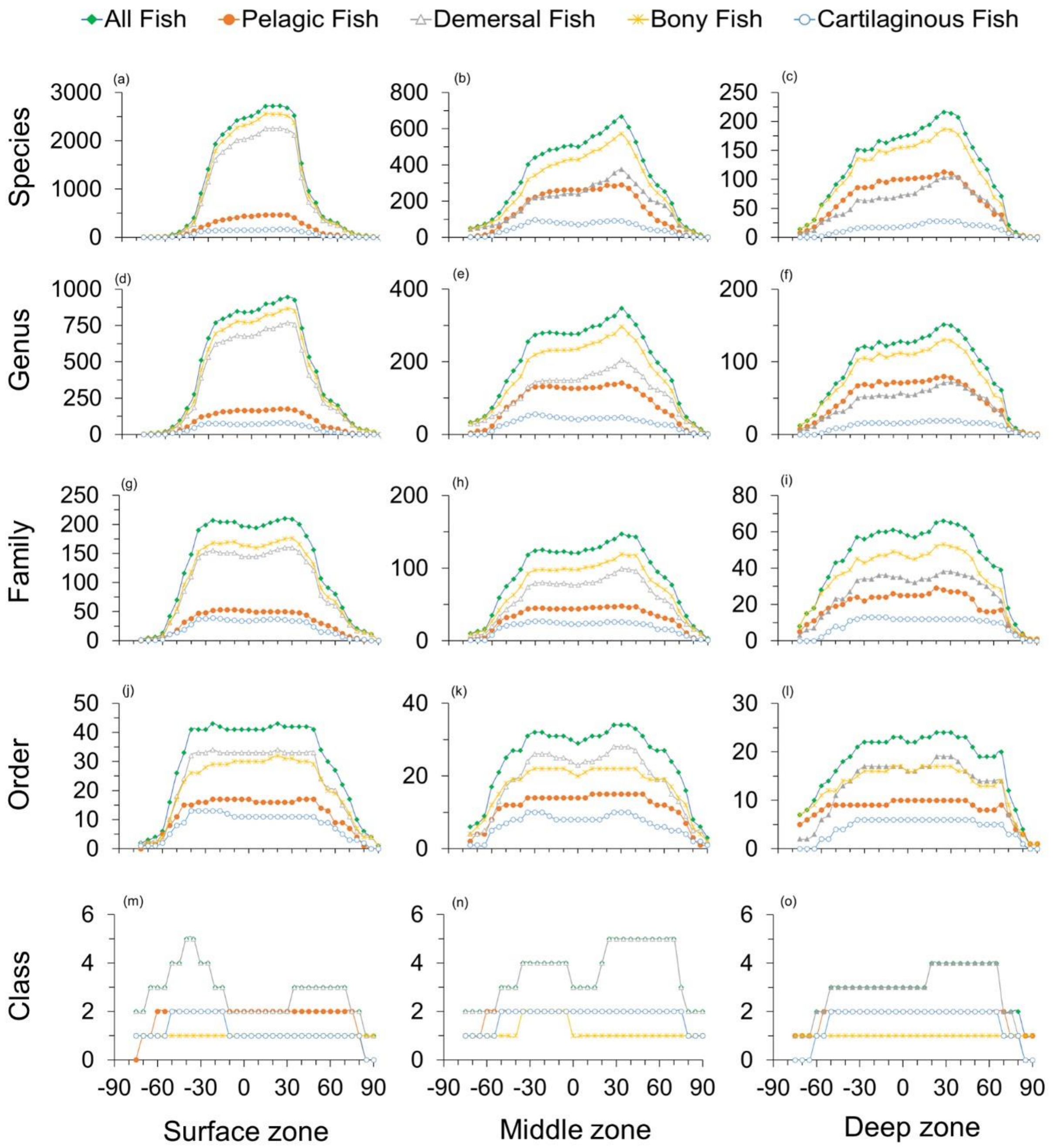


Figure A2.2. The number of taxa against latitude for the five taxonomic levels and five fish groups in three depth zones.

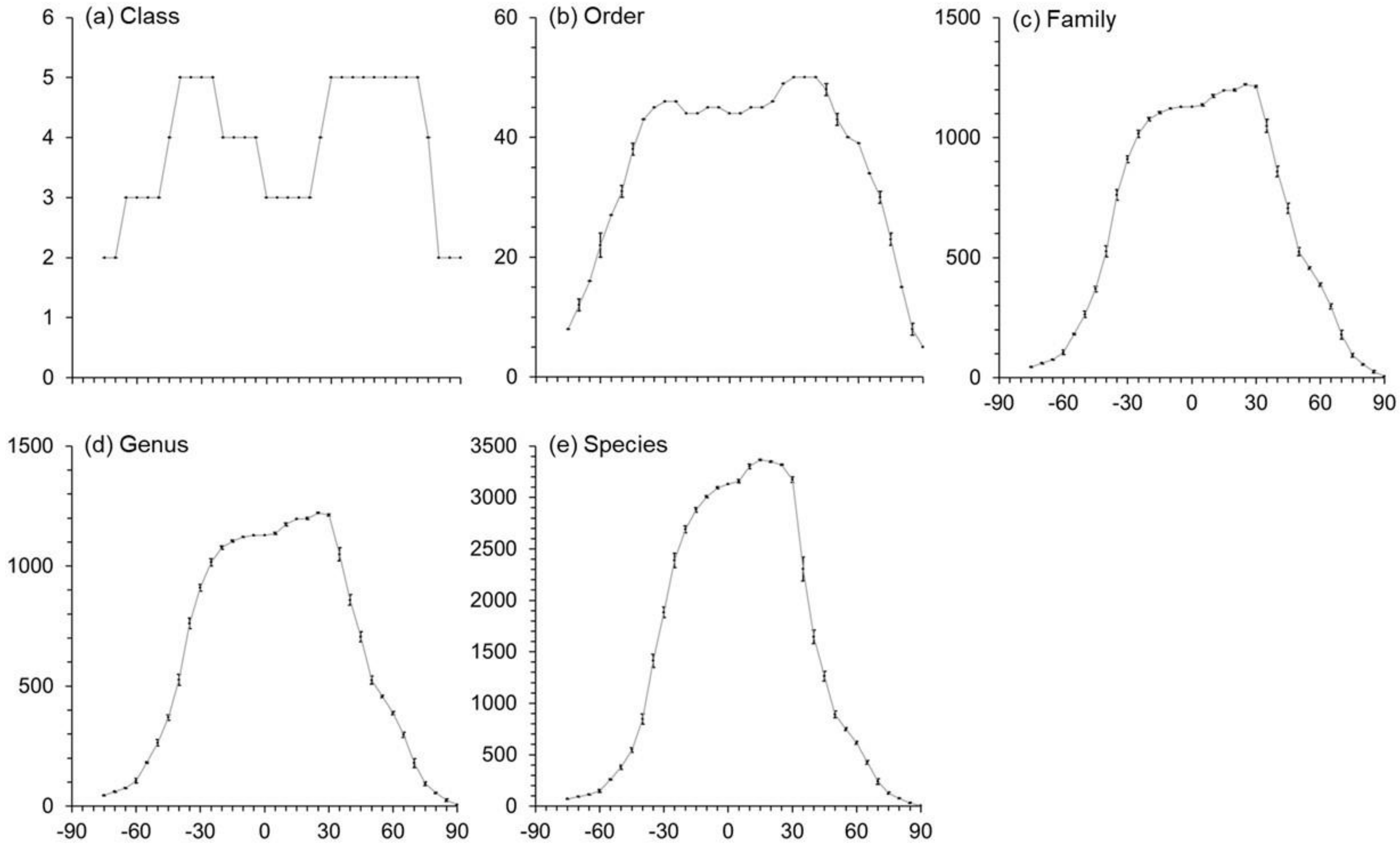


Figure A2.3. The mean richness and standard error of five taxonomic levels of all fish with latitude.

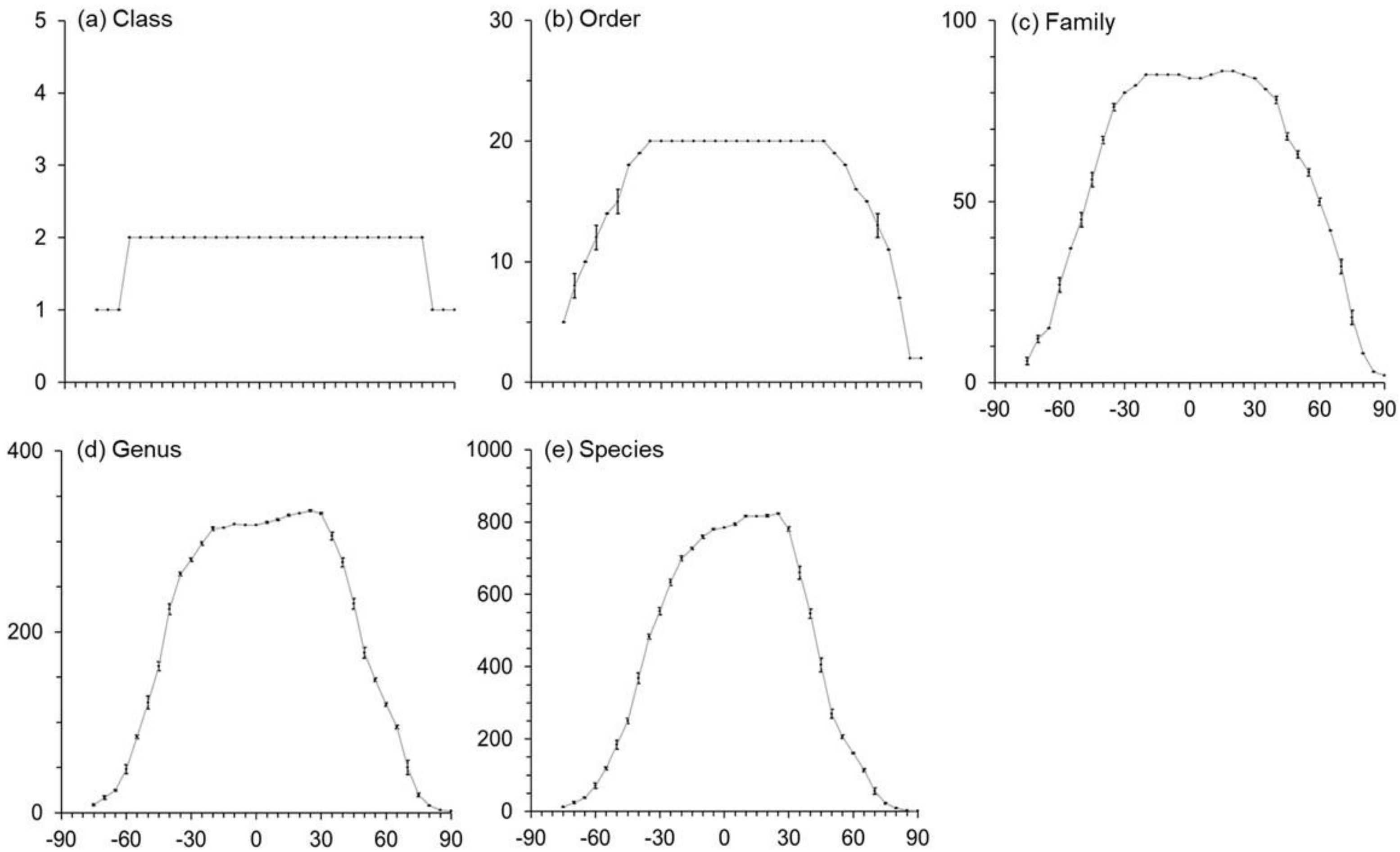


Figure A2.4. The mean richness and standard error of five taxonomic levels of pelagic fish with latitude.

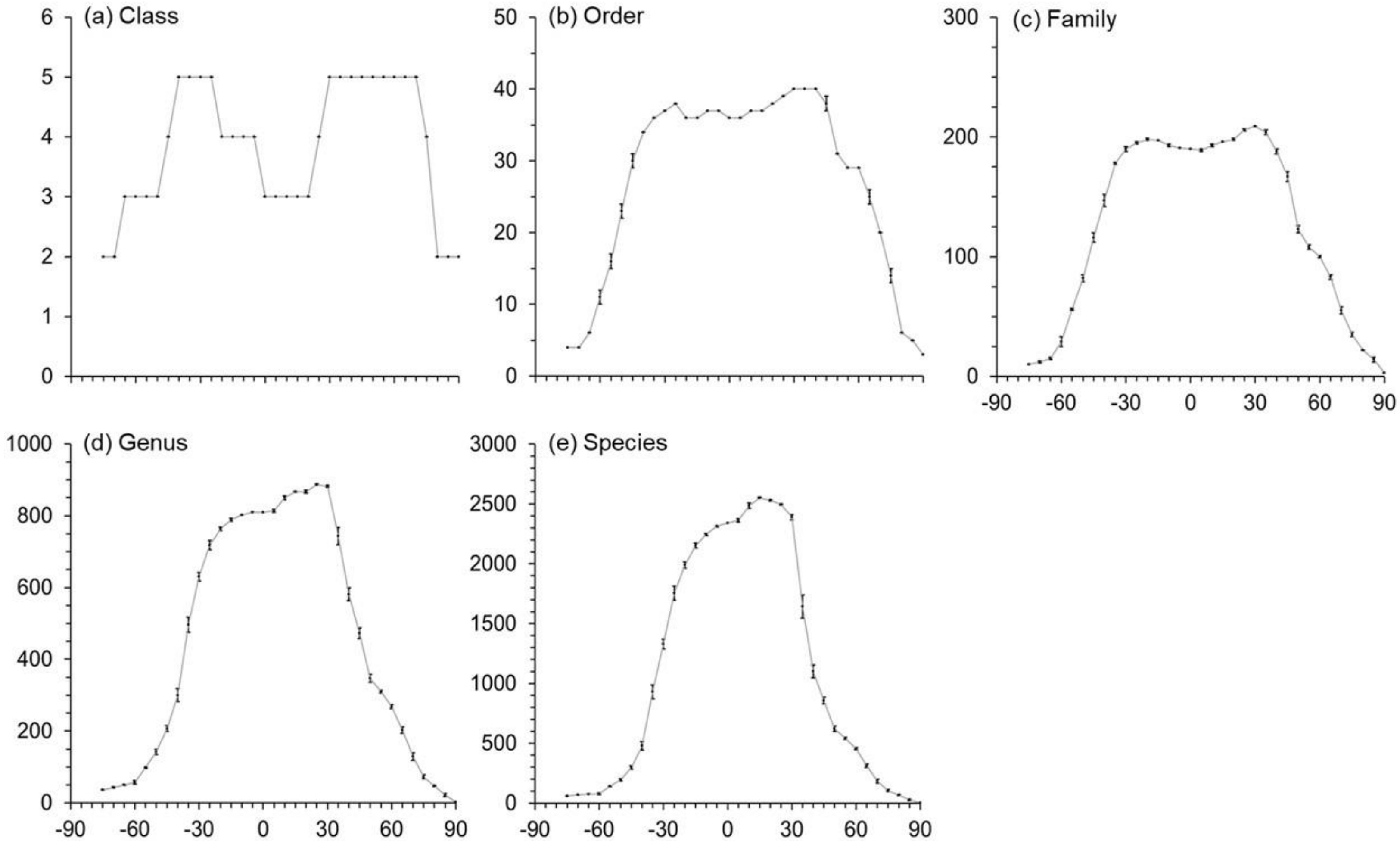


Figure A2.5. The mean richness and standard error of five taxonomic levels of demersal fish with latitude.

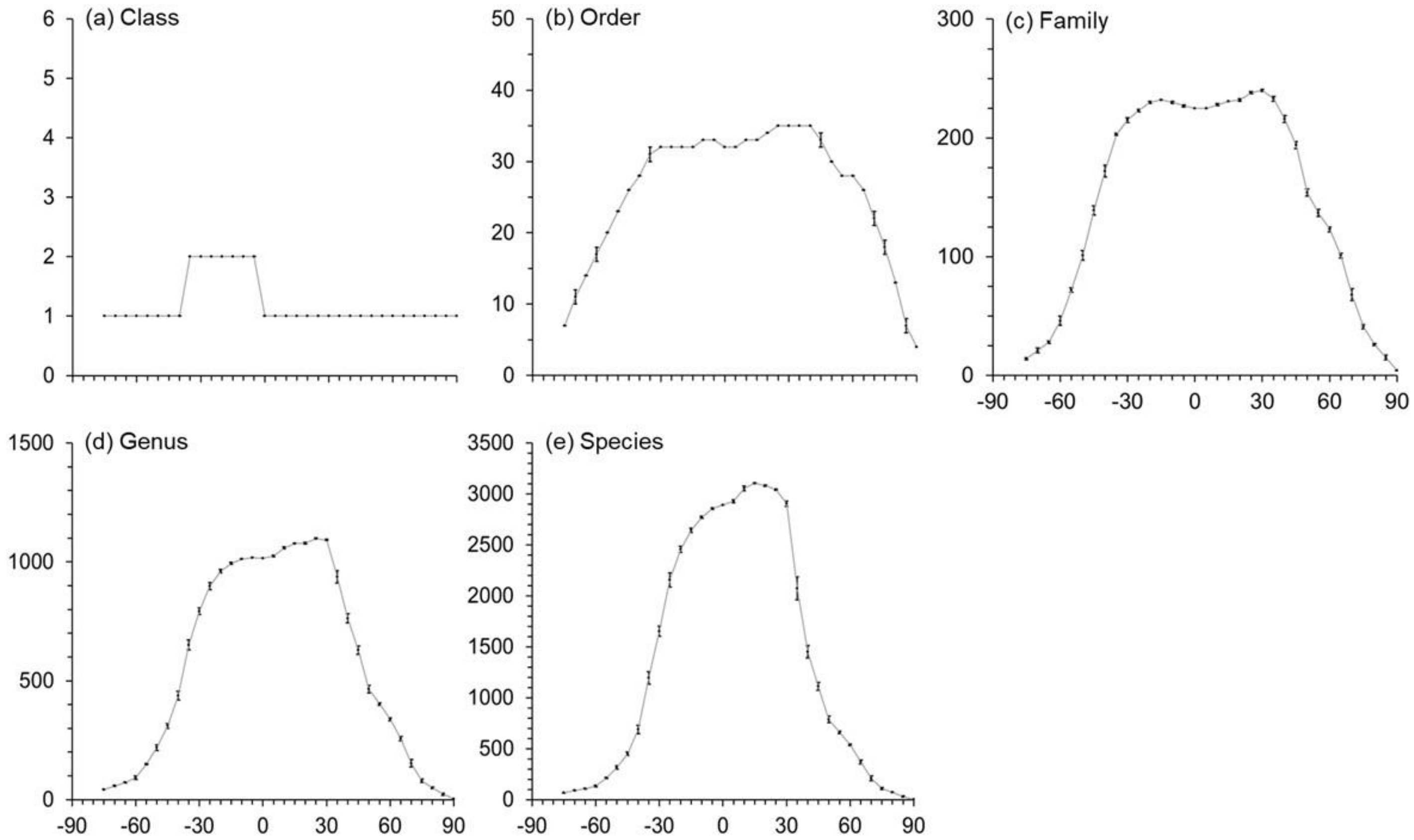


Figure A2.6. The mean richness and standard error of five taxonomic levels of bony fish with latitude.

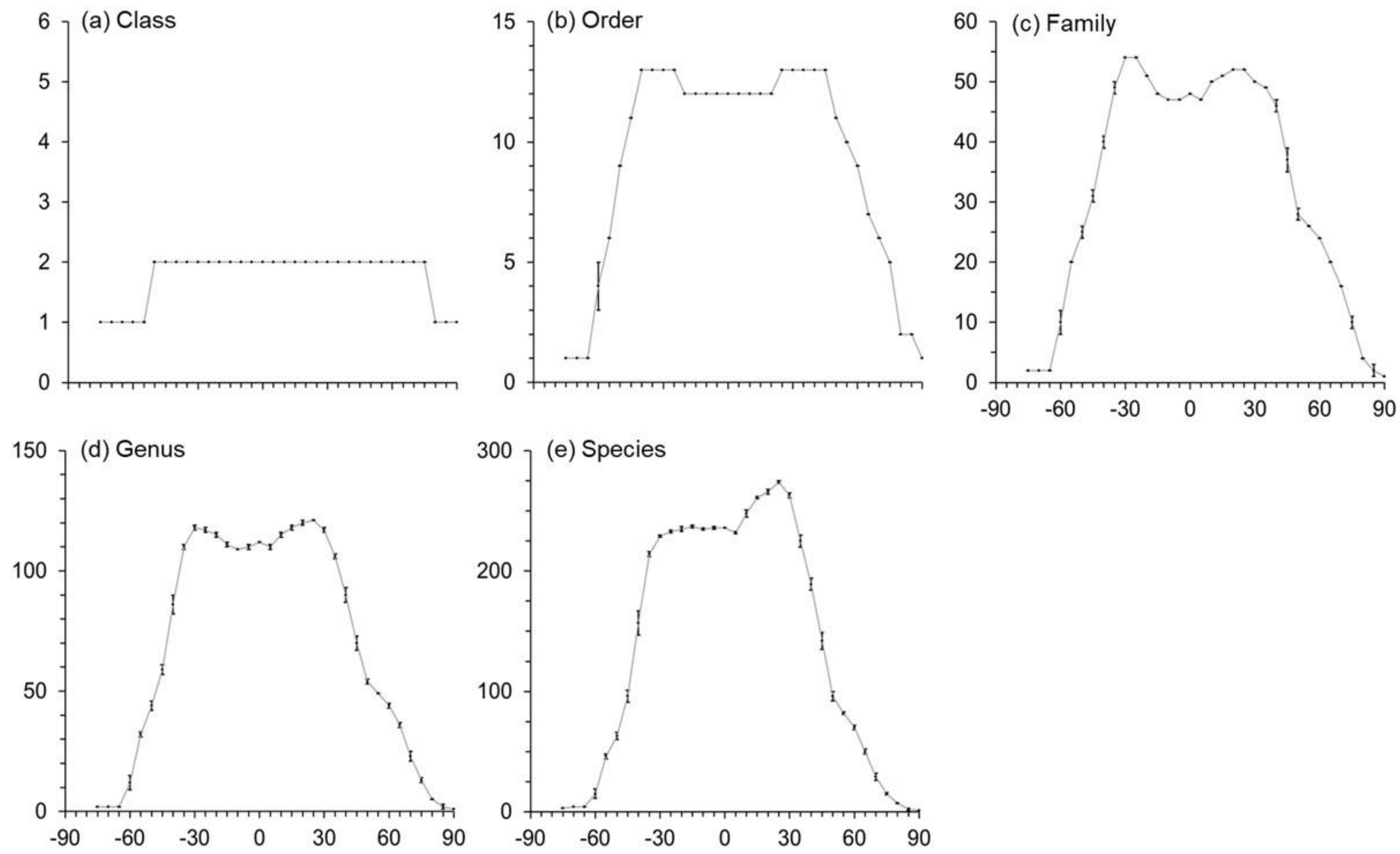


Figure A2.7. The mean richness and standard error of five taxonomic levels of cartilaginous fish with latitude.

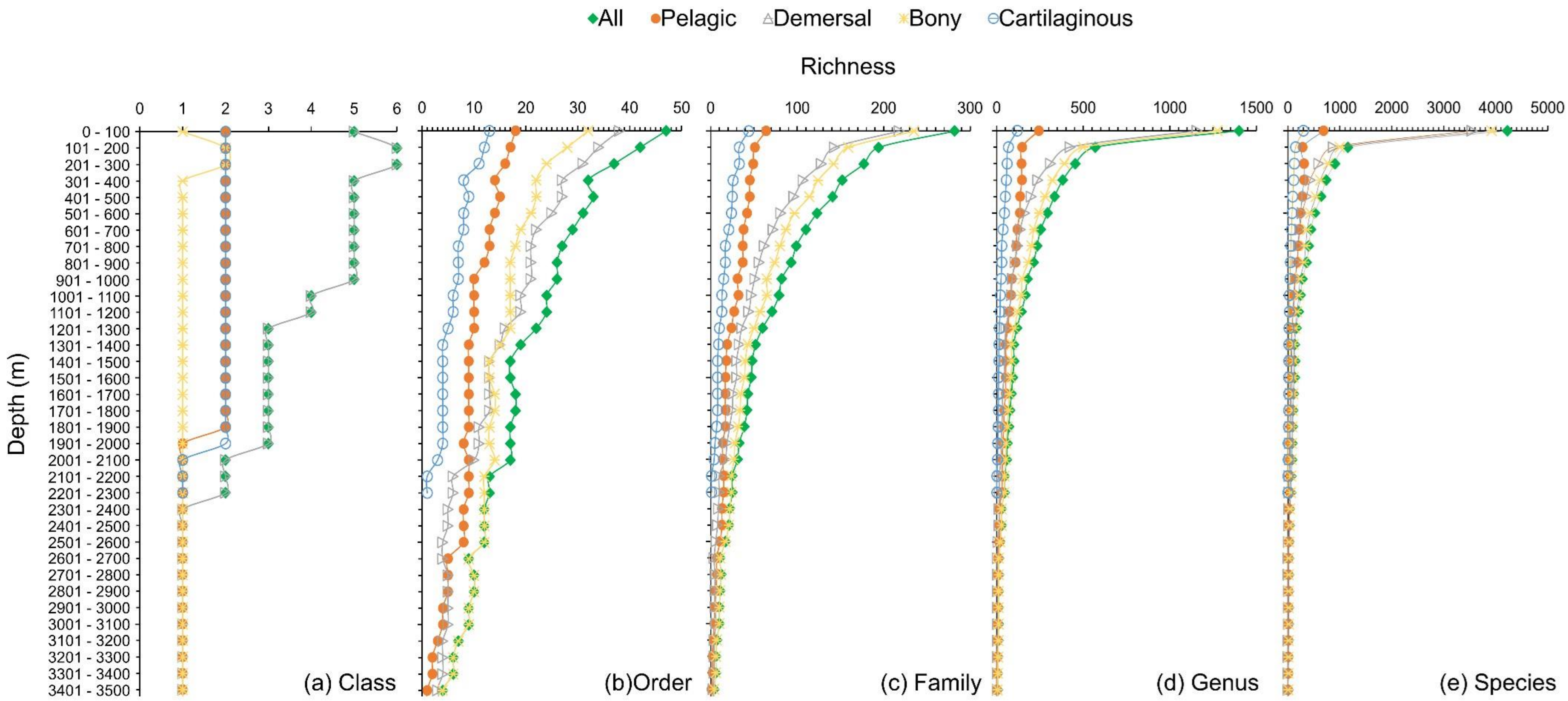


Figure A2.8. The number of taxa against depth for the five taxonomic levels and five fish groups.

Table A3.1. Taxonomic levels of 5619 marine fish used in this thesis.

Actinopterygii

Acipenseriformes
Acipenseridae
Acipenser
Acipenser brevirostrum
Acipenser gueldenstaedtii
Acipenser medirostris
Acipenser mikadoi
Acipenser naccarii
Acipenser nudiventris
Acipenser oxyrinchus
Acipenser sinensis
Acipenser stellatus
Acipenser sturio
Acipenser transmontanus
Huso
Huso huso
Albuliformes
Albulidae
Albula
Albula glossodonta
Albula vulpes
Anguilliformes
Anguillidae
Anguilla
Anguilla anguilla
Anguilla australis
Anguilla bengalensis
Anguilla bicolor
Anguilla celebesensis
Anguilla dieffenbachii
Anguilla japonica
Anguilla marmorata
Anguilla megastoma
Anguilla mossambica
Anguilla obscura
Anguilla reinhardtii
Anguilla rostrata
Chlopsidae
Chlopsis
Chlopsis olokun
Kaupichthys
Kaupichthys atronasus
Kaupichthys brachychirus
Kaupichthys hyoproroides
Colocongridae
Coloconger
Coloconger cadenati
Congridae
Ariosoma
Ariosoma balearicum
Ariosoma fasciatum
Ariosoma gilberti
Ariosoma prorigerum
Ariosoma scheelei
Bathycongrus
Bathycongrus bullisi
Bathycongrus macrurus
Bathycongrus wallacei
Bathyuroconger
Bathyuroconger vicinus
Conger
Conger cinereus
Conger conger
Conger myriaster
Conger oceanicus
Conger orbignianus
Diploconger
Diploconger polystigmatus
Gnathophis
Gnathophis cinctus
Gnathophis mystax
Gorgasia
Gorgasia punctata
Heteroconger
Heteroconger digueti
Heteroconger hassi
Japonoconger
Japonoconger africanus
Paraconger
Paraconger californiensis
Paraconger notialis
Pseudophichthys
Pseudophichthys splendens
Rhynchoconger
Rhynchoconger flavus
Rhynchoconger guppyi
Rhynchoconger nitens
Moringuidae
Moringua
Moringua ferruginea
Moringua javanica
Moringua microchir
Muraenesocidae
Congresox
Congresox talabon
Congresox talabonoides
Cynoponticus
Cynoponticus coniceps
Cynoponticus ferox
Muraenesox
Muraenesox cinereus
Muraenidae
Anarchias
Anarchias allardicei
Anarchias cantonensis
Anarchias galapagensis
Anarchias similis
Channomuraena
Channomuraena vittata
Echidna
Echidna catenata
Echidna leucotaenia
Echidna nebulosa
Echidna nocturna
Echidna peli
Echidna polyzona
Echidna unicolor
Enchelycore
Enchelycore anatina
Enchelycore bayeri
Enchelycore octaviana
Enchelycore schismatorhynchus
Enchelynassa
Enchelynassa canina
Gymnomuraena
Gymnomuraena zebra
Gymnothorax
Gymnothorax buroensis
Gymnothorax castaneus
Gymnothorax castlei
Gymnothorax conspersus
Gymnothorax dovii
Gymnothorax enigmaticus
Gymnothorax equatorialis
Gymnothorax fimbriatus
Gymnothorax flavimarginatus
Gymnothorax funebris
Gymnothorax fuscomaculatus
Gymnothorax gracilicauda
Gymnothorax hepaticus
Gymnothorax javanicus
Gymnothorax mareei
Gymnothorax margaritophorus
Gymnothorax marshallensis
Gymnothorax melatremus
Gymnothorax meleagris
Gymnothorax miliaris
Gymnothorax monostigma
Gymnothorax mordax
Gymnothorax moringa
Gymnothorax nigromarginatus
Gymnothorax nudivomer
Gymnothorax panamensis
Gymnothorax pictus
Gymnothorax polyuranodon
Gymnothorax richardsonii
Gymnothorax rueppelliae
Gymnothorax saxicola
Gymnothorax steindachneri
Gymnothorax thyrsoideus
Gymnothorax undulatus
Gymnothorax unicolor
Gymnothorax zonipectis
Muraena
Muraena argus
Muraena augusti
Muraena clepsydra
Muraena helena
Muraena melanotis
Muraena retifera
Muraena robusta
Pseudechidna
Pseudechidna brummeri
Rhinomuraena
Rhinomuraena quaesita
Scuticaria
Scuticaria tigrina
Strophidon
Strophidon sathete
Uropterygius
Uropterygius concolor
Uropterygius fuscoguttatus
Uropterygius kamar
Uropterygius macrocephalus
Uropterygius marmoratus
Uropterygius micropterus
Uropterygius nagoensis
Uropterygius polyspilus
Uropterygius polystictus
Uropterygius supraforatus
Uropterygius versutus
Uropterygius xanthopterus
Nemichthyidae
Avocettina
Avocettina infans
Labichthys
Labichthys carinatus
Nemichthys
Nemichthys curvirostris
Nemichthys larseni
Nemichthys scolopaceus
Nettastomatidae
Facciolella
Facciolella oxyrhyncha
Nettastoma
Nettastoma melanurum
Venefica
Venefica tentaculata
Ophichthidae
Aprognathodon
Aprognathodon platyventris
Apterichtus
Apterichtus anguiformis
Apterichtus ansp
Apterichtus caecus
Apterichtus equatorialis
Apterichtus kendalli
Bascanichthys
Bascanichthys bascanium
Brachysomophis
Brachysomophis cirrocheilos
Callechelys
Callechelys catostoma
Callechelys cliffi
Callechelys eristigma
Callechelys marmorata
Dalophis
Dalophis boulengeri
Dalophis imberbis
Echelus
Echelus myrus
Echelus uropterus
Echiophis
Echiophis brunneus
Echiophis intertinctus
Hemerorhinus
Hemerorhinus opici
Ichthyapus
Ichthyapus selachops
Ichthyapus vulturis
Leiuranus
Leiuranus semicinctus
Letharchus
Letharchus rosenblatti
Muraenichthys
Muraenichthys schultzei
Muraenichthys sibogae
Myrichthys
Myrichthys aspetocheiros
Myrichthys breviceps
Myrichthys colubrinus
Myrichthys maculosus
Myrichthys ocellatus
Myrichthys pardalis
Myrichthys tigrinus
Ophichthus
Ophichthus apicalis
Ophichthus cephalozona
Ophichthus cruentifer
Ophichthus frontalis
Ophichthus gomesii
Ophichthus macrochir
Ophichthus puncticeps
Ophichthus remiger
Ophichthus rufus
Ophisurus
Ophisurus serpens
Phaenomonas
Phaenomonas cooperae
Phaenomonas pinnata
Phyllophichthus
Phyllophichthus xenodontus
Pisodonophis
Pisodonophis semicinctus
Pseudomyrophis
Pseudomyrophis atlanticus
Pseudomyrophis micropinna
Quassiremus
Quassiremus nothochir
Schismorhynchus
Schismorhynchus labialis
Schultzidia
Schultzidia johnstonensis
Schultzidia retropinnis
Scolecenchelys
Scolecenchelys gymnota
Scolecenchelys laticaudata

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Scolecenchelys macroptera	***Leuresthes***	*Scopelosaurus hoedti*	**Batrachoidiformes**
Serrivomeridae	*Leuresthes tenuis*	*Scopelosaurus lepidus*	**Batrachoididae**
Serrivomer	***Membras***	*Scopelosaurus meadi*	***Amphichthys***
Serrivomer beanii	*Membras martinica*	*Scopelosaurus smithii*	*Amphichthys cryptocentrus*
Synaphobranchidae	***Menidia***	**Omosudidae**	***Batrachoides***
Diastobranchus	*Menidia beryllina*	***Omosudis***	*Batrachoides liberiensis*
Diastobranchus capensis	*Menidia menidia*	*Omosudis lowii*	*Batrachoides surinamensis*
Haptenchelys	***Odontesthes***	**Paralepididae**	***Batrachomoeus***
Haptenchelys texis	*Odontesthes argentinensis*	***Arctozenus***	*Batrachomoeus dubius*
Histiobranchus	*Odontesthes regia*	*Arctozenus risso*	*Batrachomoeus occidentalis*
Histiobranchus bathybius	**Isonidae**	***Lestidiops***	*Batrachomoeus trispinosus*
Histiobranchus bruuni	***Iso***	*Lestidiops affinis*	***Daector***
Ilyophis	*Iso hawaiiensis*	*Lestidiops pseudosphyraenoides*	*Daector dowi*
Ilyophis arx	*Iso natalensis*	*Lestidiops ringens*	*Daector schmitti*
Ilyophis blachei	**Pseudomugilidae**	*Lestidiops similis*	***Halobatrachus***
Ilyophis brunneus	***Pseudomugil***	*Lestidiops sphyrenoides*	*Halobatrachus didactylus*
Ilyophis nigeli	*Pseudomugil inconspicuus*	***Lestidium***	***Opsanus***
Meadia	**Aulopiformes**	*Lestidium atlanticum*	*Opsanus beta*
Meadia abyssalis	**Alepisauridae**	*Lestidium nudum*	*Opsanus pardus*
Simenchelys	***Alepisaurus***	***Lestrolepis***	*Opsanus tau*
Simenchelys parasitica	*Alepisaurus brevirostris*	*Lestrolepis intermedia*	***Perulibatrachus***
Synaphobranchus	*Alepisaurus ferox*	***Magnisudis***	*Perulibatrachus elminensis*
Synaphobranchus affinis	**Anotopteridae**	*Magnisudis atlantica*	***Porichthys***
Synaphobranchus brevidorsalis	***Anotopterus***	*Magnisudis prionosa*	*Porichthys analis*
Synaphobranchus calvus	*Anotopterus pharao*	***Notolepis***	*Porichthys ephippiatus*
Synaphobranchus kaupii	**Aulopidae**	*Notolepis annulata*	*Porichthys greenei*
Synaphobranchus oregoni	***Aulopus***	*Notolepis coatsi*	*Porichthys mimeticus*
Ateleopodiformes	*Aulopus bajacali*	***Paralepis***	*Porichthys myriaster*
Ateleopodidae	*Aulopus filamentosus*	*Paralepis coregonoides*	*Porichthys notatus*
Guentherus	**Bathysauridae**	***Stemonosudis***	*Porichthys plectrodon*
Guentherus altivela	***Bathysaurus***	*Stemonosudis elegans*	*Porichthys porosissimus*
Ijimaia	*Bathysaurus ferox*	***Sudis***	**Beloniformes**
Ijimaia loppei	*Bathysaurus mollis*	*Sudis atrox*	**Belonidae**
Atheriniformes	**Chlorophthalmidae**	*Sudis hyalina*	***Ablennes***
Atherinidae	***Chlorophthalmus***	***Uncisudis***	*Ablennes hians*
Atherina	*Chlorophthalmus agassizi*	*Uncisudis advena*	***Belone***
Atherina boyeri	***Parasudis***	**Scopelarchidae**	*Belone belone*
Atherina breviceps	*Parasudis fraserbrunneri*	***Benthalbella***	***Platybelone***
Atherina hepsetus	*Parasudis truculenta*	*Benthalbella dentata*	*Platybelone argalus argalus*
Atherina presbyter	**Evermannellidae**	*Benthalbella elongata*	*Platybelone argalus platyura*
Atherinason	***Evermannella***	*Benthalbella macropinna*	***Strongylura***
Atherinason hepsetoides	*Evermannella balbo*	***Scopelarchoides***	*Strongylura exilis*
Atherinomorus	**Giganturidae**	*Scopelarchoides nicholsi*	*Strongylura incisa*
Atherinomorus duodecimalis	***Gigantura***	*Scopelarchoides signifer*	*Strongylura leiura*
Atherinomorus endrachtensis	*Gigantura chuni*	***Scopelarchus***	*Strongylura marina*
Atherinomorus insularum	**Ipnopidae**	*Scopelarchus michaelsarsi*	*Strongylura notata notata*
Atherinomorus lacunosus	***Bathymicrops***	**Synodontidae**	*Strongylura senegalensis*
Atherinosoma	*Bathymicrops regis*	***Harpadon***	***Tylosurus***
Atherinosoma elongata	***Bathypterois***	*Harpadon nehereus*	*Tylosurus acus acus*
Atherinosoma microstoma	*Bathypterois atricolor*	***Saurida***	*Tylosurus acus melanotus*
Atherion	*Bathypterois dubius*	*Saurida brasiliensis*	*Tylosurus crocodilus*
Atherion elymus	*Bathypterois grallator*	*Saurida gracilis*	*Tylosurus fodiator*
Craterocephalus	*Bathypterois longifilis*	*Saurida nebulosa*	*Tylosurus pacificus*
Craterocephalus mugiloides	*Bathypterois longipes*	*Saurida tumbil*	**Exocoetidae**
Hypoatherina	*Bathypterois phenax*	*Saurida undosquamis*	***Cheilopogon***
Hypoatherina barnesi	*Bathypterois quadrifilis*	***Synodus***	*Cheilopogon abei*
Hypoatherina ovalaua	*Bathypterois viridensis*	*Synodus binotatus*	*Cheilopogon agoo*
Kestratherina	***Bathytyphlops***	*Synodus dermatogenys*	*Cheilopogon cyanopterus*
Kestratherina esox	*Bathytyphlops marionae*	*Synodus foetens*	*Cheilopogon furcatus*
Leptatherina	*Bathytyphlops sewelli*	*Synodus intermedius*	*Cheilopogon heterurus*
Leptatherina presbyteroides	***Ipnops***	*Synodus jaculum*	*Cheilopogon katoptron*
Stenatherina	*Ipnops agassizii*	*Synodus lacertinus*	*Cheilopogon melanurus*
Stenatherina panatela	**Notosudidae**	*Synodus lucioceps*	*Cheilopogon nigricans*
Atherinopsidae	***Ahliesaurus***	*Synodus poeyi*	*Cheilopogon pitcairnensis*
Atherinella	*Ahliesaurus berryi*	*Synodus rubromarmoratus*	*Cheilopogon spilonotopterus*
Atherinella brasiliensis	*Ahliesaurus brevis*	*Synodus saurus*	***Cypselurus***
Atherinella eriarcha	***Scopelosaurus***	*Synodus scituliceps*	*Cypselurus angusticeps*
Atherinella nepenthe	*Scopelosaurus adleri*	*Synodus sechurae*	*Cypselurus callopterus*
Atherinops	*Scopelosaurus ahlstromi*	*Synodus synodus*	*Cypselurus naresii*
Atherinops affinis	*Scopelosaurus argenteus*	*Synodus variegatus*	*Cypselurus oligolepis*
Atherinopsis	*Scopelosaurus hamiltoni*	***Trachinocephalus***	*Cypselurus opisthopus*
Atherinopsis californiensis	*Scopelosaurus harryi*	*Trachinocephalus myops*	*Cypselurus poecilopterus*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Exocoetus	*Myripristis kuntee*	*Alosa alosa*	*Opisthonema bulleri*
Exocoetus monocirrhus	*Myripristis leiognathus*	*Alosa chrysochloris*	*Opisthonema libertate*
Exocoetus obtusirostris	*Myripristis murdjan*	*Alosa fallax*	*Opisthonema medirastre*
Fodiator	*Myripristis pralinia*	*Alosa immaculata*	*Opisthonema oglinum*
Fodiator rostratus	*Myripristis violacea*	*Alosa mediocris*	***Pellonula***
Hirundichthys	*Myripristis vittata*	*Alosa pseudoharengus*	*Pellonula leonensis*
Hirundichthys affinis	*Myripristis woodsi*	*Alosa sapidissima*	***Ramnogaster***
Hirundichthys marginatus	***Neoniphon***	*Alosa tanaica*	*Ramnogaster arcuata*
Hirundichthys oxycephalus	*Neoniphon argenteus*	***Amblygaster***	***Sardina***
Hirundichthys rondeletii	*Neoniphon aurolineatus*	*Amblygaster clupeoides*	*Sardina pilchardus*
Hirundichthys speculiger	*Neoniphon marianus*	*Amblygaster leiogaster*	***Sardinella***
Parexocoetus	*Neoniphon opercularis*	*Amblygaster sirm*	*Sardinella albella*
Parexocoetus brachypterus	*Neoniphon sammara*	***Anodontostoma***	*Sardinella aurita*
Parexocoetus mento	***Ostichthys***	*Anodontostoma chacunda*	*Sardinella brachysoma*
Prognichthys	*Ostichthys archiepiscopus*	*Anodontostoma selangkat*	*Sardinella brasiliensis*
Prognichthys occidentalis	*Ostichthys trachypoma*	*Anodontostoma thailandiae*	*Sardinella fijiense*
Prognichthys tringa	***Plectrypops***	***Brevoortia***	*Sardinella fimbriata*
Hemiramphidae	*Plectrypops lima*	*Brevoortia aurea*	*Sardinella gibbosa*
Arrhamphus	***Sargocentron***	*Brevoortia gunteri*	*Sardinella hualiensis*
Arrhamphus sclerolepis	*Sargocentron caudimaculatum*	*Brevoortia patronus*	*Sardinella jussieu*
Hemiramphus	*Sargocentron cornutum*	*Brevoortia pectinata*	*Sardinella lemuru*
Hemiramphus balao	*Sargocentron coruscum*	*Brevoortia smithi*	*Sardinella longiceps*
Hemiramphus brasiliensis	*Sargocentron diadema*	*Brevoortia tyrannus*	*Sardinella maderensis*
Hemiramphus far	*Sargocentron hastatum*	***Clupanodon***	*Sardinella marquesensis*
Hemiramphus robustus	*Sargocentron iota*	*Clupanodon thrissa*	*Sardinella melanura*
Hyporhamphus	*Sargocentron ittodai*	***Clupea***	*Sardinella richardsoni*
Hyporhamphus acutus	*Sargocentron melanospilos*	*Clupea harengus*	*Sardinella rouxi*
Hyporhamphus australis	*Sargocentron microstoma*	*Clupea pallasii pallasii*	*Sardinella sindensis*
Hyporhamphus gilli	*Sargocentron punctatissimum*	***Clupeonella***	*Sardinella zunasi*
Hyporhamphus melanochir	*Sargocentron rubrum*	*Clupeonella cultriventris*	***Spratelloides***
Hyporhamphus picarti	*Sargocentron spiniferum*	***Dorosoma***	*Spratelloides delicatulus*
Hyporhamphus sajori	*Sargocentron suborbitale*	*Dorosoma cepedianum*	*Spratelloides lewisi*
Hyporhamphus unifasciatus	*Sargocentron tiere*	*Dorosoma petenense*	*Spratelloides robustus*
Oxyporhamphus	*Sargocentron tiereoides*	***Escualosa***	***Sprattus***
Oxyporhamphus micropterus	*Sargocentron violaceum*	*Escualosa thoracata*	*Sprattus antipodum*
Scomberesocidae	**Monocentridae**	***Ethmalosa***	*Sprattus fuegensis*
Cololabis	***Cleidopus***	*Ethmalosa fimbriata*	*Sprattus muelleri*
Cololabis saira	*Cleidopus gloriamaris*	***Harengula***	*Sprattus novaehollandiae*
Scomberesox	**Trachichthyidae**	*Harengula clupeola*	*Sprattus sprattus*
Scomberesox saurus	***Gephyroberyx***	*Harengula humeralis*	***Tenualosa***
Beryciformes	*Gephyroberyx darwinii*	*Harengula jaguana*	*Tenualosa ilisha*
Anomalopidae	***Hoplostethus***	*Harengula thrissina*	*Tenualosa macrura*
Anomalops	*Hoplostethus atlanticus*	***Herklotsichthys***	*Tenualosa reevesii*
Anomalops katoptron	*Hoplostethus cadenati*	*Herklotsichthys blackburni*	*Tenualosa toli*
Photoblepharon	*Hoplostethus crassispinus*	*Herklotsichthys castelnaui*	**Dussumieriidae**
Photoblepharon palpebratum	*Hoplostethus melanopeza*	*Herklotsichthys dispilonotus*	***Dussumieria***
Anoplogastridae	**Cetomimiformes**	*Herklotsichthys gotoi*	*Dussumieria acuta*
Anoplogaster	**Cetomimidae**	*Herklotsichthys koningsbergeri*	*Dussumieria elopsoides*
Anoplogaster cornuta	***Cetostoma***	*Herklotsichthys lippa*	***Etrumeus***
Berycidae	*Cetostoma regani*	*Herklotsichthys lossei*	*Etrumeus whiteheadi*
Beryx	***Danacetichthys***	*Herklotsichthys punctatus*	**Engraulidae**
Beryx decadactylus	*Danacetichthys galathenus*	*Herklotsichthys quadrimaculatus*	***Anchoa***
Beryx splendens	***Ditropichthys***	*Herklotsichthys spilurus*	*Anchoa argentivittata*
Centroberyx	*Ditropichthys storeri*	***Hilsa***	*Anchoa cayorum*
Centroberyx affinis	***Eutaeniophorus***	*Hilsa kelee*	*Anchoa chamensis*
Centroberyx gerrardi	*Eutaeniophorus festivus*	***Hyperlophus***	*Anchoa colonensis*
Diretmidae	***Gyrinomimus***	*Hyperlophus vittatus*	*Anchoa compressa*
Diretmichthys	*Gyrinomimus bruuni*	***Jenkinsia***	*Anchoa cubana*
Diretmichthys parini	*Gyrinomimus grahami*	*Jenkinsia lamprotaenia*	*Anchoa curta*
Diretmus	***Parataeniophorus***	*Jenkinsia majua*	*Anchoa delicatissima*
Diretmus argenteus	*Parataeniophorus gulosus*	*Jenkinsia stolifera*	*Anchoa eigenmannia*
Holocentridae	**Rondeletiidae**	***Konosirus***	*Anchoa exigua*
Holocentrus	***Rondeletia***	*Konosirus punctatus*	*Anchoa filifera*
Holocentrus adscensionis	*Rondeletia loricata*	***Lile***	*Anchoa helleri*
Holocentrus rufus	**Clupeiformes**	*Lile piquitinga*	*Anchoa hepsetus*
Myripristis	**Chirocentridae**	*Lile stolifera*	*Anchoa ischana*
Myripristis adusta	***Chirocentrus***	***Nematalosa***	*Anchoa lamprotaenia*
Myripristis amaena	*Chirocentrus dorab*	*Nematalosa galatheae*	*Anchoa lucida*
Myripristis berndti	*Chirocentrus nudus*	*Nematalosa japonica*	*Anchoa lyolepis*
Myripristis chryseres	**Clupeidae**	*Nematalosa nasus*	*Anchoa mitchilli*
Myripristis hexagona	***Alosa***	***Opisthonema***	*Anchoa nasus*
Myripristis jacobus	*Alosa aestivalis*	*Opisthonema berlangai*	*Anchoa panamensis*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Anchoa parva	*Thryssa setirostris*	***Gadus***	*Coelorinchus karrerae*
Anchoa pectoralis	*Thryssa spinidens*	*Gadus macrocephalus*	*Coelorinchus kishinouyei*
Anchoa scofieldi	*Thryssa vitrirostris*	*Gadus morhua*	*Coelorinchus labiatus*
Anchoa spinifer	**Pristigasteridae**	***Melanogrammus***	*Coelorinchus macrochir*
Anchoa starksi	***Chirocentrodon***	*Melanogrammus aeglefinus*	*Coelorinchus marinii*
Anchoa tricolor	*Chirocentrodon bleekerianus*	***Merlangius***	*Coelorinchus mirus*
Anchoa walkeri	***Ilisha***	*Merlangius merlangus*	*Coelorinchus mycterismus*
Anchovia	*Ilisha africana*	***Microgadus***	*Coelorinchus occa*
Anchovia clupeoides	*Ilisha elongata*	*Microgadus proximus*	*Coelorinchus oliverianus*
Anchovia macrolepidota	*Ilisha filigera*	*Microgadus tomcod*	*Coelorinchus parallelus*
Anchoviella	*Ilisha fuerthii*	***Micromesistius***	*Coelorinchus scaphopsis*
Anchoviella brevirostris	*Ilisha kampeni*	*Micromesistius australis*	*Coelorinchus supernasutus*
Anchoviella lepidentostole	*Ilisha macrogaster*	*Micromesistius poutassou*	*Coelorinchus thurla*
Anchoviella perfasciata	*Ilisha megaloptera*	***Pollachius***	*Coelorinchus ventrilux*
Cetengraulis	*Ilisha melastoma*	*Pollachius pollachius*	***Coryphaenoides***
Cetengraulis edentulus	*Ilisha sirishai*	*Pollachius virens*	*Coryphaenoides acrolepis*
Cetengraulis mysticetus	*Ilisha striatula*	***Raniceps***	*Coryphaenoides anguliceps*
Coilia	***Neoopisthopterus***	*Raniceps raninus*	*Coryphaenoides ariommus*
Coilia dussumieri	*Neoopisthopterus tropicus*	***Trisopterus***	*Coryphaenoides armatus*
Coilia grayii	***Odontognathus***	*Trisopterus esmarkii*	*Coryphaenoides boops*
Coilia nasus	*Odontognathus mucronatus*	*Trisopterus luscus*	*Coryphaenoides bucephalus*
Coilia neglecta	***Opisthopterus***	*Trisopterus minutus*	*Coryphaenoides bulbiceps*
Coilia reynaldi	*Opisthopterus dovii*	**Lotidae**	*Coryphaenoides capito*
Encrasicholina	*Opisthopterus tardoore*	***Brosme***	*Coryphaenoides carminifer*
Encrasicholina devisi	*Opisthopterus valenciennesi*	*Brosme brosme*	*Coryphaenoides cinereus*
Encrasicholina heteroloba	***Pellona***	***Ciliata***	*Coryphaenoides delsolari*
Encrasicholina punctifer	*Pellona ditchela*	*Ciliata mustela*	*Coryphaenoides ferrieri*
Encrasicholina purpurea	*Pellona harroweri*	*Ciliata septentrionalis*	*Coryphaenoides filicauda*
Engraulis	***Pliosteostoma***	***Enchelyopus***	*Coryphaenoides filifer*
Engraulis anchoita	*Pliosteostoma lutipinnis*	*Enchelyopus cimbrius*	*Coryphaenoides guentheri*
Engraulis australis	***Raconda***	***Gaidropsarus***	*Coryphaenoides lecointei*
Engraulis encrasicolus	*Raconda russeliana*	*Gaidropsarus argentatus*	*Coryphaenoides leptolepis*
Engraulis eurystole	**Cyprinodontiformes**	*Gaidropsarus biscayensis*	*Coryphaenoides longifilis*
Engraulis japonicus	**Cyprinodontidae**	*Gaidropsarus ensis*	*Coryphaenoides marginatus*
Engraulis mordax	***Aphanius***	*Gaidropsarus granti*	*Coryphaenoides mediterraneus*
Engraulis ringens	*Aphanius fasciatus*	*Gaidropsarus guttatus*	*Coryphaenoides mexicanus*
Lycengraulis	**Fundulidae**	*Gaidropsarus macrophthalmus*	*Coryphaenoides rudis*
Lycengraulis grossidens	***Fundulus***	*Gaidropsarus mediterraneus*	*Coryphaenoides rupestris*
Lycengraulis poeyi	*Fundulus confluentus*	*Gaidropsarus vulgaris*	*Coryphaenoides serrulatus*
Setipinna	*Fundulus heteroclitus*	***Molva***	*Coryphaenoides subserrulatus*
Setipinna breviceps	*Fundulus majalis*	*Molva dypterygia*	*Coryphaenoides zaniophorus*
Setipinna melanochir	*Fundulus similis*	*Molva macrophthalma*	***Cynomacrurus***
Setipinna taty	***Lucania***	*Molva molva*	*Cynomacrurus piriei*
Setipinna tenuifilis	*Lucania parva*	**Macrouridae**	***Echinomacrurus***
Stolephorus	**Elopiformes**	***Albatrossia***	*Echinomacrurus mollis*
Stolephorus advenus	**Elopidae**	*Albatrossia pectoralis*	***Gadomus***
Stolephorus andhraensis	***Elops***	***Bathygadus***	*Gadomus arcuatus*
Stolephorus apiensis	*Elops hawaiensis*	*Bathygadus macrops*	*Gadomus longifilis*
Stolephorus baganensis	*Elops lacerta*	*Bathygadus melanobranchus*	***Hymenocephalus***
Stolephorus brachycephalus	*Elops machnata*	***Coelorinchus***	*Hymenocephalus italicus*
Stolephorus carpentariae	*Elops saurus*	*Coelorinchus acanthiger*	***Lepidorhynchus***
Stolephorus chinensis	**Megalopidae**	*Coelorinchus aconcagua*	*Lepidorhynchus denticulatus*
Stolephorus commersonnii	***Megalops***	*Coelorinchus anatirostris*	***Lucigadus***
Stolephorus dubiosus	*Megalops atlanticus*	*Coelorinchus argentatus*	*Lucigadus nigromaculatus*
Stolephorus holodon	*Megalops cyprinoides*	*Coelorinchus argus*	***Macrourus***
Stolephorus indicus	**Gadiformes**	*Coelorinchus aspercephalus*	*Macrourus berglax*
Stolephorus insularis	**Bregmacerotidae**	*Coelorinchus australis*	*Macrourus carinatus*
Stolephorus tri	***Bregmaceros***	*Coelorinchus biclinozonalis*	*Macrourus holotrachys*
Stolephorus waitei	*Bregmaceros bathymaster*	*Coelorinchus caelorhincus*	*Macrourus whitsoni*
Thryssa	*Bregmaceros japonicus*	*Coelorinchus canus*	***Malacocephalus***
Thryssa aestuaria	*Bregmaceros mcclellandi*	*Coelorinchus caribbaeus*	*Malacocephalus laevis*
Thryssa baelama	**Gadidae**	*Coelorinchus celaenostomus*	*Malacocephalus occidentalis*
Thryssa brevicauda	***Arctogadus***	*Coelorinchus charius*	***Mataeocephalus***
Thryssa dayi	*Arctogadus glacialis*	*Coelorinchus chilensis*	*Mataeocephalus acipenserinus*
Thryssa dussumieri	***Boreogadus***	*Coelorinchus denticulatus*	*Mataeocephalus tenuicauda*
Thryssa encrasicholoides	*Boreogadus saida*	*Coelorinchus fasciatus*	***Mesobius***
Thryssa gautamiensis	***Eleginus***	*Coelorinchus formosanus*	*Mesobius berryi*
Thryssa hamiltonii	*Eleginus gracilis*	*Coelorinchus horribilis*	***Nezumia***
Thryssa kammalensis	*Eleginus nawaga*	*Coelorinchus innotabilis*	*Nezumia aequalis*
Thryssa malabarica	***Gadiculus***	*Coelorinchus japonicus*	*Nezumia atlantica*
Thryssa mystax	*Gadiculus argenteus*	*Coelorinchus kaiyomaru*	*Nezumia bairdii*
Thryssa purava	*Gadiculus thori*	*Coelorinchus kamoharai*	*Nezumia brevibarbata*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Nezumia condylura	*Eeyorius hutchinsi*	***Hypoptychus***	*Antennarius commerson*
Nezumia convergens	***Gadella***	*Hypoptychus dybowskii*	*Antennarius hispidus*
Nezumia duodecim	*Gadella brocca*	**Pegasidae**	*Antennarius maculatus*
Nezumia kapala	*Gadella imberbis*	***Eurypegasus***	*Antennarius multiocellatus*
Nezumia latirostrata	*Gadella maraldi*	*Eurypegasus draconis*	*Antennarius pardalis*
Nezumia liolepis	***Halargyreus***	*Eurypegasus papilio*	*Antennarius pictus*
Nezumia loricata	*Halargyreus johnsonii*	***Pegasus***	*Antennarius randalli*
Nezumia micronychodon	***Laemonema***	*Pegasus lancifer*	*Antennarius striatus*
Nezumia milleri	*Laemonema barbatulum*	*Pegasus laternarius*	***Antennatus***
Nezumia orbitalis	*Laemonema goodebeanorum*	*Pegasus volitans*	*Antennatus analis*
Nezumia parini	*Laemonema laureysi*	**Gobiesociformes**	*Antennatus coccineus*
Nezumia propinqua	*Laemonema longipes*	**Gobiesocidae**	*Antennatus dorehensis*
Nezumia proxima	*Laemonema verecundum*	***Apletodon***	*Antennatus nummifer*
Nezumia pudens	*Laemonema yarrellii*	*Apletodon dentatus*	*Antennatus rosaceus*
Nezumia pulchella	***Lepidion***	*Apletodon incognitus*	*Antennatus sanguineus*
Nezumia sclerorhynchus	*Lepidion ensiferus*	***Diplecogaster***	*Antennatus strigatus*
Nezumia stelgidolepis	*Lepidion eques*	*Diplecogaster bimaculata*	*Antennatus tuberosus*
Sphagemacrurus	*Lepidion guentheri*	***Gobiesox***	***Echinophryne***
Sphagemacrurus grenadae	*Lepidion lepidion*	*Gobiesox maeandricus*	*Echinophryne crassispina*
Sphagemacrurus hirundo	***Mora***	*Gobiesox strumosus*	*Echinophryne reynoldsi*
Trachonurus	*Mora moro*	***Gouania***	***Fowlerichthys***
Trachonurus gagates	***Notophycis***	*Gouania willdenowi*	*Fowlerichthys avalonis*
Trachonurus robinsi	*Notophycis marginata*	***Lepadichthys***	*Fowlerichthys ocellatus*
Trachonurus sulcatus	***Physiculus***	*Lepadichthys caritus*	*Fowlerichthys radiosus*
Trachyrincus	*Physiculus dalwigki*	*Lepadichthys minor*	***Histrio***
Trachyrincus helolepis	*Physiculus huloti*	***Lepadogaster***	*Histrio histrio*
Trachyrincus scabrus	*Physiculus japonicus*	*Lepadogaster candolii*	***Kuiterichthys***
Trachyrincus villegai	*Physiculus nematopus*	*Lepadogaster lepadogaster*	*Kuiterichthys furcipilis*
Ventrifossa	*Physiculus rastrelliger*	***Rimicola***	***Lophiocharon***
Ventrifossa atherodon	***Pseudophycis***	*Rimicola muscarum*	*Lophiocharon trisignatus*
Ventrifossa ctenomelas	*Pseudophycis bachus*	**Gonorynchiformes**	***Phyllophryne***
Ventrifossa divergens	*Pseudophycis barbata*	**Chanidae**	*Phyllophryne scortea*
Ventrifossa garmani	*Pseudophycis breviuscula*	***Chanos***	***Rhycherus***
Ventrifossa macropogon	***Salilota***	*Chanos chanos*	*Rhycherus filamentosus*
Ventrifossa misakia	*Salilota australis*	**Gonorynchidae**	***Tathicarpus***
Ventrifossa mucocephalus	***Tripterophycis***	***Gonorynchus***	*Tathicarpus butleri*
Ventrifossa nasuta	*Tripterophycis gilchristi*	*Gonorynchus forsteri*	**Brachionichthyidae**
Ventrifossa nigrodorsalis	**Muraenolepididae**	*Gonorynchus gonorynchus*	***Brachionichthys***
Ventrifossa petersonii	***Muraenolepis***	*Gonorynchus greyi*	*Brachionichthys hirsutus*
Melanonidae	*Muraenolepis marmorata*	**Lampriformes**	**Centrophrynidae**
Melanonus	*Muraenolepis microps*	**Lampridae**	***Centrophryne***
Melanonus gracilis	*Muraenolepis orangiensis*	***Lampris***	*Centrophryne spinulosa*
Melanonus zugmayeri	***Notomuraenobathys***	*Lampris guttatus*	**Ceratiidae**
Merlucciidae	*Notomuraenobathys microcephalus*	*Lampris immaculatus*	***Ceratias***
Lyconus	**Phycidae**	**Lophotidae**	*Ceratias holboelli*
Lyconus brachycolus	***Phycis***	***Lophotus***	*Ceratias tentaculatus*
Macruronus	*Phycis blennoides*	*Lophotus lacepede*	***Cryptopsaras***
Macruronus capensis	*Phycis chesteri*	**Radiicephalidae**	*Cryptopsaras couesii*
Macruronus magellanicus	*Phycis phycis*	***Radiicephalus***	**Chaunacidae**
Macruronus novaezelandiae	***Urophycis***	*Radiicephalus elongatus*	***Chaunacops***
Merluccius	*Urophycis brasiliensis*	**Regalecidae**	*Chaunacops melanostomus*
Merluccius albidus	*Urophycis chuss*	***Agrostichthys***	***Chaunax***
Merluccius angustimanus	*Urophycis cirrata*	*Agrostichthys parkeri*	*Chaunax abei*
Merluccius australis	*Urophycis earllii*	***Regalecus***	*Chaunax endeavouri*
Merluccius bilinearis	*Urophycis floridana*	*Regalecus glesne*	*Chaunax fimbriatus*
Merluccius capensis	*Urophycis regia*	**Stylephoridae**	*Chaunax nebulosus*
Merluccius gayi gayi	*Urophycis tenuis*	***Stylephorus***	*Chaunax stigmaeus*
Merluccius hubbsi	**Gasterosteiformes**	*Stylephorus chordatus*	*Chaunax suttkusi*
Merluccius merluccius	**Aulorhynchidae**	**Trachipteridae**	**Gigantactinidae**
Merluccius paradoxus	***Aulorhynchus***	***Desmodema***	***Gigantactis***
Merluccius polli	*Aulorhynchus flavidus*	*Desmodema lorum*	*Gigantactis vanhoeffeni*
Merluccius productus	**Gasterosteidae**	*Desmodema polystictum*	**Linophrynidae**
Merluccius senegalensis	***Apeltes***	***Trachipterus***	***Borophryne***
Steindachneria	*Apeltes quadracus*	*Trachipterus altivelis*	*Borophryne apogon*
Steindachneria argentea	***Gasterosteus***	*Trachipterus arcticus*	**Lophiidae**
Moridae	*Gasterosteus aculeatus*	*Trachipterus trachypterus*	***Lophiodes***
Antimora	*Gasterosteus wheatlandi*	**Lophiiformes**	*Lophiodes caulinaris*
Antimora microlepis	***Pungitius***	**Antennariidae**	*Lophiodes insidiator*
Antimora rostrata	*Pungitius pungitius*	***Allenichthys***	*Lophiodes kempi*
Auchenoceros	***Spinachia***	*Allenichthys glauerti*	*Lophiodes monodi*
Auchenoceros punctatus	*Spinachia spinachia*	***Antennarius***	*Lophiodes reticulatus*
Eeyorius	**Hypoptychidae**	*Antennarius biocellatus*	*Lophiodes spilurus*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Lophius	***Neochelon***	*Electrona carlsbergi*	*Nannobrachium atrum*
Lophius americanus	*Neochelon falcipinnis*	*Electrona paucirastra*	*Nannobrachium cuprarium*
Lophius budegassa	***Neomyxus***	*Electrona risso*	*Nannobrachium hawaiiensis*
Lophius gastrophysus	*Neomyxus leuciscus*	*Electrona subaspera*	*Nannobrachium idostigma*
Lophius piscatorius	***Oedalechilus***	***Gonichthys***	*Nannobrachium lineatum*
Lophius vaillanti	*Oedalechilus labeo*	*Gonichthys barnesi*	*Nannobrachium regale*
Lophius vomerinus	***Osteomugil***	*Gonichthys cocco*	*Nannobrachium ritteri*
Melanocetidae	*Osteomugil engeli*	*Gonichthys tenuiculus*	***Notolychnus***
Melanocetus	***Planiliza***	***Gymnoscopelus***	*Notolychnus valdiviae*
Melanocetus johnsonii	*Planiliza alata*	*Gymnoscopelus bolini*	***Notoscopelus***
Melanocetus murrayi	*Planiliza haematocheila*	*Gymnoscopelus braueri*	*Notoscopelus bolini*
Melanocetus polyactis	*Planiliza macrolepis*	*Gymnoscopelus fraseri*	*Notoscopelus caudispinosus*
Ogcocephalidae	*Planiliza melinopterus*	*Gymnoscopelus hintonoides*	*Notoscopelus elongatus*
Halieutaea	*Planiliza subviridis*	*Gymnoscopelus nicholsi*	*Notoscopelus japonicus*
Halieutaea brevicauda	***Plicomugil***	*Gymnoscopelus opisthopterus*	*Notoscopelus kroyeri*
Halieutichthys	*Plicomugil labiosus*	*Gymnoscopelus piabilis*	*Notoscopelus resplendens*
Halieutichthys aculeatus	***Pseudomyxus***	***Hintonia***	***Parvilux***
Ogcocephalus	*Pseudomyxus capensis*	*Hintonia candens*	*Parvilux ingens*
Ogcocephalus corniger	**Myctophiformes**	***Hygophum***	***Protomyctophum***
Ogcocephalus cubifrons	**Myctophidae**	*Hygophum atratum*	*Protomyctophum andriashevi*
Ogcocephalus radiatus	***Benthosema***	*Hygophum benoiti*	*Protomyctophum arcticum*
Ogcocephalus rostellum	*Benthosema fibulatum*	*Hygophum hanseni*	*Protomyctophum beckeri*
Ogcocephalus vespertilio	*Benthosema glaciale*	*Hygophum hygomii*	*Protomyctophum bolini*
Oneirodidae	*Benthosema panamense*	***Krefftichthys***	*Protomyctophum choriodon*
Bertella	*Benthosema suborbitale*	*Krefftichthys anderssoni*	*Protomyctophum crockeri*
Bertella idiomorpha	***Bolinichthys***	***Lampadena***	*Protomyctophum gemmatum*
Chaenophryne	*Bolinichthys distofax*	*Lampadena anomala*	*Protomyctophum luciferum*
Chaenophryne draco	*Bolinichthys indicus*	*Lampadena atlantica*	*Protomyctophum normani*
Chaenophryne longiceps	*Bolinichthys longipes*	*Lampadena chavesi*	*Protomyctophum parallelum*
Chaenophryne melanorhabdus	*Bolinichthys photothorax*	*Lampadena luminosa*	*Protomyctophum subparallelum*
Oneirodes	*Bolinichthys supralateralis*	*Lampadena notialis*	*Protomyctophum tenisoni*
Oneirodes acanthias	***Centrobranchus***	*Lampadena speculigera*	*Protomyctophum thompsoni*
Oneirodes bulbosus	*Centrobranchus nigroocellatus*	*Lampadena urophaos*	***Scopelopsis***
Oneirodes clarkei	***Ceratoscopelus***	***Lampanyctodes***	*Scopelopsis multipunctatus*
Oneirodes kreffti	*Ceratoscopelus townsendi*	*Lampanyctodes hectoris*	***Stenobrachius***
Oneirodes macronema	*Ceratoscopelus warmingii*	***Lampanyctus***	*Stenobrachius leucopsarus*
Oneirodes notius	***Diaphus***	*Lampanyctus alatus*	*Stenobrachius nannochir*
Oneirodes thompsoni	*Diaphus adenomus*	*Lampanyctus australis*	***Symbolophorus***
Mugiliformes	*Diaphus anderseni*	*Lampanyctus crocodilus*	*Symbolophorus boops*
Mugilidae	*Diaphus antonbruuni*	*Lampanyctus festivus*	*Symbolophorus californiensis*
Agonostomus	*Diaphus bertelseni*	*Lampanyctus intricarius*	*Symbolophorus kreffti*
Agonostomus monticola	*Diaphus brachycephalus*	*Lampanyctus lepidolychnus*	*Symbolophorus veranyi*
Aldrichetta	*Diaphus chrysorhynchus*	*Lampanyctus macdonaldi*	***Taaningichthys***
Aldrichetta forsteri	*Diaphus diademophilus*	*Lampanyctus macropterus*	*Taaningichthys bathyphilus*
Chaenomugil	*Diaphus dumerilii*	*Lampanyctus nobilis*	*Taaningichthys minimus*
Chaenomugil proboscideus	*Diaphus effulgens*	*Lampanyctus pusillus*	*Taaningichthys paurolychnus*
Chelon	*Diaphus fragilis*	*Lampanyctus steinbecki*	***Tarletonbeania***
Chelon auratus	*Diaphus fulgens*	***Lampichthys***	*Tarletonbeania crenularis*
Chelon dumerili	*Diaphus garmani*	*Lampichthys procerus*	***Triphoturus***
Chelon labrosus	*Diaphus holti*	***Lepidophanes***	*Triphoturus mexicanus*
Chelon planiceps	*Diaphus hudsoni*	*Lepidophanes guentheri*	*Triphoturus nigrescens*
Chelon ramada	*Diaphus lucidus*	***Lobianchia***	**Neoscopelidae**
Chelon richardsonii	*Diaphus luetkeni*	*Lobianchia dofleini*	***Neoscopelus***
Chelon saliens	*Diaphus malayanus*	*Lobianchia gemellarii*	*Neoscopelus macrolepidotus*
Crenimugil	*Diaphus megalops*	***Loweina***	*Neoscopelus microchir*
Crenimugil buchanani	*Diaphus metopoclampus*	*Loweina rara*	***Scopelengys***
Crenimugil crenilabis	*Diaphus mollis*	***Metelectrona***	*Scopelengys tristis*
Crenimugil heterocheilos	*Diaphus perspicillatus*	*Metelectrona ventralis*	**Notacanthiformes**
Crenimugil seheli	*Diaphus phillipsi*	***Myctophum***	**Halosauridae**
Ellochelon	*Diaphus problematicus*	*Myctophum affine*	***Aldrovandia***
Ellochelon vaigiensis	*Diaphus rafinesquii*	*Myctophum asperum*	*Aldrovandia gracilis*
Gracilimugil	*Diaphus schmidti*	*Myctophum aurolaternatum*	*Aldrovandia oleosa*
Gracilimugil argenteus	*Diaphus splendidus*	*Myctophum fissunovi*	*Aldrovandia rostrata*
Mugil	*Diaphus subtilis*	*Myctophum lychnobium*	***Halosauropsis***
Mugil cephalus	*Diaphus taaningi*	*Myctophum nitidulum*	*Halosauropsis macrochir*
Mugil curema	*Diaphus termophilus*	*Myctophum obtusirostre*	***Halosaurus***
Mugil curvidens	*Diaphus theta*	*Myctophum phengodes*	*Halosaurus johnsonianus*
Mugil gaimardianus	***Diogenichthys***	*Myctophum punctatum*	*Halosaurus ovenii*
Mugil incilis	*Diogenichthys atlanticus*	*Myctophum selenops*	**Notacanthidae**
Mugil liza	*Diogenichthys panurgus*	*Myctophum spinosum*	***Lipogenys***
Mugil thoburni	***Electrona***	***Nannobrachium***	*Lipogenys gillii*
Mugil trichodon	*Electrona antarctica*	*Nannobrachium achirus*	***Notacanthus***

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Notacanthus bonaparte	***Lepophidium***	***Einara***	*Nansenia atlantica*
Notacanthus chemnitzii	*Lepophidium aporrhox*	*Einara edentula*	*Nansenia candida*
Polyacanthonotus	*Lepophidium brevibarbe*	*Einara macrolepis*	*Nansenia crassa*
Polyacanthonotus africanus	*Lepophidium collettei*	***Herwigia***	*Nansenia groenlandica*
Polyacanthonotus rissoanus	*Lepophidium crossotum*	*Herwigia kreffti*	*Nansenia oblita*
Ophidiiformes	*Lepophidium cultratum*	***Leptoderma***	*Nansenia tenera*
Aphyonidae	*Lepophidium entomelan*	*Leptoderma macrops*	**Opisthoproctidae**
Nybelinella	*Lepophidium gilmorei*	***Mirognathus***	***Bathylychnops***
Nybelinella erikssoni	*Lepophidium inca*	*Mirognathus normani*	*Bathylychnops exilis*
Bythitidae	*Lepophidium jeannae*	***Narcetes***	***Dolichopteroides***
Brosmophyciops	*Lepophidium kallion*	*Narcetes lloydi*	*Dolichopteroides binocularis*
Brosmophyciops pautzkei	*Lepophidium marmoratum*	*Narcetes stomias*	***Dolichopteryx***
Brosmophycis	*Lepophidium microlepis*	***Photostylus***	*Dolichopteryx longipes*
Brosmophycis marginata	*Lepophidium negropinna*	*Photostylus pycnopterus*	***Macropinna***
Cataetyx	*Lepophidium pardale*	***Rinoctes***	*Macropinna microstoma*
Cataetyx alleni	*Lepophidium pheromystax*	*Rinoctes nasutus*	***Monacoa***
Cataetyx laticeps	*Lepophidium profundorum*	***Rouleina***	*Monacoa grimaldii*
Cataetyx messieri	*Lepophidium prorates*	*Rouleina attrita*	***Opisthoproctus***
Cataetyx rubrirostris	*Lepophidium robustum*	*Rouleina guentheri*	*Opisthoproctus soleatus*
Dermatopsis	*Lepophidium staurophor*	*Rouleina maderensis*	***Rhynchohyalus***
Dermatopsis hoesei	*Lepophidium wileyi*	*Rouleina squamilatera*	*Rhynchohyalus natalensis*
Dermatopsis multiradiatus	*Lepophidium zophochir*	***Talismania***	***Winteria***
Dinematichthys	***Monomitopus***	*Talismania antillarum*	*Winteria telescopa*
Dinematichthys iluocoeteoides	*Monomitopus magnus*	*Talismania bifurcata*	**Osmeridae**
Dipulus	*Monomitopus metriostoma*	*Talismania homoptera*	***Allosmerus***
Dipulus caecus	***Ophidion***	*Talismania longifilis*	*Allosmerus elongatus*
Lucifuga	*Ophidion barbatum*	*Talismania mekistonema*	***Hypomesus***
Lucifuga spelaeotes	*Ophidion galeoides*	***Xenodermichthys***	*Hypomesus pretiosus*
Ogilbia	*Ophidion grayi*	*Xenodermichthys copei*	***Mallotus***
Ogilbia nudiceps	*Ophidion holbrookii*	**Argentinidae**	*Mallotus villosus*
Ogilbia sedorae	*Ophidion iris*	***Argentina***	***Osmerus***
Ogilbia ventralis	*Ophidion lozanoi*	*Argentina aliceae*	*Osmerus eperlanus*
Carapidae	*Ophidion marginatum*	*Argentina australiae*	*Osmerus mordax*
Carapus	*Ophidion metoecus*	*Argentina euchus*	***Spirinchus***
Carapus acus	*Ophidion rochei*	*Argentina sialis*	*Spirinchus starksi*
Carapus dubius	*Ophidion selenops*	*Argentina silus*	*Spirinchus thaleichthys*
Echiodon	***Otophidium***	*Argentina sphyraena*	***Thaleichthys***
Echiodon drummondii	*Otophidium omostigma*	*Argentina striata*	*Thaleichthys pacificus*
Encheliophis	***Parophidion***	***Glossanodon***	**Platytroctidae**
Encheliophis homei	*Parophidion vassali*	*Glossanodon leioglossus*	***Holtbyrnia***
Encheliophis vermicularis	***Raneya***	*Glossanodon semifasciatus*	*Holtbyrnia anomala*
Pyramodon	*Raneya brasiliensis*	**Bathylagidae**	*Holtbyrnia conocephala*
Pyramodon ventralis	***Selachophidium***	***Bathylagichthys***	*Holtbyrnia cyanocephala*
Ophidiidae	*Selachophidium guentheri*	*Bathylagichthys greyae*	*Holtbyrnia laticauda*
Abyssobrotula	***Spectrunculus***	***Bathylagoides***	*Holtbyrnia latifrons*
Abyssobrotula galatheae	*Spectrunculus grandis*	*Bathylagoides argyrogaster*	*Holtbyrnia macrops*
Acanthonus	**Osmeriformes**	*Bathylagoides nigrigenys*	***Maulisia***
Acanthonus armatus	**Alepocephalidae**	*Bathylagoides wesethi*	*Maulisia argipalla*
Benthocometes	***Alepocephalus***	***Bathylagus***	*Maulisia mauli*
Benthocometes robustus	*Alepocephalus agassizii*	*Bathylagus antarcticus*	*Maulisia microlepis*
Brotula	*Alepocephalus australis*	*Bathylagus gracilis*	***Normichthys***
Brotula barbata	*Alepocephalus bairdii*	*Bathylagus pacificus*	*Normichthys operosus*
Brotula clarkae	*Alepocephalus productus*	*Bathylagus tenuis*	*Normichthys yahganorum*
Brotula multibarbata	*Alepocephalus rostratus*	***Dolicholagus***	***Persparsia***
Brotula townsendi	*Alepocephalus triangularis*	*Dolicholagus longirostris*	*Persparsia kopua*
Cherublemma	***Asquamiceps***	***Leuroglossus***	***Platytroctes***
Cherublemma emmelas	*Asquamiceps caeruleus*	*Leuroglossus schmidti*	*Platytroctes apus*
Chilara	***Bajacalifornia***	***Lipolagus***	*Platytroctes mirus*
Chilara taylori	*Bajacalifornia megalops*	*Lipolagus ochotensis*	***Sagamichthys***
Epetriodus	***Bathylaco***	***Melanolagus***	*Sagamichthys schnakenbecki*
Epetriodus freddyi	*Bathylaco nigricans*	*Melanolagus bericoides*	***Searsia***
Genypterus	***Bathyprion***	**Galaxiidae**	*Searsia koefoedi*
Genypterus blacodes	*Bathyprion danae*	***Galaxias***	**Plecoglossidae**
Genypterus brasiliensis	***Bathytroctes***	*Galaxias truttaceus*	***Plecoglossus***
Genypterus capensis	*Bathytroctes macrolepis*	**Leptochilichthyidae**	*Plecoglossus altivelis*
Genypterus chilensis	*Bathytroctes michaelsarsi*	***Leptochilichthys***	**Perciformes**
Genypterus maculatus	*Bathytroctes microlepis*	*Leptochilichthys agassizii*	**Acanthuridae**
Genypterus tigerinus	*Bathytroctes oligolepis*	*Leptochilichthys pinguis*	***Acanthurus***
Lamprogrammus	***Conocara***	**Microstomatidae**	*Acanthurus achilles*
Lamprogrammus exutus	*Conocara macropterum*	***Microstoma***	*Acanthurus albipectoralis*
Lamprogrammus shcherbachevi	*Conocara murrayi*	*Microstoma microstoma*	*Acanthurus auranticavus*
	Conocara salmoneum	***Nansenia***	*Acanthurus bahianus*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Acanthurus bariene	*Parascombrops spinosus*	*Cheilodipterus parazonatus*	*Sphaeramia orbicularis*
Acanthurus blochii	***Synagrops***	*Cheilodipterus quinquelineatus*	***Taeniamia***
Acanthurus chirurgus	*Synagrops bellus*	*Cheilodipterus singapurensis*	*Taeniamia biguttata*
Acanthurus coeruleus	*Synagrops japonicus*	*Cheilodipterus zonatus*	*Taeniamia fucata*
Acanthurus dussumieri	**Amarsipidae**	***Fibramia***	*Taeniamia zosterophora*
Acanthurus gahhm	***Amarsipus***	*Fibramia amboinensis*	***Verulux***
Acanthurus grammoptilus	*Amarsipus carlsbergi*	*Fibramia lateralis*	*Verulux cypselurus*
Acanthurus guttatus	**Ambassidae**	***Foa***	***Zapogon***
Acanthurus leucocheilus	***Ambassis***	*Foa brachygramma*	*Zapogon evermanni*
Acanthurus leucopareius	*Ambassis interrupta*	***Fowleria***	***Zoramia***
Acanthurus leucosternon	*Ambassis jacksoniensis*	*Fowleria aurita*	*Zoramia fragilis*
Acanthurus lineatus	*Ambassis miops*	*Fowleria flammea*	*Zoramia gilberti*
Acanthurus maculiceps	*Ambassis natalensis*	*Fowleria isostigma*	*Zoramia leptacantha*
Acanthurus mata	*Ambassis vachellii*	*Fowleria marmorata*	*Zoramia perlita*
Acanthurus monroviae	**Ammodytidae**	*Fowleria punctulata*	**Ariommatidae**
Acanthurus nigricans	***Ammodytes***	*Fowleria variegata*	***Ariomma***
Acanthurus nigricauda	*Ammodytes americanus*	***Gymnapogon***	*Ariomma bondi*
Acanthurus nigrofuscus	*Ammodytes dubius*	*Gymnapogon philippinus*	*Ariomma indicum*
Acanthurus nigroris	*Ammodytes hexapterus*	*Gymnapogon urospilotus*	*Ariomma luridum*
Acanthurus olivaceus	*Ammodytes marinus*	***Jaydia***	*Ariomma melanum*
Acanthurus pyroferus	*Ammodytes personatus*	*Jaydia ellioti*	*Ariomma regulus*
Acanthurus thompsoni	*Ammodytes tobianus*	***Nectamia***	**Arripidae**
Acanthurus triostegus	***Ammodytoides***	*Nectamia annularis*	***Arripis***
Acanthurus tristis	*Ammodytoides pylei*	*Nectamia bandanensis*	*Arripis georgianus*
Acanthurus xanthopterus	***Bleekeria***	*Nectamia fusca*	*Arripis trutta*
Ctenochaetus	*Bleekeria mitsukurii*	*Nectamia ignitops*	*Arripis truttacea*
Ctenochaetus binotatus	***Gymnammodytes***	*Nectamia luxuria*	**Artedidraconidae**
Ctenochaetus cyanocheilus	*Gymnammodytes capensis*	*Nectamia similis*	***Artedidraco***
Ctenochaetus hawaiiensis	*Gymnammodytes cicerelus*	*Nectamia viria*	*Artedidraco lonnbergi*
Ctenochaetus marginatus	*Gymnammodytes semisquamatus*	***Ostorhinchus***	*Artedidraco mirus*
Ctenochaetus striatus	***Hyperoplus***	*Ostorhinchus angustatus*	*Artedidraco orianae*
Ctenochaetus strigosus	*Hyperoplus immaculatus*	*Ostorhinchus aureus*	*Artedidraco shackletoni*
Ctenochaetus tominiensis	*Hyperoplus lanceolatus*	*Ostorhinchus compressus*	*Artedidraco skottsbergi*
Naso	**Anarhichadidae**	*Ostorhinchus cyanosoma*	***Dolloidraco***
Naso annulatus	***Anarhichas***	*Ostorhinchus dispar*	*Dolloidraco longedorsalis*
Naso brachycentron	*Anarhichas denticulatus*	*Ostorhinchus diversus*	***Histiodraco***
Naso brevirostris	*Anarhichas lupus*	*Ostorhinchus hartzfeldii*	*Histiodraco velifer*
Naso elegans	*Anarhichas minor*	*Ostorhinchus margaritophorus*	***Pogonophryne***
Naso hexacanthus	*Anarhichas orientalis*	*Ostorhinchus nigrofasciatus*	*Pogonophryne barsukovi*
Naso lituratus	***Anarrhichthys***	*Ostorhinchus novemfasciatus*	*Pogonophryne lanceobarbata*
Naso lopezi	*Anarrhichthys ocellatus*	*Ostorhinchus rubrimacula*	*Pogonophryne marmorata*
Naso maculatus	**Aplodactylidae**	*Ostorhinchus rueppellii*	*Pogonophryne permitini*
Naso mcdadei	***Aplodactylus***	*Ostorhinchus sealei*	*Pogonophryne scotti*
Naso unicornis	*Aplodactylus arctidens*	*Ostorhinchus taeniophorus*	*Pogonophryne ventrimaculata*
Naso vlamingii	**Apogonidae**	***Paroncheilus***	**Bathydraconidae**
Paracanthurus	***Apogon***	*Paroncheilus affinis*	***Akarotaxis***
Paracanthurus hepatus	*Apogon binotatus*	***Phaeoptyx***	*Akarotaxis nudiceps*
Prionurus	*Apogon caudicinctus*	*Phaeoptyx pigmentaria*	***Bathydraco***
Prionurus laticlavius	*Apogon coccineus*	***Pristiapogon***	*Bathydraco antarcticus*
Prionurus microlepidotus	*Apogon doryssa*	*Pristiapogon exostigma*	*Bathydraco joannae*
Prionurus punctatus	*Apogon dovii*	*Pristiapogon fraenatus*	*Bathydraco macrolepis*
Zebrasoma	*Apogon imberbis*	*Pristiapogon kallopterus*	*Bathydraco marri*
Zebrasoma desjardinii	*Apogon maculatus*	*Pristiapogon taeniopterus*	***Cygnodraco***
Zebrasoma flavescens	*Apogon phenax*	***Pristicon***	*Cygnodraco mawsoni*
Zebrasoma scopas	*Apogon pseudomaculatus*	*Pristicon trimaculatus*	***Gerlachea***
Zebrasoma velifer	***Apogonichthyoides***	***Pseudamia***	*Gerlachea australis*
Zebrasoma xanthurum	*Apogonichthyoides brevicaudatus*	*Pseudamia amblyuroptera*	***Gymnodraco***
Acropomatidae	*Apogonichthyoides melas*	*Pseudamia gelatinosa*	*Gymnodraco acuticeps*
Acropoma	*Apogonichthyoides pseudotaeniatus*	*Pseudamia hayashii*	***Parachaenichthys***
Acropoma japonicum	***Apogonichthys***	*Pseudamia tarri*	*Parachaenichthys charcoti*
Apogonops	*Apogonichthys ocellatus*	*Pseudamia zonata*	*Parachaenichthys georgianus*
Apogonops anomalus	*Apogonichthys perdix*	***Pseudamiops***	***Prionodraco***
Caraibops	***Astrapogon***	*Pseudamiops gracilicauda*	*Prionodraco evansii*
Caraibops trispinosus	*Astrapogon alutus*	***Rhabdamia***	***Psilodraco***
Doederleinia	*Astrapogon stellatus*	*Rhabdamia gracilis*	*Psilodraco breviceps*
Doederleinia berycoides	***Cheilodipterus***	***Siphamia***	***Racovitzia***
Kaperangus	*Cheilodipterus arabicus*	*Siphamia cephalotes*	*Racovitzia glacialis*
Kaperangus microlepis	*Cheilodipterus artus*	*Siphamia fistulosa*	***Vomeridens***
Malakichthys	*Cheilodipterus isostigmus*	*Siphamia fuscolineata*	*Vomeridens infuscipinnis*
Malakichthys elegans	*Cheilodipterus lachneri*	*Siphamia randalli*	**Bathymasteridae**
Parascombrops	*Cheilodipterus macrodon*	***Sphaeramia***	***Bathymaster***
Parascombrops philippinensis	*Cheilodipterus novemstriatus*	*Sphaeramia nematoptera*	*Bathymaster caeruleofasciatus*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Blenniidae	***Glyptoparus***	*Salarias luctuosus*	***Diplogrammus***
Aidablennius	*Glyptoparus delicatulus*	***Scartichthys***	*Diplogrammus goramensis*
Aidablennius sphynx	***Hypleurochilus***	*Scartichthys gigas*	*Diplogrammus pauciradiatus*
Alticus	*Hypleurochilus bermudensis*	*Scartichthys variolatus*	***Foetorepus***
Alticus saliens	*Hypleurochilus geminatus*	***Stanulus***	*Foetorepus agassizii*
Aspidontus	***Hypsoblennius***	*Stanulus seychellensis*	*Foetorepus phasis*
Aspidontus dussumieri	*Hypsoblennius gentilis*	***Xiphasia***	***Neosynchiropus***
Aspidontus taeniatus	*Hypsoblennius gilberti*	*Xiphasia matsubarai*	*Neosynchiropus ocellatus*
Atrosalarias	*Hypsoblennius hentz*	**Bovichtidae**	***Synchiropus***
Atrosalarias fuscus	*Hypsoblennius invemar*	***Cottoperca***	*Synchiropus altivelis*
Atrosalarias holomelas	***Istiblennius***	*Cottoperca gobio*	*Synchiropus circularis*
Blenniella	*Istiblennius edentulus*	**Bramidae**	*Synchiropus goodenbeani*
Blenniella bilitonensis	*Istiblennius lineatus*	***Brama***	*Synchiropus laddi*
Blenniella caudolineata	*Istiblennius unicolor*	*Brama brama*	*Synchiropus morrisoni*
Blenniella chrysospilos	***Lipophrys***	*Brama dussumieri*	*Synchiropus phaeton*
Blenniella periophthalmus	*Lipophrys pholis*	*Brama japonica*	*Synchiropus picturatus*
Blennius	*Lipophrys trigloides*	***Eumegistus***	**Caproidae**
Blennius ocellaris	***Litobranchus***	*Eumegistus brevorti*	***Antigonia***
Chasmodes	*Litobranchus fowleri*	***Pterycombus***	*Antigonia capros*
Chasmodes bosquianus	***Meiacanthus***	*Pterycombus brama*	*Antigonia combatia*
Chasmodes saburrae	*Meiacanthus anema*	***Taractes***	*Antigonia rhomboidea*
Cirripectes	*Meiacanthus atrodorsalis*	*Taractes asper*	***Capros***
Cirripectes alboapicalis	*Meiacanthus ditrema*	***Taractichthys***	*Capros aper*
Cirripectes auritus	*Meiacanthus grammistes*	*Taractichthys longipinnis*	**Carangidae**
Cirripectes castaneus	*Meiacanthus luteus*	*Taractichthys steindachneri*	***Alectis***
Cirripectes chelomatus	***Microlipophrys***	**Caesionidae**	*Alectis alexandrina*
Cirripectes filamentosus	*Microlipophrys adriaticus*	***Caesio***	*Alectis ciliaris*
Cirripectes fuscoguttatus	*Microlipophrys canevae*	*Caesio caerulaurea*	*Alectis indica*
Cirripectes gilberti	*Microlipophrys nigriceps*	*Caesio cuning*	***Alepes***
Cirripectes hutchinsi	***Nannosalarias***	*Caesio lunaris*	*Alepes djedaba*
Cirripectes imitator	*Nannosalarias nativitatis*	*Caesio striata*	*Alepes kleinii*
Cirripectes jenningsi	***Omobranchus***	*Caesio suevica*	*Alepes melanoptera*
Cirripectes obscurus	*Omobranchus obliquus*	*Caesio teres*	***Atule***
Cirripectes perustus	*Omobranchus punctatus*	*Caesio varilineata*	*Atule mate*
Cirripectes polyzona	***Omox***	*Caesio xanthonota*	***Campogramma***
Cirripectes quagga	*Omox biporos*	***Dipterygonotus***	*Campogramma glaycos*
Cirripectes randalli	***Ophioblennius***	*Dipterygonotus balteatus*	***Carangoides***
Cirripectes springeri	*Ophioblennius steindachneri*	***Gymnocaesio***	*Carangoides armatus*
Cirripectes stigmaticus	***Parablennius***	*Gymnocaesio gymnoptera*	*Carangoides bajad*
Cirripectes vanderbilti	*Parablennius gattorugine*	***Pterocaesio***	*Carangoides bartholomaei*
Cirripectes variolosus	*Parablennius incognitus*	*Pterocaesio chrysozona*	*Carangoides chrysophrys*
Coryphoblennius	*Parablennius marmoreus*	*Pterocaesio digramma*	*Carangoides coeruleopinnatus*
Coryphoblennius galerita	*Parablennius parvicornis*	*Pterocaesio lativittata*	*Carangoides dinema*
Ecsenius	*Parablennius pilicornis*	*Pterocaesio marri*	*Carangoides equula*
Ecsenius axelrodi	*Parablennius rouxi*	*Pterocaesio pisang*	*Carangoides ferdau*
Ecsenius bicolor	*Parablennius sanguinolentus*	*Pterocaesio randalli*	*Carangoides fulvoguttatus*
Ecsenius bimaculatus	*Parablennius tentacularis*	*Pterocaesio tessellata*	*Carangoides gymnostethus*
Ecsenius dilemma	*Parablennius zvonimiri*	*Pterocaesio tile*	*Carangoides orthogrammus*
Ecsenius fourmanoiri	***Paralticus***	*Pterocaesio trilineata*	*Carangoides otrynter*
Ecsenius lividanalis	*Paralticus amboinensis*	**Callanthiidae**	*Carangoides plagiotaenia*
Ecsenius melarchus	***Parenchelyurus***	***Callanthias***	***Caranx***
Ecsenius monoculus	*Parenchelyurus hepburni*	*Callanthias ruber*	*Caranx bucculentus*
Ecsenius namiyei	***Petroscirtes***	***Grammatonotus***	*Caranx caballus*
Ecsenius oculus	*Petroscirtes breviceps*	*Grammatonotus laysanus*	*Caranx caninus*
Ecsenius opsifrontalis	*Petroscirtes mitratus*	**Callionymidae**	*Caranx crysos*
Ecsenius pictus	*Petroscirtes thepassii*	***Anaora***	*Caranx heberi*
Ecsenius sellifer	*Petroscirtes variabilis*	*Anaora tentaculata*	*Caranx hippos*
Ecsenius stigmatura	*Petroscirtes xestus*	***Callionymus***	*Caranx ignobilis*
Ecsenius yaeyamaensis	***Plagiotremus***	*Callionymus bairdi*	*Caranx latus*
Enchelyurus	*Plagiotremus laudandus*	*Callionymus delicatulus*	*Caranx lugubris*
Enchelyurus kraussii	*Plagiotremus rhinorhynchos*	*Callionymus enneactis*	*Caranx melampygus*
Entomacrodus	*Plagiotremus tapeinosoma*	*Callionymus fasciatus*	*Caranx papuensis*
Entomacrodus caudofasciatus	***Praealticus***	*Callionymus filamentosus*	*Caranx rhonchus*
Entomacrodus chiostictus	*Praealticus natalis*	*Callionymus hindsii*	*Caranx ruber*
Entomacrodus decussatus	***Rhabdoblennius***	*Callionymus lyra*	*Caranx senegallus*
Entomacrodus nigricans	*Rhabdoblennius rhabdotrachelus*	*Callionymus maculatus*	*Caranx sexfasciatus*
Entomacrodus niuafoouensis	***Salaria***	*Callionymus pusillus*	*Caranx tille*
Entomacrodus sealei	*Salaria basilisca*	*Callionymus reticulatus*	*Caranx vinctus*
Entomacrodus striatus	*Salaria fluviatilis*	*Callionymus risso*	***Chloroscombrus***
Entomacrodus thalassinus	*Salaria pavo*	*Callionymus sagitta*	*Chloroscombrus chrysurus*
Exallias	***Salarias***	*Callionymus simplicicornis*	*Chloroscombrus orqueta*
Exallias brevis	*Salarias fasciatus*		***Decapterus***

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Decapterus kurroides	*Trachurus murphyi*	***Coralliozetus***	***Hemitaurichthys***
Decapterus macarellus	*Trachurus novaezelandiae*	*Coralliozetus angelicus*	*Hemitaurichthys polylepis*
Decapterus macrosoma	*Trachurus picturatus*	***Emblemaria***	*Hemitaurichthys thompsoni*
Decapterus maruadsi	*Trachurus symmetricus*	*Emblemaria atlantica*	***Heniochus***
Decapterus punctatus	*Trachurus trecae*	*Emblemaria pandionis*	*Heniochus acuminatus*
Decapterus russelli	***Uraspis***	*Emblemaria piratula*	*Heniochus chrysostomus*
Decapterus tabl	*Uraspis helvola*	***Neoclinus***	*Heniochus diphreutes*
Elagatis	*Uraspis uraspis*	*Neoclinus blanchardi*	*Heniochus monoceros*
Elagatis bipinnulata	**Caristiidae**	*Neoclinus stephensae*	*Heniochus singularius*
Hemicaranx	***Caristius***	*Neoclinus uninotatus*	*Heniochus varius*
Hemicaranx amblyrhynchus	*Caristius macropus*	***Stathmonotus***	***Johnrandallia***
Hemicaranx leucurus	***Neocaristius***	*Stathmonotus sinuscalifornici*	*Johnrandallia nigrirostris*
Hemicaranx zelotes	*Neocaristius heemstrai*	**Chaetodontidae**	***Prognathodes***
Lichia	***Paracaristius***	***Amphichaetodon***	*Prognathodes aculeatus*
Lichia amia	*Paracaristius aquilus*	*Amphichaetodon melbae*	*Prognathodes aya*
Megalaspis	*Paracaristius maderensis*	***Chaetodon***	*Prognathodes marcellae*
Megalaspis cordyla	*Paracaristius nemorosus*	*Chaetodon adiergastos*	**Champsodontidae**
Naucrates	*Paracaristius nudarcus*	*Chaetodon assarius*	***Champsodon***
Naucrates ductor	***Platyberyx***	*Chaetodon aureofasciatus*	*Champsodon guentheri*
Oligoplites	*Platyberyx andriashevi*	*Chaetodon auriga*	**Channichthyidae**
Oligoplites altus	*Platyberyx opalescens*	*Chaetodon auripes*	***Chaenocephalus***
Oligoplites palometa	**Centrolophidae**	*Chaetodon austriacus*	*Chaenocephalus aceratus*
Oligoplites refulgens	***Centrolophus***	*Chaetodon baronessa*	***Chaenodraco***
Oligoplites saliens	*Centrolophus niger*	*Chaetodon bennetti*	*Chaenodraco wilsoni*
Oligoplites saurus	***Hyperoglyphe***	*Chaetodon burgessi*	***Champsocephalus***
Parastromateus	*Hyperoglyphe antarctica*	*Chaetodon capistratus*	*Champsocephalus esox*
Parastromateus niger	*Hyperoglyphe bythites*	*Chaetodon citrinellus*	*Champsocephalus gunnari*
Parona	*Hyperoglyphe perciformis*	*Chaetodon ephippium*	***Channichthys***
Parona signata	***Icichthys***	*Chaetodon falcula*	*Channichthys rhinoceratus*
Pseudocaranx	*Icichthys australis*	*Chaetodon flavirostris*	***Chionobathyscus***
Pseudocaranx dentex	*Icichthys lockingtoni*	*Chaetodon humeralis*	*Chionobathyscus dewitti*
Scomberoides	***Psenopsis***	*Chaetodon interruptus*	***Chionodraco***
Scomberoides lysan	*Psenopsis anomala*	*Chaetodon kleinii*	*Chionodraco hamatus*
Scomberoides tala	***Schedophilus***	*Chaetodon lineolatus*	*Chionodraco myersi*
Selar	*Schedophilus medusophagus*	*Chaetodon marleyi*	*Chionodraco rastrospinosus*
Selar boops	*Schedophilus ovalis*	*Chaetodon melannotus*	***Cryodraco***
Selar crumenophthalmus	*Schedophilus velaini*	*Chaetodon mertensii*	*Cryodraco antarcticus*
Selaroides	***Seriolella***	*Chaetodon meyeri*	***Dacodraco***
Selaroides leptolepis	*Seriolella brama*	*Chaetodon nippon*	*Dacodraco hunteri*
Selene	*Seriolella caerulea*	*Chaetodon ocellatus*	***Neopagetopsis***
Selene brevoortii	*Seriolella porosa*	*Chaetodon ocellicaudus*	*Neopagetopsis ionah*
Selene dorsalis	*Seriolella punctata*	*Chaetodon octofasciatus*	***Pagetopsis***
Selene orstedii	**Centropomidae**	*Chaetodon ornatissimus*	*Pagetopsis macropterus*
Selene setapinnis	***Centropomus***	*Chaetodon oxycephalus*	*Pagetopsis maculatus*
Selene vomer	*Centropomus armatus*	*Chaetodon pelewensis*	***Pseudochaenichthys***
Seriola	*Centropomus ensiferus*	*Chaetodon plebeius*	*Pseudochaenichthys georgianus*
Seriola dumerili	*Centropomus medius*	*Chaetodon punctatofasciatus*	**Cheilodactylidae**
Seriola fasciata	*Centropomus mexicanus*	*Chaetodon quadrimaculatus*	***Cheilodactylus***
Seriola hippos	*Centropomus nigrescens*	*Chaetodon rafflesii*	*Cheilodactylus variegatus*
Seriola lalandi	*Centropomus parallelus*	*Chaetodon rainfordi*	***Chirodactylus***
Seriola peruana	*Centropomus pectinatus*	*Chaetodon reticulatus*	*Chirodactylus brachydactylus*
Seriola rivoliana	*Centropomus robalito*	*Chaetodon robustus*	*Chirodactylus grandis*
Seriola zonata	*Centropomus undecimalis*	*Chaetodon sedentarius*	*Chirodactylus jessicalenorum*
Seriolina	*Centropomus unionensis*	*Chaetodon semeion*	***Nemadactylus***
Seriolina nigrofasciata	*Centropomus viridis*	*Chaetodon speculum*	*Nemadactylus bergi*
Trachinotus	**Cepolidae**	*Chaetodon striatus*	*Nemadactylus douglasii*
Trachinotus baillonii	***Acanthocepola***	*Chaetodon tinkeri*	*Nemadactylus macropterus*
Trachinotus blochii	*Acanthocepola abbreviata*	*Chaetodon tricinctus*	**Chiasmodontidae**
Trachinotus carolinus	*Acanthocepola krusensternii*	*Chaetodon trifascialis*	***Chiasmodon***
Trachinotus cayennensis	*Acanthocepola limbata*	*Chaetodon ulietensis*	*Chiasmodon niger*
Trachinotus falcatus	***Cepola***	*Chaetodon unimaculatus*	*Chiasmodon subniger*
Trachinotus goodei	*Cepola macrophthalma*	*Chaetodon vagabundus*	***Dysalotus***
Trachinotus goreensis	**Chaenopsidae**	***Chelmon***	*Dysalotus alcocki*
Trachinotus kennedyi	***Acanthemblemaria***	*Chelmon marginalis*	*Dysalotus oligoscolus*
Trachinotus ovatus	*Acanthemblemaria aspera*	*Chelmon muelleri*	***Kali***
Trachinotus teraia	*Acanthemblemaria balanorum*	***Chelmonops***	*Kali indica*
Trachurus	*Acanthemblemaria crockeri*	*Chelmonops curiosus*	***Pseudoscopelus***
Trachurus capensis	*Acanthemblemaria exilispinus*	***Coradion***	*Pseudoscopelus sagamianus*
Trachurus declivis	*Acanthemblemaria hancocki*	*Coradion chrysozonus*	*Pseudoscopelus scriptus*
Trachurus japonicus	*Acanthemblemaria macrospilus*	***Forcipiger***	**Chironemidae**
Trachurus lathami	*Acanthemblemaria maria*	*Forcipiger flavissimus*	***Chironemus***
Trachurus mediterraneus	*Acanthemblemaria spinosa*	*Forcipiger longirostris*	*Chironemus marmoratus*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Cichlidae	*Drepane punctata*	**Ephippidae**	*Eucinostomus jonesii*
Tilapia	**Echeneidae**	***Chaetodipterus***	*Eucinostomus melanopterus*
Tilapia sparrmanii	***Echeneis***	*Chaetodipterus faber*	***Eugerres***
Cirrhitidae	*Echeneis naucrates*	*Chaetodipterus zonatus*	*Eugerres brasilianus*
Amblycirrhitus	*Echeneis neucratoides*	***Parapsettus***	*Eugerres plumieri*
Amblycirrhitus bimacula	***Remora***	*Parapsettus panamensis*	***Gerres***
Amblycirrhitus unimacula	*Remora osteochir*	***Platax***	*Gerres cinereus*
Cirrhitichthys	*Remora remora*	*Platax orbicularis*	*Gerres erythrourus*
Cirrhitichthys falco	**Eleginopsidae**	*Platax pinnatus*	*Gerres filamentosus*
Cirrhitichthys oxycephalus	***Eleginops***	*Platax teira*	*Gerres longirostris*
Cirrhitus	*Eleginops maclovinus*	**Epigonidae**	*Gerres methueni*
Cirrhitus pinnulatus	**Eleotridae**	***Epigonus***	*Gerres nigri*
Cirrhitus rivulatus	***Bunaka***	*Epigonus constanciae*	*Gerres oblongus*
Neocirrhites	*Bunaka gyrinoides*	*Epigonus crassicaudus*	*Gerres oyena*
Neocirrhites armatus	***Calumia***	*Epigonus denticulatus*	***Parequula***
Oxycirrhites	*Calumia godeffroyi*	*Epigonus lenimen*	*Parequula melbournensis*
Oxycirrhites typus	***Dormitator***	*Epigonus pandionis*	***Ulaema***
Paracirrhites	*Dormitator latifrons*	*Epigonus robustus*	*Ulaema lefroyi*
Paracirrhites arcatus	*Dormitator lebretonis*	*Epigonus telescopus*	**Glaucosomatidae**
Paracirrhites forsteri	*Dormitator maculatus*	**Gempylidae**	***Glaucosoma***
Paracirrhites hemistictus	***Eleotris***	***Diplospinus***	*Glaucosoma buergeri*
Clinidae	*Eleotris fusca*	*Diplospinus multistriatus*	*Glaucosoma hebraicum*
Blennophis	*Eleotris melanosoma*	***Epinnula***	*Glaucosoma magnificum*
Blennophis anguillaris	*Eleotris pisonis*	*Epinnula magistralis*	*Glaucosoma scapulare*
Clinitrachus	*Eleotris senegalensis*	***Gempylus***	**Gobiidae**
Clinitrachus argentatus	***Giuris***	*Gempylus serpens*	***Acanthogobius***
Clinus	*Giuris margaritacea*	***Lepidocybium***	*Acanthogobius flavimanus*
Clinus agilis	***Gobiomorphus***	*Lepidocybium flavobrunneum*	***Acentrogobius***
Clinus superciliosus	*Gobiomorphus gobioides*	***Nealotus***	*Acentrogobius caninus*
Clinus venustris	***Gobiomorus***	*Nealotus tripes*	*Acentrogobius nebulosus*
Gibbonsia	*Gobiomorus dormitor*	***Neoepinnula***	***Amblyeleotris***
Gibbonsia elegans	**Embiotocidae**	*Neoepinnula americana*	*Amblyeleotris fasciata*
Gibbonsia metzi	***Amphistichus***	*Neoepinnula orientalis*	*Amblyeleotris fontanesii*
Gibbonsia montereyensis	*Amphistichus argenteus*	***Nesiarchus***	*Amblyeleotris guttata*
Heterostichus	*Amphistichus koelzi*	*Nesiarchus nasutus*	*Amblyeleotris periophthalma*
Heterostichus rostratus	*Amphistichus rhodoterus*	***Paradiplospinus***	*Amblyeleotris randalli*
Muraenoclinus	***Brachyistius***	*Paradiplospinus antarcticus*	*Amblyeleotris steinitzi*
Muraenoclinus dorsalis	*Brachyistius frenatus*	*Paradiplospinus gracilis*	*Amblyeleotris wheeleri*
Pavoclinus	***Cymatogaster***	***Promethichthys***	***Amblygobius***
Pavoclinus pavo	*Cymatogaster aggregata*	*Promethichthys prometheus*	*Amblygobius decussatus*
Springeratus	***Embiotoca***	***Rexea***	*Amblygobius nocturnus*
Springeratus xanthosoma	*Embiotoca jacksoni*	*Rexea alisae*	***Aphia***
Coryphaenidae	*Embiotoca lateralis*	*Rexea antefurcata*	*Aphia minuta*
Coryphaena	***Hyperprosopon***	*Rexea bengalensis*	***Asterropteryx***
Coryphaena equiselis	*Hyperprosopon anale*	*Rexea brevilineata*	*Asterropteryx ensifera*
Coryphaena hippurus	*Hyperprosopon argenteum*	*Rexea nakamurai*	*Asterropteryx semipunctata*
Creediidae	*Hyperprosopon ellipticum*	*Rexea prometheoides*	***Bathygobius***
Chalixodytes	***Hypsurus***	*Rexea solandri*	*Bathygobius coalitus*
Chalixodytes tauensis	*Hypsurus caryi*	***Rexichthys***	*Bathygobius cocosensis*
Cryptacanthodidae	***Micrometrus***	*Rexichthys johnpaxtoni*	*Bathygobius cotticeps*
Cryptacanthodes	*Micrometrus aurora*	***Ruvettus***	*Bathygobius curacao*
Cryptacanthodes giganteus	*Micrometrus minimus*	*Ruvettus pretiosus*	*Bathygobius fuscus*
Cryptacanthodes maculatus	***Phanerodon***	***Thyrsites***	*Bathygobius soporator*
Dactyloscopidae	*Phanerodon atripes*	*Thyrsites atun*	***Bollmannia***
Dactyloscopus	*Phanerodon furcatus*	***Thyrsitoides***	*Bollmannia chlamydes*
Dactyloscopus crossotus	***Rhacochilus***	*Thyrsitoides marleyi*	***Bryaninops***
Dactyloscopus foraminosus	*Rhacochilus toxotes*	***Thyrsitops***	*Bryaninops amplus*
Dactyloscopus moorei	*Rhacochilus vacca*	*Thyrsitops lepidopoides*	*Bryaninops erythrops*
Dactyloscopus tridigitatus	***Zalembius***	***Tongaichthys***	*Bryaninops natans*
Gillellus	*Zalembius rosaceus*	*Tongaichthys robustus*	*Bryaninops ridens*
Gillellus healae	**Emmelichthyidae**	**Gerreidae**	*Bryaninops yongei*
Dichistiidae	***Emmelichthys***	***Diapterus***	***Buenia***
Dichistius	*Emmelichthys nitidus nitidus*	*Diapterus auratus*	*Buenia affinis*
Dichistius capensis	*Emmelichthys ruber*	*Diapterus peruvianus*	*Buenia jeffreysii*
Dinopercidae	***Erythrocles***	*Diapterus rhombeus*	***Cabillus***
Centrarchops	*Erythrocles monodi*	***Eucinostomus***	*Cabillus tongarevae*
Centrarchops chapini	*Erythrocles scintillans*	*Eucinostomus argenteus*	***Callogobius***
Dinoperca	***Plagiogeneion***	*Eucinostomus currani*	*Callogobius centrolepis*
Dinoperca petersi	*Plagiogeneion rubiginosum*	*Eucinostomus entomelas*	*Callogobius hasseltii*
Drepaneidae	**Enoplosidae**	*Eucinostomus gracilis*	*Callogobius maculipinnis*
Drepane	***Enoplosus***	*Eucinostomus gula*	*Callogobius mucosus*
Drepane africana	*Enoplosus armatus*	*Eucinostomus havana*	*Callogobius okinawae*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Callogobius sclateri	*Glossogobius celebius*	***Millerigobius***	***Tigrigobius***
Chromogobius	*Glossogobius giuris*	*Millerigobius macrocephalus*	*Tigrigobius multifasciatus*
Chromogobius quadrivittatus	***Gnatholepis***	***Mugilogobius***	***Trimma***
Clevelandia	*Gnatholepis cauerensis*	*Mugilogobius littoralis*	*Trimma naudei*
Clevelandia ios	*Gnatholepis thompsoni*	***Neogobius***	*Trimma okinawae*
Coryphopterus	***Gobiodon***	*Neogobius melanostomus*	*Trimma taylori*
Coryphopterus glaucofraenum	*Gobiodon albofasciatus*	***Nes***	*Trimma tevegae*
Coryphopterus hyalinus	*Gobiodon citrinus*	*Nes longus*	*Trimma trioculatum*
Coryphopterus lipernes	*Gobiodon okinawae*	***Nesogobius***	***Trimmatom***
Coryphopterus personatus	*Gobiodon quinquestrigatus*	*Nesogobius hinsbyi*	*Trimmatom eviotops*
Coryphopterus urospilus	*Gobiodon rivulatus*	***Odondebuenia***	*Trimmatom nanus*
Croilia	***Gobionellus***	*Odondebuenia balearica*	***Valenciennea***
Croilia mossambica	*Gobionellus occidentalis*	***Oplopomops***	*Valenciennea helsdingenii*
Cryptocentroides	*Gobionellus oceanicus*	*Oplopomops diacanthus*	*Valenciennea muralis*
Cryptocentroides insignis	***Gobiopsis***	***Opua***	*Valenciennea puellaris*
Cryptocentrus	*Gobiopsis bravoi*	*Opua nephodes*	*Valenciennea sexguttata*
Cryptocentrus cinctus	***Gobiosoma***	***Oxyurichthys***	*Valenciennea strigata*
Cryptocentrus strigilliceps	*Gobiosoma bosc*	*Oxyurichthys stigmalophius*	***Vanderhorstia***
Crystallogobius	*Gobiosoma ginsburgi*	***Paragobiodon***	*Vanderhorstia ambanoro*
Crystallogobius linearis	***Gobius***	*Paragobiodon echinocephalus*	*Vanderhorstia ornatissima*
Ctenogobiops	*Gobius auratus*	*Paragobiodon lacunicolus*	***Zebrus***
Ctenogobiops aurocingulus	*Gobius bucchichi*	*Paragobiodon melanosomus*	*Zebrus zebrus*
Ctenogobiops feroculus	*Gobius cobitis*	*Paragobiodon modestus*	***Zosterisessor***
Ctenogobiops pomastictus	*Gobius couchi*	*Paragobiodon xanthosoma*	*Zosterisessor ophiocephalus*
Ctenogobiops tangaroai	*Gobius cruentatus*	***Periophthalmus***	**Grammatidae**
Ctenogobius	*Gobius gasteveni*	*Periophthalmus barbarus*	***Gramma***
Ctenogobius boleosoma	*Gobius geniporus*	*Periophthalmus kalolo*	*Gramma brasiliensis*
Ctenogobius sagittula	*Gobius niger*	***Pleurosicya***	**Haemulidae**
Deltentosteus	*Gobius paganellus*	*Pleurosicya bilobata*	***Anisotremus***
Deltentosteus quadrimaculatus	*Gobius vittatus*	*Pleurosicya micheli*	*Anisotremus caesius*
Elacatinus	*Gobius xanthocephalus*	*Pleurosicya muscarum*	*Anisotremus davidsonii*
Elacatinus figaro	***Gobiusculus***	***Pomatoschistus***	*Anisotremus interruptus*
Elacatinus oceanops	*Gobiusculus flavescens*	*Pomatoschistus bathi*	*Anisotremus moricandi*
Elacatinus xanthiprora	***Ilypnus***	*Pomatoschistus lozanoi*	*Anisotremus scapularis*
Evermannichthys	*Ilypnus gilberti*	*Pomatoschistus marmoratus*	*Anisotremus surinamensis*
Evermannichthys metzelaari	***Istigobius***	*Pomatoschistus microps*	*Anisotremus taeniatus*
Eviota	*Istigobius campbelli*	*Pomatoschistus minutus*	*Anisotremus virginicus*
Eviota afelei	*Istigobius decoratus*	*Pomatoschistus norvegicus*	***Brachydeuterus***
Eviota albolineata	*Istigobius hoesei*	*Pomatoschistus pictus*	*Brachydeuterus auritus*
Eviota atriventris	*Istigobius hoshinonis*	*Pomatoschistus quagga*	***Conodon***
Eviota bifasciata	*Istigobius nigroocellatus*	***Priolepis***	*Conodon nobilis*
Eviota distigma	*Istigobius ornatus*	*Priolepis cincta*	*Conodon serrifer*
Eviota fasciola	*Istigobius rigilius*	*Priolepis inhaca*	***Diagramma***
Eviota herrei	*Istigobius spence*	*Priolepis semidoliata*	*Diagramma pictum*
Eviota hinanoae	***Kelloggella***	***Proterorhinus***	***Genyatremus***
Eviota infulata	*Kelloggella cardinalis*	*Proterorhinus marmoratus*	*Genyatremus dovii*
Eviota lachdeberei	***Knipowitschia***	***Pseudaphya***	*Genyatremus luteus*
Eviota latifasciata	*Knipowitschia caucasica*	*Pseudaphya ferreri*	*Genyatremus pacifici*
Eviota melasma	***Koumansetta***	***Redigobius***	***Haemulon***
Eviota pellucida	*Koumansetta hectori*	*Redigobius bikolanus*	*Haemulon album*
Eviota prasina	*Koumansetta rainfordi*	*Redigobius tambujon*	*Haemulon aurolineatum*
Eviota queenslandica	***Lebetus***	***Rhinogobiops***	*Haemulon boschmae*
Eviota saipanensis	*Lebetus guilleti*	*Rhinogobiops nicholsii*	*Haemulon californiensis*
Eviota sebreei	*Lebetus scorpioides*	***Rhinogobius***	*Haemulon carbonarium*
Eviota smaragdus	***Lepidogobius***	*Rhinogobius brunneus*	*Haemulon chrysargyreum*
Eviota sparsa	*Lepidogobius lepidus*	*Rhinogobius giurinus*	*Haemulon flaviguttatum*
Eviota zonura	***Lesueurigobius***	***Sicyopterus***	*Haemulon flavolineatum*
Evorthodus	*Lesueurigobius friesii*	*Sicyopterus lagocephalus*	*Haemulon macrostomum*
Evorthodus lyricus	*Lesueurigobius sanzi*	***Signigobius***	*Haemulon maculicauda*
Exyrias	*Lesueurigobius suerii*	*Signigobius biocellatus*	*Haemulon melanurum*
Exyrias belissimus	***Lophogobius***	***Silhouettea***	*Haemulon parra*
Exyrias puntang	*Lophogobius cyprinoides*	*Silhouettea aegyptia*	*Haemulon plumierii*
Fusigobius	***Lotilia***	***Stonogobiops***	*Haemulon sciurus*
Fusigobius neophytus	*Lotilia graciliosa*	*Stonogobiops dracula*	*Haemulon scudderii*
Gillichthys	***Macrodontogobius***	*Stonogobiops medon*	*Haemulon sexfasciatum*
Gillichthys mirabilis	*Macrodontogobius wilburi*	*Stonogobiops nematodes*	*Haemulon squamipinna*
Ginsburgellus	***Mahidolia***	*Stonogobiops xanthorhinica*	*Haemulon steindachneri*
Ginsburgellus novemlineatus	*Mahidolia mystacina*	***Sufflogobius***	*Haemulon striatum*
Gladiogobius	***Microgobius***	*Sufflogobius bibarbatus*	*Haemulon vittatum*
Gladiogobius ensifer	*Microgobius carri*	***Thorogobius***	***Haemulopsis***
Glossogobius	*Microgobius gulosus*	*Thorogobius angolensis*	*Haemulopsis axillaris*
Glossogobius bicirrhosus	*Microgobius thalassinus*	*Thorogobius ephippiatus*	*Haemulopsis leuciscus*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Haemulopsis nitidus	*Kuhlia sandvicensis*	*Coris variegata*	***Labrus***
Isacia	**Kyphosidae**	*Coris venusta*	*Labrus bergylta*
Isacia conceptionis	***Girella***	***Ctenolabrus***	*Labrus merula*
Orthopristis	*Girella elevata*	*Ctenolabrus rupestris*	*Labrus mixtus*
Orthopristis cantharinus	*Girella nigricans*	***Cymolutes***	*Labrus viridis*
Orthopristis chalceus	*Girella punctata*	*Cymolutes praetextatus*	***Lachnolaimus***
Orthopristis chrysoptera	*Girella simplicidens*	*Cymolutes torquatus*	*Lachnolaimus maximus*
Orthopristis reddingi	*Girella tricuspidata*	***Decodon***	***Macropharyngodon***
Parapristipoma	*Girella zonata*	*Decodon melasma*	*Macropharyngodon meleagris*
Parapristipoma octolineatum	***Kyphosus***	*Decodon puellaris*	*Macropharyngodon negrosensis*
Parapristipoma trilineatum	*Kyphosus analogus*	***Diproctacanthus***	***Novaculichthys***
Plectorhinchus	*Kyphosus azureus*	*Diproctacanthus xanthurus*	*Novaculichthys taeniourus*
Plectorhinchus albovittatus	*Kyphosus bigibbus*	***Doratonotus***	***Novaculoides***
Plectorhinchus chaetodonoides	*Kyphosus cinerascens*	*Doratonotus megalepis*	*Novaculoides macrolepidotus*
Plectorhinchus diagrammus	*Kyphosus elegans*	***Epibulus***	***Oxycheilinus***
Plectorhinchus gaterinus	*Kyphosus incisor*	*Epibulus insidiator*	*Oxycheilinus arenatus*
Plectorhinchus gibbosus	*Kyphosus ocyurus*	***Gomphosus***	*Oxycheilinus bimaculatus*
Plectorhinchus macrolepis	*Kyphosus sectatrix*	*Gomphosus varius*	*Oxycheilinus digramma*
Plectorhinchus mediterraneus	*Kyphosus vaigiensis*	***Halichoeres***	*Oxycheilinus orientalis*
Plectorhinchus obscurus	***Medialuna***	*Halichoeres aestuaricola*	*Oxycheilinus unifasciatus*
Plectorhinchus picus	*Medialuna californiensis*	*Halichoeres bathyphilus*	***Oxyjulis***
Plectorhinchus polytaenia	***Neoscorpis***	*Halichoeres biocellatus*	*Oxyjulis californica*
Plectorhinchus schotaf	*Neoscorpis lithophilus*	*Halichoeres bivittatus*	***Paracheilinus***
Plectorhinchus sordidus	**Labridae**	*Halichoeres caudalis*	*Paracheilinus carpenteri*
Plectorhinchus vittatus	***Acantholabrus***	*Halichoeres chierchiae*	*Paracheilinus lineopunctatus*
Pomadasys	*Acantholabrus palloni*	*Halichoeres chloropterus*	*Paracheilinus octotaenia*
Pomadasys argenteus	***Anampses***	*Halichoeres chrysus*	***Polylepion***
Pomadasys branickii	*Anampses caeruleopunctatus*	*Halichoeres claudia*	*Polylepion cruentum*
Pomadasys crocro	*Anampses geographicus*	*Halichoeres cyanocephalus*	***Pseudocheilinops***
Pomadasys incisus	*Anampses lennardi*	*Halichoeres dispilus*	*Pseudocheilinops ataenia*
Pomadasys jubelini	*Anampses melanurus*	*Halichoeres garnoti*	***Pseudocheilinus***
Pomadasys kaakan	*Anampses meleagrides*	*Halichoeres hortulanus*	*Pseudocheilinus evanidus*
Pomadasys macracanthus	*Anampses twistii*	*Halichoeres leucoxanthus*	*Pseudocheilinus hexataenia*
Pomadasys olivaceus	***Bodianus***	*Halichoeres leucurus*	*Pseudocheilinus octotaenia*
Pomadasys panamensis	*Bodianus anthioides*	*Halichoeres maculipinna*	*Pseudocheilinus tetrataenia*
Pomadasys stridens	*Bodianus axillaris*	*Halichoeres margaritaceus*	***Pseudocoris***
Xenichthys	*Bodianus bilunulatus*	*Halichoeres marginatus*	*Pseudocoris yamashiroi*
Xenichthys xanti	*Bodianus bimaculatus*	*Halichoeres melanochir*	***Pseudodax***
Harpagiferidae	*Bodianus diana*	*Halichoeres melanotis*	*Pseudodax moluccanus*
Harpagifer	*Bodianus diplotaenia*	*Halichoeres melanurus*	***Pseudojuloides***
Harpagifer bispinis	*Bodianus loxozonus*	*Halichoeres melasmapomus*	*Pseudojuloides atavai*
Harpagifer kerguelensis	*Bodianus mesothorax*	*Halichoeres nebulosus*	*Pseudojuloides cerasinus*
Harpagifer spinosus	*Bodianus opercularis*	*Halichoeres nicholsi*	***Pseudolabrus***
Howellidae	*Bodianus pulchellus*	*Halichoeres notospilus*	*Pseudolabrus luculentus*
Howella	*Bodianus rufus*	*Halichoeres pictus*	***Pteragogus***
Howella atlantica	***Centrolabrus***	*Halichoeres poeyi*	*Pteragogus cryptus*
Icosteidae	*Centrolabrus exoletus*	*Halichoeres prosopeion*	*Pteragogus enneacanthus*
Icosteus	*Centrolabrus melanocercus*	*Halichoeres radiatus*	*Pteragogus guttatus*
Icosteus aenigmaticus	***Cheilinus***	*Halichoeres richmondi*	***Semicossyphus***
Istiophoridae	*Cheilinus chlorourus*	*Halichoeres scapularis*	*Semicossyphus pulcher*
Istiompax	*Cheilinus fasciatus*	*Halichoeres semicinctus*	***Stethojulis***
Istiompax indica	*Cheilinus oxycephalus*	*Halichoeres trimaculatus*	*Stethojulis bandanensis*
Istiophorus	*Cheilinus trilobatus*	***Hemigymnus***	*Stethojulis interrupta*
Istiophorus albicans	*Cheilinus undulatus*	*Hemigymnus fasciatus*	*Stethojulis strigiventer*
Istiophorus platypterus	***Cheilio***	*Hemigymnus melapterus*	*Stethojulis trilineata*
Kajikia	*Cheilio inermis*	***Hologymnosus***	***Suezichthys***
Kajikia albida	***Choerodon***	*Hologymnosus annulatus*	*Suezichthys arquatus*
Kajikia audax	*Choerodon anchorago*	*Hologymnosus doliatus*	*Suezichthys aylingi*
Makaira	*Choerodon oligacanthus*	***Iniistius***	*Suezichthys caudavittatus*
Makaira mazara	***Cirrhilabrus***	*Iniistius aneitensis*	*Suezichthys gracilis*
Makaira nigricans	*Cirrhilabrus cyanopleura*	*Iniistius pavo*	*Suezichthys notatus*
Tetrapturus	*Cirrhilabrus exquisitus*	***Labrichthys***	*Suezichthys soelae*
Tetrapturus angustirostris	*Cirrhilabrus luteovittatus*	*Labrichthys unilineatus*	***Symphodus***
Tetrapturus belone	***Clepticus***	***Labroides***	*Symphodus cinereus*
Tetrapturus georgii	*Clepticus parrae*	*Labroides bicolor*	*Symphodus doderleini*
Tetrapturus pfluegeri	***Coris***	*Labroides dimidiatus*	*Symphodus mediterraneus*
Kraemeriidae	*Coris aygula*	*Labroides pectoralis*	*Symphodus melops*
Kraemeria	*Coris batuensis*	***Labropsis***	*Symphodus ocellatus*
Kraemeria samoensis	*Coris flavovittata*	*Labropsis alleni*	*Symphodus roissali*
Kuhliidae	*Coris gaimard*	*Labropsis australis*	*Symphodus rostratus*
Kuhlia	*Coris julis*	*Labropsis micronesica*	*Symphodus tinca*
Kuhlia mugil	*Coris picta*	*Labropsis xanthonota*	*Symphodus trutta*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Tautoga	**Lethrinidae**	*Lutjanus bengalensis*	*Pristipomoides flavipinnis*
Tautoga onitis	***Gnathodentex***	*Lutjanus biguttatus*	*Pristipomoides freemani*
Tautogolabrus	*Gnathodentex aureolineatus*	*Lutjanus bitaeniatus*	*Pristipomoides macrophthalmus*
Tautogolabrus adspersus	***Gymnocranius***	*Lutjanus bohar*	*Pristipomoides multidens*
Thalassoma	*Gymnocranius audleyi*	*Lutjanus boutton*	*Pristipomoides sieboldii*
Thalassoma amblycephalum	*Gymnocranius elongatus*	*Lutjanus buccanella*	*Pristipomoides typus*
Thalassoma ascensionis	*Gymnocranius euanus*	*Lutjanus campechanus*	*Pristipomoides zonatus*
Thalassoma bifasciatum	*Gymnocranius frenatus*	*Lutjanus carponotatus*	***Randallichthys***
Thalassoma cupido	*Gymnocranius grandoculis*	*Lutjanus coeruleolineatus*	*Randallichthys filamentosus*
Thalassoma duperrey	*Gymnocranius griseus*	*Lutjanus colorado*	***Rhomboplites***
Thalassoma grammaticum	*Gymnocranius microdon*	*Lutjanus cyanopterus*	*Rhomboplites aurorubens*
Thalassoma hardwicke	***Lethrinus***	*Lutjanus decussatus*	***Symphorichthys***
Thalassoma hebraicum	*Lethrinus amboinensis*	*Lutjanus dentatus*	*Symphorichthys spilurus*
Thalassoma jansenii	*Lethrinus atkinsoni*	*Lutjanus dodecacanthoides*	***Symphorus***
Thalassoma lucasanum	*Lethrinus atlanticus*	*Lutjanus ehrenbergii*	*Symphorus nematophorus*
Thalassoma lunare	*Lethrinus borbonicus*	*Lutjanus erythropterus*	**Luvaridae**
Thalassoma lutescens	*Lethrinus conchyliatus*	*Lutjanus fulgens*	***Luvarus***
Thalassoma nigrofasciatum	*Lethrinus crocineus*	*Lutjanus fulviflamma*	*Luvarus imperialis*
Thalassoma pavo	*Lethrinus enigmaticus*	*Lutjanus fulvus*	**Malacanthidae**
Thalassoma purpureum	*Lethrinus erythracanthus*	*Lutjanus gibbus*	***Branchiostegus***
Thalassoma quinquevittatum	*Lethrinus erythropterus*	*Lutjanus goreensis*	*Branchiostegus japonicus*
Thalassoma trilobatum	*Lethrinus genivittatus*	*Lutjanus griseus*	*Branchiostegus sawakinensis*
Wetmorella	*Lethrinus haematopterus*	*Lutjanus guilcheri*	*Branchiostegus semifasciatus*
Wetmorella albofasciata	*Lethrinus harak*	*Lutjanus guttatus*	***Caulolatilus***
Wetmorella nigropinnata	*Lethrinus laticaudis*	*Lutjanus inermis*	*Caulolatilus chrysops*
Xyrichtys	*Lethrinus lentjan*	*Lutjanus jocu*	*Caulolatilus cyanops*
Xyrichtys splendens	*Lethrinus mahsena*	*Lutjanus johnii*	*Caulolatilus guppyi*
Labrisomidae	*Lethrinus microdon*	*Lutjanus jordani*	*Caulolatilus hubbsi*
Gobioclinus	*Lethrinus miniatus*	*Lutjanus kasmira*	*Caulolatilus intermedius*
Gobioclinus bucciferus	*Lethrinus nebulosus*	*Lutjanus lemniscatus*	*Caulolatilus microps*
Labrisomus	*Lethrinus obsoletus*	*Lutjanus lunulatus*	***Hoplolatilus***
Labrisomus nuchipinnis	*Lethrinus olivaceus*	*Lutjanus lutjanus*	*Hoplolatilus cuniculus*
Labrisomus philippii	*Lethrinus ornatus*	*Lutjanus madras*	*Hoplolatilus fronticinctus*
Malacoctenus	*Lethrinus ravus*	*Lutjanus mahogoni*	*Hoplolatilus starcki*
Malacoctenus boehlkei	*Lethrinus reticulatus*	*Lutjanus malabaricus*	***Lopholatilus***
Malacoctenus macropus	*Lethrinus rubrioperculatus*	*Lutjanus mizenkoi*	*Lopholatilus chamaeleonticeps*
Paraclinus	*Lethrinus semicinctus*	*Lutjanus monostigma*	*Lopholatilus villarii*
Paraclinus fasciatus	*Lethrinus variegatus*	*Lutjanus notatus*	***Malacanthus***
Paraclinus nigripinnis	*Lethrinus xanthochilus*	*Lutjanus novemfasciatus*	*Malacanthus brevirostris*
Starksia	***Monotaxis***	*Lutjanus peru*	*Malacanthus latovittatus*
Starksia ocellata	*Monotaxis grandoculis*	*Lutjanus purpureus*	*Malacanthus plumieri*
Lactariidae	***Wattsia***	*Lutjanus quinquelineatus*	**Menidae**
Lactarius	*Wattsia mossambica*	*Lutjanus rivulatus*	***Mene***
Lactarius lactarius	**Lobotidae**	*Lutjanus rufolineatus*	*Mene maculata*
Lateolabracidae	***Lobotes***	*Lutjanus russellii*	**Microdesmidae**
Lateolabrax	*Lobotes surinamensis*	*Lutjanus sanguineus*	***Gunnellichthys***
Lateolabrax japonicus	**Lutjanidae**	*Lutjanus sebae*	*Gunnellichthys monostigma*
Latidae	***Aphareus***	*Lutjanus semicinctus*	*Gunnellichthys pleurotaenia*
Lates	*Aphareus furca*	*Lutjanus synagris*	*Gunnellichthys viridescens*
Lates calcarifer	*Aphareus rutilans*	*Lutjanus timoriensis*	***Microdesmus***
Latridae	***Aprion***	*Lutjanus viridis*	*Microdesmus longipinnis*
Latridopsis	*Aprion virescens*	*Lutjanus vitta*	***Nemateleotris***
Latridopsis ciliaris	***Apsilus***	*Lutjanus vivanus*	*Nemateleotris decora*
Leiognathidae	*Apsilus dentatus*	***Macolor***	*Nemateleotris helfrichi*
Aurigequula	*Apsilus fuscus*	*Macolor macularis*	*Nemateleotris magnifica*
Aurigequula fasciata	***Etelis***	*Macolor niger*	***Parioglossus***
Equulites	*Etelis carbunculus*	***Ocyurus***	*Parioglossus formosus*
Equulites elongatus	*Etelis coruscans*	*Ocyurus chrysurus*	*Parioglossus nudus*
Equulites leuciscus	*Etelis oculatus*	***Paracaesio***	*Parioglossus palustris*
Equulites lineolatus	*Etelis radiosus*	*Paracaesio gonzalesi*	*Parioglossus raoi*
Equulites stercorarius	***Hoplopagrus***	*Paracaesio kusakarii*	***Ptereleotris***
Eubleekeria	*Hoplopagrus guentherii*	*Paracaesio sordida*	*Ptereleotris arabica*
Eubleekeria splendens	***Lipocheilus***	*Paracaesio stonei*	*Ptereleotris evides*
Gazza	*Lipocheilus carnolabrum*	*Paracaesio xanthura*	*Ptereleotris grammica*
Gazza achlamys	***Lutjanus***	***Pinjalo***	*Ptereleotris hanae*
Gazza minuta	*Lutjanus adetii*	*Pinjalo lewisi*	*Ptereleotris heteroptera*
Leiognathus	*Lutjanus agennes*	*Pinjalo pinjalo*	*Ptereleotris microlepis*
Leiognathus equulus	*Lutjanus analis*	***Pristipomoides***	*Ptereleotris monoptera*
Nuchequula	*Lutjanus apodus*	*Pristipomoides aquilonaris*	*Ptereleotris uroditaenia*
Nuchequula longicornis	*Lutjanus aratus*	*Pristipomoides argyrogrammicus*	*Ptereleotris zebra*
Photopectoralis	*Lutjanus argentimaculatus*	*Pristipomoides auricilla*	**Monodactylidae**
Photopectoralis bindus	*Lutjanus argentiventris*	*Pristipomoides filamentosus*	***Monodactylus***

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Monodactylus argenteus	***Parascolopsis***	***Paranotothenia***	*Percophis brasiliensis*
Monodactylus sebae	*Parascolopsis aspinosa*	*Paranotothenia magellanica*	**Pholidae**
Moronidae	*Parascolopsis boesemani*	***Patagonotothen***	***Apodichthys***
Dicentrarchus	*Parascolopsis eriomma*	*Patagonotothen brevicauda*	*Apodichthys flavidus*
Dicentrarchus labrax	*Parascolopsis inermis*	*Patagonotothen guntheri*	***Pholis***
Dicentrarchus punctatus	*Parascolopsis rufomaculatus*	*Patagonotothen ramsayi*	*Pholis fasciata*
Morone	*Parascolopsis tanyactis*	*Patagonotothen wiltoni*	*Pholis gunnellus*
Morone americana	*Parascolopsis tosensis*	***Pleuragramma***	*Pholis ornata*
Morone saxatilis	*Parascolopsis townsendi*	*Pleuragramma antarctica*	*Pholis schultzi*
Mullidae	***Pentapodus***	***Trematomus***	**Pholidichthyidae**
Mulloidichthys	*Pentapodus bifasciatus*	*Trematomus bernacchii*	***Pholidichthys***
Mulloidichthys flavolineatus	*Pentapodus caninus*	*Trematomus eulepidotus*	*Pholidichthys leucotaenia*
Mulloidichthys martinicus	*Pentapodus emeryii*	*Trematomus hansoni*	**Pinguipedidae**
Mulloidichthys pfluegeri	*Pentapodus nagasakiensis*	*Trematomus lepidorhinus*	***Parapercis***
Mulloidichthys vanicolensis	*Pentapodus paradiseus*	*Trematomus loennbergii*	*Parapercis clathrata*
Mullus	*Pentapodus porosus*	*Trematomus newnesi*	*Parapercis colias*
Mullus argentinae	*Pentapodus setosus*	*Trematomus nicolai*	*Parapercis cylindrica*
Mullus auratus	*Pentapodus trivittatus*	*Trematomus pennellii*	*Parapercis dockinsi*
Mullus barbatus barbatus	***Scaevius***	*Trematomus scotti*	*Parapercis hexophtalma*
Mullus surmuletus	*Scaevius milii*	*Trematomus tokarevi*	*Parapercis lineopunctata*
Parupeneus	***Scolopsis***	**Odacidae**	*Parapercis millepunctata*
Parupeneus barberinoides	*Scolopsis affinis*	***Haletta***	*Parapercis nebulosa*
Parupeneus barberinus	*Scolopsis aurata*	*Haletta semifasciata*	*Parapercis ramsayi*
Parupeneus ciliatus	*Scolopsis bilineata*	***Heteroscarus***	*Parapercis roseoviridis*
Parupeneus crassilabris	*Scolopsis bimaculata*	*Heteroscarus acroptilus*	***Pinguipes***
Parupeneus cyclostomus	*Scolopsis ciliata*	***Neoodax***	*Pinguipes brasilianus*
Parupeneus heptacanthus	*Scolopsis frenata*	*Neoodax balteatus*	***Prolatilus***
Parupeneus indicus	*Scolopsis ghanam*	***Olisthops***	*Prolatilus jugularis*
Parupeneus macronemus	*Scolopsis lineata*	*Olisthops cyanomelas*	***Pseudopercis***
Parupeneus multifasciatus	*Scolopsis margaritifera*	***Siphonognathus***	*Pseudopercis numida*
Parupeneus pleurostigma	*Scolopsis monogramma*	*Siphonognathus argyrophanes*	*Pseudopercis semifasciata*
Parupeneus porphyreus	*Scolopsis taeniata*	*Siphonognathus attenuatus*	**Plesiopidae**
Parupeneus spilurus	*Scolopsis taenioptera*	*Siphonognathus beddomei*	***Acanthoclinus***
Parupeneus trifasciatus	*Scolopsis temporalis*	*Siphonognathus caninis*	*Acanthoclinus fuscus*
Pseudupeneus	*Scolopsis trilineata*	*Siphonognathus radiatus*	***Acanthoplesiops***
Pseudupeneus maculatus	*Scolopsis vosmeri*	*Siphonognathus tanyourus*	*Acanthoplesiops hiatti*
Pseudupeneus prayensis	*Scolopsis xenochrous*	**Opistognathidae**	***Belonepterygion***
Upeneus	**Nomeidae**	***Opistognathus***	*Belonepterygion fasciolatum*
Upeneus moluccensis	***Cubiceps***	*Opistognathus maxillosus*	***Calloplesiops***
Upeneus parvus	*Cubiceps baxteri*	*Opistognathus melachasme*	*Calloplesiops altivelis*
Upeneus sulphureus	*Cubiceps capensis*	*Opistognathus papuensis*	***Plesiops***
Upeneus taeniopterus	*Cubiceps pauciradiatus*	**Pempheridae**	*Plesiops coeruleolineatus*
Upeneus tragula	***Nomeus***	***Parapriacanthus***	*Plesiops corallicola*
Upeneus vittatus	*Nomeus gronovii*	*Parapriacanthus ransonneti*	**Polynemidae**
Nematistiidae	***Psenes***	***Pempheris***	***Eleutheronema***
Nematistius	*Psenes arafurensis*	*Pempheris multiradiata*	*Eleutheronema rhadinum*
Nematistius pectoralis	*Psenes cyanophrys*	*Pempheris oualensis*	*Eleutheronema tetradactylum*
Nemipteridae	*Psenes maculatus*	*Pempheris vanicolensis*	*Eleutheronema tridactylum*
Nemipterus	*Psenes pellucidus*	**Pentacerotidae**	***Filimanus***
Nemipterus aurora	**Nototheniidae**	***Evistias***	*Filimanus heptadactyla*
Nemipterus balinensis	***Cryothenia***	*Evistias acutirostris*	*Filimanus sealei*
Nemipterus balinensoides	*Cryothenia peninsulae*	***Paristiopterus***	*Filimanus xanthonema*
Nemipterus bathybius	***Dissostichus***	*Paristiopterus gallipavo*	***Galeoides***
Nemipterus bipunctatus	*Dissostichus eleginoides*	*Paristiopterus labiosus*	*Galeoides decadactylus*
Nemipterus celebicus	*Dissostichus mawsoni*	***Pentaceros***	***Leptomelanosoma***
Nemipterus furcosus	***Gobionotothen***	*Pentaceros richardsoni*	*Leptomelanosoma indicum*
Nemipterus gracilis	*Gobionotothen acuta*	*Pentaceros wheeleri*	***Pentanemus***
Nemipterus hexodon	*Gobionotothen gibberifrons*	**Percophidae**	*Pentanemus quinquarius*
Nemipterus isacanthus	*Gobionotothen marionensis*	***Acanthaphritis***	***Polydactylus***
Nemipterus japonicus	***Lepidonotothen***	*Acanthaphritis barbata*	*Polydactylus approximans*
Nemipterus marginatus	*Lepidonotothen squamifrons*	***Bembrops***	*Polydactylus macrochir*
Nemipterus mesoprion	***Lindbergichthys***	*Bembrops filiferus*	*Polydactylus microstomus*
Nemipterus nematophorus	*Lindbergichthys mizops*	*Bembrops gobioides*	*Polydactylus mullani*
Nemipterus nematopus	*Lindbergichthys nudifrons*	*Bembrops greyi*	*Polydactylus multiradiatus*
Nemipterus nemurus	***Notothenia***	*Bembrops heterurus*	*Polydactylus nigripinnis*
Nemipterus peronii	*Notothenia coriiceps*	***Chrionema***	*Polydactylus octonemus*
Nemipterus tambuloides	*Notothenia rossii*	*Chrionema pallidum*	*Polydactylus oligodon*
Nemipterus theodorei	***Nototheniops***	***Matsubaraea***	*Polydactylus opercularis*
Nemipterus thosaporni	*Nototheniops larseni*	*Matsubaraea fusiforme*	*Polydactylus plebeius*
Nemipterus virgatus	***Pagothenia***	***Osopsaron***	*Polydactylus quadrifilis*
Nemipterus vitiensis	*Pagothenia borchgrevinki*	*Osopsaron karlik*	*Polydactylus sexfilis*
Nemipterus zysron	*Pagothenia brachysoma*	***Percophis***	*Polydactylus sextarius*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Polydactylus virginicus	*Abudefduf troschelii*	*Chromis leucura*	***Neopomacentrus***
Polynemus	*Abudefduf vaigiensis*	*Chromis limbata*	*Neopomacentrus anabatoides*
Polynemus paradiseus	*Abudefduf whitleyi*	*Chromis limbaughi*	*Neopomacentrus azysron*
Polyprionidae	***Acanthochromis***	*Chromis lineata*	*Neopomacentrus cyanomos*
Polyprion	*Acanthochromis polyacanthus*	*Chromis margaritifer*	*Neopomacentrus fuliginosus*
Polyprion americanus	***Amblyglyphidodon***	*Chromis multilineata*	*Neopomacentrus metallicus*
Polyprion oxygeneios	*Amblyglyphidodon aureus*	*Chromis nigrura*	*Neopomacentrus taeniurus*
Stereolepis	*Amblyglyphidodon curacao*	*Chromis nitida*	*Neopomacentrus violascens*
Stereolepis gigas	*Amblyglyphidodon flavilatus*	*Chromis pamae*	***Parma***
Pomacanthidae	*Amblyglyphidodon leucogaster*	*Chromis punctipinnis*	*Parma alboscapularis*
Apolemichthys	*Amblyglyphidodon ternatensis*	*Chromis retrofasciata*	*Parma microlepis*
Apolemichthys arcuatus	***Amblypomacentrus***	*Chromis scotti*	***Plectroglyphidodon***
Apolemichthys griffisi	*Amblypomacentrus breviceps*	*Chromis struhsakeri*	*Plectroglyphidodon dickii*
Apolemichthys trimaculatus	***Amphiprion***	*Chromis ternatensis*	*Plectroglyphidodon imparipennis*
Apolemichthys xanthopunctatus	*Amphiprion akallopisos*	*Chromis vanderbilti*	*Plectroglyphidodon johnstonianus*
Centropyge	*Amphiprion akindynos*	*Chromis verater*	*Plectroglyphidodon lacrymatus*
Centropyge argi	*Amphiprion allardi*	*Chromis viridis*	*Plectroglyphidodon leucozonus*
Centropyge aurantia	*Amphiprion bicinctus*	*Chromis weberi*	*Plectroglyphidodon phoenixensis*
Centropyge bicolor	*Amphiprion chagosensis*	*Chromis woodsi*	***Pomacentrus***
Centropyge bispinosa	*Amphiprion chrysogaster*	*Chromis xanthochira*	*Pomacentrus adelus*
Centropyge colini	*Amphiprion chrysopterus*	*Chromis xanthura*	*Pomacentrus amboinensis*
Centropyge flavissima	*Amphiprion clarkii*	***Chrysiptera***	*Pomacentrus baenschi*
Centropyge heraldi	*Amphiprion ephippium*	*Chrysiptera biocellata*	*Pomacentrus bankanensis*
Centropyge loriculus	*Amphiprion frenatus*	*Chrysiptera brownriggii*	*Pomacentrus brachialis*
Centropyge multicolor	*Amphiprion fuscocaudatus*	*Chrysiptera caeruleolineata*	*Pomacentrus burroughi*
Centropyge nigriocella	*Amphiprion latezonatus*	*Chrysiptera cyanea*	*Pomacentrus chrysurus*
Centropyge nox	*Amphiprion latifasciatus*	*Chrysiptera glauca*	*Pomacentrus coelestis*
Centropyge potteri	*Amphiprion leucokranos*	*Chrysiptera oxycephala*	*Pomacentrus emarginatus*
Centropyge tibicen	*Amphiprion mccullochi*	*Chrysiptera parasema*	*Pomacentrus grammorhynchus*
Centropyge vrolikii	*Amphiprion melanopus*	*Chrysiptera rapanui*	*Pomacentrus lepidogenys*
Chaetodontoplus	*Amphiprion nigripes*	*Chrysiptera rex*	*Pomacentrus moluccensis*
Chaetodontoplus mesoleucus	*Amphiprion ocellaris*	*Chrysiptera rollandi*	*Pomacentrus nagasakiensis*
Genicanthus	*Amphiprion omanensis*	*Chrysiptera sinclairi*	*Pomacentrus nigromanus*
Genicanthus bellus	*Amphiprion percula*	*Chrysiptera springeri*	*Pomacentrus opisthostigma*
Genicanthus melanospilos	*Amphiprion perideraion*	*Chrysiptera starcki*	*Pomacentrus pavo*
Genicanthus personatus	*Amphiprion polymnus*	*Chrysiptera talboti*	*Pomacentrus philippinus*
Genicanthus watanabei	*Amphiprion rubrocinctus*	*Chrysiptera traceyi*	*Pomacentrus reidi*
Holacanthus	*Amphiprion sandaracinos*	*Chrysiptera tricincta*	*Pomacentrus simsiang*
Holacanthus bermudensis	*Amphiprion sebae*	*Chrysiptera unimaculata*	*Pomacentrus stigma*
Holacanthus ciliaris	*Amphiprion tricinctus*	***Dascyllus***	*Pomacentrus sulfureus*
Holacanthus passer	***Azurina***	*Dascyllus albisella*	*Pomacentrus vaiuli*
Holacanthus tricolor	*Azurina eupalama*	*Dascyllus aruanus*	***Pomachromis***
Paracentropyge	*Azurina hirundo*	*Dascyllus melanurus*	*Pomachromis exilis*
Paracentropyge multifasciata	***Cheiloprion***	*Dascyllus reticulatus*	*Pomachromis richardsoni*
Pomacanthus	*Cheiloprion labiatus*	*Dascyllus strasburgi*	***Premnas***
Pomacanthus annularis	***Chromis***	*Dascyllus trimaculatus*	*Premnas biaculeatus*
Pomacanthus arcuatus	*Chromis abyssicola*	***Dischistodus***	***Similiparma***
Pomacanthus imperator	*Chromis acares*	*Dischistodus chrysopoecilus*	*Similiparma lurida*
Pomacanthus navarchus	*Chromis agilis*	*Dischistodus fasciatus*	***Stegastes***
Pomacanthus paru	*Chromis alpha*	*Dischistodus melanotus*	*Stegastes acapulcoensis*
Pomacanthus semicirculatus	*Chromis alta*	*Dischistodus perspicillatus*	*Stegastes adustus*
Pomacanthus sexstriatus	*Chromis amboinensis*	*Dischistodus prosopotaenia*	*Stegastes albifasciatus*
Pomacanthus xanthometopon	*Chromis analis*	*Dischistodus pseudochrysopoecilus*	*Stegastes altus*
Pomacanthus zonipectus	*Chromis atrilobata*	***Hemiglyphidodon***	*Stegastes apicalis*
Pygoplites	*Chromis atripectoralis*	*Hemiglyphidodon plagiometopon*	*Stegastes arcifrons*
Pygoplites diacanthus	*Chromis atripes*	***Hypsypops***	*Stegastes aureus*
Pomacentridae	*Chromis brevirostris*	*Hypsypops rubicundus*	*Stegastes beebei*
Abudefduf	*Chromis caudalis*	***Lepidozygus***	*Stegastes emeryi*
Abudefduf abdominalis	*Chromis chromis*	*Lepidozygus tapeinosoma*	*Stegastes fasciolatus*
Abudefduf bengalensis	*Chromis chrysura*	***Microspathodon***	*Stegastes flavilatus*
Abudefduf concolor	*Chromis cinerascens*	*Microspathodon bairdii*	*Stegastes gascoynei*
Abudefduf conformis	*Chromis cyanea*	*Microspathodon chrysurus*	*Stegastes insularis*
Abudefduf declivifrons	*Chromis delta*	*Microspathodon dorsalis*	*Stegastes leucorus*
Abudefduf lorenzi	*Chromis earina*	*Microspathodon frontatus*	*Stegastes leucostictus*
Abudefduf natalensis	*Chromis elerae*	***Neoglyphidodon***	*Stegastes limbatus*
Abudefduf notatus	*Chromis enchrysura*	*Neoglyphidodon bonang*	*Stegastes nigricans*
Abudefduf saxatilis	*Chromis flavicauda*	*Neoglyphidodon carlsoni*	*Stegastes obreptus*
Abudefduf septemfasciatus	*Chromis flavipectoralis*	*Neoglyphidodon crossi*	*Stegastes partitus*
Abudefduf sexfasciatus	*Chromis flavomaculata*	*Neoglyphidodon melas*	*Stegastes pelicieri*
Abudefduf sordidus	*Chromis hanui*	*Neoglyphidodon nigroris*	*Stegastes punctatus*
Abudefduf sparoides	*Chromis hypsilepis*	*Neoglyphidodon polyacanthus*	*Stegastes rectifraenum*
Abudefduf taurus	*Chromis lepidolepis*	*Neoglyphidodon thoracotaeniatus*	*Stegastes variabilis*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Pomatomidae	*Chlorurus sordidus*	***Ctenosciaena***	*Odontoscion eurymesops*
Pomatomus	***Cryptotomus***	*Ctenosciaena gracilicirrhus*	*Odontoscion xanthops*
Pomatomus saltatrix	*Cryptotomus roseus*	*Ctenosciaena peruviana*	***Ophioscion***
Priacanthidae	***Hipposcarus***	***Cynoscion***	*Ophioscion imiceps*
Cookeolus	*Hipposcarus longiceps*	*Cynoscion acoupa*	*Ophioscion scierus*
Cookeolus japonicus	***Leptoscarus***	*Cynoscion analis*	***Otolithes***
Heteropriacanthus	*Leptoscarus vaigiensis*	*Cynoscion arenarius*	*Otolithes ruber*
Heteropriacanthus cruentatus	***Nicholsina***	*Cynoscion guatucupa*	***Otolithoides***
Priacanthus	*Nicholsina denticulata*	*Cynoscion jamaicensis*	*Otolithoides biauritus*
Priacanthus alalaua	*Nicholsina usta*	*Cynoscion leiarchus*	***Paralonchurus***
Priacanthus arenatus	***Scarus***	*Cynoscion microlepidotus*	*Paralonchurus goodei*
Priacanthus hamrur	*Scarus altipinnis*	*Cynoscion nannus*	*Paralonchurus peruanus*
Priacanthus macracanthus	*Scarus chameleon*	*Cynoscion nebulosus*	***Pareques***
Priacanthus tayenus	*Scarus coelestinus*	*Cynoscion nortoni*	*Pareques acuminatus*
Pristigenys	*Scarus coeruleus*	*Cynoscion nothus*	*Pareques umbrosus*
Pristigenys alta	*Scarus compressus*	*Cynoscion parvipinnis*	*Pareques viola*
Pristigenys serrula	*Scarus dimidiatus*	*Cynoscion phoxocephalus*	***Pennahia***
Pseudochromidae	*Scarus festivus*	*Cynoscion regalis*	*Pennahia argentata*
Anisochromis	*Scarus flavipectoralis*	*Cynoscion reticulatus*	***Pentheroscion***
Anisochromis kenyae	*Scarus forsteni*	*Cynoscion similis*	*Pentheroscion mbizi*
Blennodesmus	*Scarus frenatus*	*Cynoscion squamipinnis*	***Pogonias***
Blennodesmus scapularis	*Scarus ghobban*	*Cynoscion steindachneri*	*Pogonias cromis*
Congrogadus	*Scarus globiceps*	*Cynoscion stolzmanni*	***Protonibea***
Congrogadus subducens	*Scarus guacamaia*	*Cynoscion striatus*	*Protonibea diacanthus*
Halidesmus	*Scarus hoefleri*	*Cynoscion virescens*	***Pseudotolithus***
Halidesmus scapularis	*Scarus hypselopterus*	***Elattarchus***	*Pseudotolithus elongatus*
Halimuraena	*Scarus iseri*	*Elattarchus archidium*	*Pseudotolithus epipercus*
Halimuraena hexagonata	*Scarus niger*	***Equetus***	*Pseudotolithus moorii*
Halimuraena lepopareia	*Scarus oviceps*	*Equetus lanceolatus*	*Pseudotolithus senegalensis*
Halimuraena shakai	*Scarus prasiognathos*	*Equetus punctatus*	*Pseudotolithus senegallus*
Haliophis	*Scarus psittacus*	***Genyonemus***	*Pseudotolithus typus*
Haliophis guttatus	*Scarus quoyi*	*Genyonemus lineatus*	***Pteroscion***
Manonichthys	*Scarus rubroviolaceus*	***Isopisthus***	*Pteroscion peli*
Manonichthys polynemus	*Scarus schlegeli*	*Isopisthus parvipinnis*	***Roncador***
Pictichromis	*Scarus spinus*	*Isopisthus remifer*	*Roncador stearnsii*
Pictichromis porphyrea	*Scarus taeniopterus*	***Johnius***	***Sciaena***
Pseudochromis	*Scarus vetula*	*Johnius borneensis*	*Sciaena umbra*
Pseudochromis ammeri	***Sparisoma***	***Larimichthys***	***Sciaenops***
Pseudochromis cyanotaenia	*Sparisoma atomarium*	*Larimichthys crocea*	*Sciaenops ocellatus*
Pseudochromis eichleri	*Sparisoma aurofrenatum*	*Larimichthys polyactis*	***Seriphus***
Pseudochromis fuligifinis	*Sparisoma chrysopterum*	***Larimus***	*Seriphus politus*
Pseudochromis fuscus	*Sparisoma cretense*	*Larimus acclivis*	***Stellifer***
Pseudochromis marshallensis	*Sparisoma radians*	*Larimus argenteus*	*Stellifer chrysoleuca*
Pseudochromis nigrovittatus	*Sparisoma rubripinne*	*Larimus breviceps*	*Stellifer ericymba*
Pseudochromis striatus	*Sparisoma tuiupiranga*	*Larimus effulgens*	*Stellifer illecebrosus*
Pseudochromis tapeinosoma	*Sparisoma viride*	*Larimus fasciatus*	*Stellifer lanceolatus*
Pseudoplesiops	**Scatophagidae**	*Larimus pacificus*	*Stellifer mancorensis*
Pseudoplesiops howensis	***Scatophagus***	***Leiostomus***	*Stellifer minor*
Pseudoplesiops revellei	*Scatophagus argus*	*Leiostomus xanthurus*	***Totoaba***
Pseudoplesiops rosae	*Scatophagus tetracanthus*	***Macrodon***	*Totoaba macdonaldi*
Pseudoplesiops typus	**Sciaenidae**	*Macrodon ancylodon*	***Umbrina***
Ptilichthyidae	***Argyrosomus***	***Menticirrhus***	*Umbrina bussingi*
Ptilichthys	*Argyrosomus hololepidotus*	*Menticirrhus americanus*	*Umbrina canariensis*
Ptilichthys goodei	*Argyrosomus inodorus*	*Menticirrhus elongatus*	*Umbrina canosai*
Rachycentridae	*Argyrosomus japonicus*	*Menticirrhus littoralis*	*Umbrina cirrosa*
Rachycentron	*Argyrosomus regius*	*Menticirrhus nasus*	*Umbrina coroides*
Rachycentron canadum	*Argyrosomus thorpei*	*Menticirrhus paitensis*	*Umbrina roncador*
Scaridae	***Atractoscion***	*Menticirrhus panamensis*	*Umbrina ronchus*
Bolbometopon	*Atractoscion aequidens*	*Menticirrhus saxatilis*	*Umbrina xanti*
Bolbometopon muricatum	*Atractoscion nobilis*	*Menticirrhus undulatus*	**Scombridae**
Calotomus	***Atrobucca***	***Micropogonias***	***Acanthocybium***
Calotomus carolinus	*Atrobucca nibe*	*Micropogonias altipinnis*	*Acanthocybium solandri*
Calotomus japonicus	***Bairdiella***	*Micropogonias ectenes*	***Allothunnus***
Calotomus spinidens	*Bairdiella ensifera*	*Micropogonias furnieri*	*Allothunnus fallai*
Cetoscarus	*Bairdiella ronchus*	*Micropogonias undulatus*	***Auxis***
Cetoscarus bicolor	***Cheilotrema***	***Miracorvina***	*Auxis rochei*
Chlorurus	*Cheilotrema saturnum*	*Miracorvina angolensis*	*Auxis thazard*
Chlorurus bleekeri	***Cilus***	***Nibea***	***Cybiosarda***
Chlorurus bowersi	*Cilus gilberti*	*Nibea albiflora*	*Cybiosarda elegans*
Chlorurus frontalis	***Corvula***	*Nibea soldado*	***Euthynnus***
Chlorurus japanensis	*Corvula macrops*	***Odontoscion***	*Euthynnus affinis*
Chlorurus microrhinos	*Corvula sanctaeluciae*	*Odontoscion dentex*	*Euthynnus alletteratus*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Euthynnus lineatus	*Anthias anthias*	*Epinephelus bleekeri*	*Hemanthias leptus*
Gasterochisma	*Anthias asperilinguis*	*Epinephelus bontoides*	*Hemanthias peruanus*
Gasterochisma melampus	*Anthias menezesi*	*Epinephelus bruneus*	*Hemanthias signifer*
Grammatorcynus	*Anthias nicholsi*	*Epinephelus caninus*	***Hypoplectrus***
Grammatorcynus bicarinatus	*Anthias noeli*	*Epinephelus chabaudi*	*Hypoplectrus nigricans*
Grammatorcynus bilineatus	***Anyperodon***	*Epinephelus chlorostigma*	*Hypoplectrus unicolor*
Gymnosarda	*Anyperodon leucogrammicus*	*Epinephelus cifuentesi*	***Hyporthodus***
Gymnosarda unicolor	***Aulacocephalus***	*Epinephelus coeruleopunctatus*	*Hyporthodus acanthistius*
Katsuwonus	*Aulacocephalus temminckii*	*Epinephelus coioides*	*Hyporthodus ergastularius*
Katsuwonus pelamis	***Baldwinella***	*Epinephelus corallicola*	*Hyporthodus flavolimbatus*
Orcynopsis	*Baldwinella aureorubens*	*Epinephelus costae*	*Hyporthodus haifensis*
Orcynopsis unicolor	*Baldwinella vivanus*	*Epinephelus cyanopodus*	*Hyporthodus mystacinus*
Rastrelliger	***Bathyanthias***	*Epinephelus daemelii*	*Hyporthodus nigritus*
Rastrelliger brachysoma	*Bathyanthias mexicanus*	*Epinephelus diacanthus*	*Hyporthodus niphobles*
Rastrelliger faughni	***Belonoperca***	*Epinephelus drummondhayi*	*Hyporthodus niveatus*
Rastrelliger kanagurta	*Belonoperca chabanaudi*	*Epinephelus erythrurus*	*Hyporthodus octofasciatus*
Sarda	***Centropristis***	*Epinephelus fasciatomaculosus*	*Hyporthodus quernus*
Sarda australis	*Centropristis ocyurus*	*Epinephelus fasciatus*	*Hyporthodus septemfasciatus*
Sarda chiliensis	*Centropristis philadelphica*	*Epinephelus faveatus*	***Liopropoma***
Sarda lineolata	*Centropristis striata*	*Epinephelus flavocaeruleus*	*Liopropoma africanum*
Sarda orientalis	***Cephalopholis***	*Epinephelus fuscoguttatus*	*Liopropoma carmabi*
Sarda sarda	*Cephalopholis aitha*	*Epinephelus goreensis*	*Liopropoma eukrines*
Scomber	*Cephalopholis argus*	*Epinephelus heniochus*	*Liopropoma fasciatum*
Scomber australasicus	*Cephalopholis aurantia*	*Epinephelus hexagonatus*	*Liopropoma mitratum*
Scomber japonicus	*Cephalopholis boenak*	*Epinephelus howlandi*	*Liopropoma mowbrayi*
Scomber scombrus	*Cephalopholis cruentata*	*Epinephelus itajara*	*Liopropoma multilineatum*
Scomberomorus	*Cephalopholis cyanostigma*	*Epinephelus lanceolatus*	*Liopropoma pallidum*
Scomberomorus brasiliensis	*Cephalopholis formosa*	*Epinephelus latifasciatus*	*Liopropoma susumi*
Scomberomorus cavalla	*Cephalopholis fulva*	*Epinephelus longispinis*	*Liopropoma tonstrinum*
Scomberomorus commerson	*Cephalopholis hemistiktos*	*Epinephelus macrospilos*	***Luzonichthys***
Scomberomorus concolor	*Cephalopholis igarashiensis*	*Epinephelus maculatus*	*Luzonichthys waitei*
Scomberomorus guttatus	*Cephalopholis leopardus*	*Epinephelus magniscuttis*	*Luzonichthys whitleyi*
Scomberomorus koreanus	*Cephalopholis microprion*	*Epinephelus malabaricus*	***Mycteroperca***
Scomberomorus lineolatus	*Cephalopholis miniata*	*Epinephelus marginatus*	*Mycteroperca acutirostris*
Scomberomorus maculatus	*Cephalopholis nigri*	*Epinephelus melanostigma*	*Mycteroperca fusca*
Scomberomorus munroi	*Cephalopholis nigripinnis*	*Epinephelus merra*	*Mycteroperca interstitialis*
Scomberomorus niphonius	*Cephalopholis oligosticta*	*Epinephelus miliaris*	*Mycteroperca jordani*
Scomberomorus plurilineatus	*Cephalopholis panamensis*	*Epinephelus morio*	*Mycteroperca microlepis*
Scomberomorus queenslandicus	*Cephalopholis polleni*	*Epinephelus morrhua*	*Mycteroperca olfax*
Scomberomorus regalis	*Cephalopholis polyspila*	*Epinephelus multinotatus*	*Mycteroperca phenax*
Scomberomorus semifasciatus	*Cephalopholis sexmaculata*	*Epinephelus ongus*	*Mycteroperca prionura*
Scomberomorus sierra	*Cephalopholis sonnerati*	*Epinephelus poecilonotus*	*Mycteroperca rosacea*
Scomberomorus sinensis	*Cephalopholis spiloparaea*	*Epinephelus polylepis*	*Mycteroperca rubra*
Scomberomorus tritor	*Cephalopholis taeniops*	*Epinephelus polyphekadion*	*Mycteroperca tigris*
Thunnus	*Cephalopholis urodeta*	*Epinephelus posteli*	*Mycteroperca venenosa*
Thunnus alalunga	***Cromileptes***	*Epinephelus quoyanus*	*Mycteroperca xenarcha*
Thunnus albacares	*Cromileptes altivelis*	*Epinephelus radiatus*	***Niphon***
Thunnus atlanticus	***Dermatolepis***	*Epinephelus retouti*	*Niphon spinosus*
Thunnus maccoyii	*Dermatolepis dermatolepis*	*Epinephelus rivulatus*	***Paralabrax***
Thunnus obesus	*Dermatolepis inermis*	*Epinephelus sexfasciatus*	*Paralabrax auroguttatus*
Thunnus orientalis	*Dermatolepis striolata*	*Epinephelus socialis*	*Paralabrax clathratus*
Thunnus thynnus	***Diplectrum***	*Epinephelus spilotoceps*	*Paralabrax humeralis*
Thunnus tonggol	*Diplectrum bivittatum*	*Epinephelus stictus*	*Paralabrax loro*
Scombrolabracidae	*Diplectrum eumelum*	*Epinephelus stoliczkae*	*Paralabrax maculatofasciatus*
Scombrolabrax	*Diplectrum euryplectrum*	*Epinephelus striatus*	*Paralabrax nebulifer*
Scombrolabrax heterolepis	*Diplectrum formosum*	*Epinephelus summana*	***Paranthias***
Scombropidae	*Diplectrum labarum*	*Epinephelus tauvina*	*Paranthias colonus*
Scombrops	*Diplectrum macropoma*	*Epinephelus timorensis*	*Paranthias furcifer*
Scombrops oculatus	*Diplectrum pacificum*	*Epinephelus trimaculatus*	***Plectranthias***
Serranidae	*Diplectrum rostrum*	*Epinephelus tuamotuensis*	*Plectranthias alleni*
Acanthistius	*Diplectrum sciurus*	*Epinephelus tukula*	*Plectranthias exsul*
Acanthistius brasilianus	***Diploprion***	*Epinephelus undulatostriatus*	*Plectranthias fourmanoiri*
Acanthistius ocellatus	*Diploprion bifasciatum*	*Epinephelus undulosus*	*Plectranthias garrupellus*
Acanthistius paxtoni	***Epinephelus***	***Gonioplectrus***	*Plectranthias kamii*
Acanthistius sebastoides	*Epinephelus adscensionis*	*Gonioplectrus hispanus*	*Plectranthias longimanus*
Acanthistius serratus	*Epinephelus aeneus*	***Gracila***	*Plectranthias nanus*
Aethaloperca	*Epinephelus akaara*	*Gracila albomarginata*	*Plectranthias robertsi*
Aethaloperca rogaa	*Epinephelus albomarginatus*	***Grammistes***	*Plectranthias winniensis*
Alphestes	*Epinephelus amblycephalus*	*Grammistes sexlineatus*	***Plectropomus***
Alphestes afer	*Epinephelus areolatus*	***Grammistops***	*Plectropomus areolatus*
Alphestes immaculatus	*Epinephelus awoara*	*Grammistops ocellatus*	*Plectropomus laevis*
Anthias	*Epinephelus bilobatus*	***Hemanthias***	*Plectropomus leopardus*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Plectropomus maculatus	*Siganus punctatissimus*	*Chrysoblephus cristiceps*	*Sphyraena acutipinnis*
Plectropomus oligacanthus	*Siganus punctatus*	*Chrysoblephus gibbiceps*	*Sphyraena afra*
Plectropomus pessuliferus	*Siganus randalli*	***Cymatoceps***	*Sphyraena argentea*
Plectropomus punctatus	*Siganus spinus*	*Cymatoceps nasutus*	*Sphyraena barracuda*
Pogonoperca	*Siganus stellatus*	***Dentex***	*Sphyraena borealis*
Pogonoperca punctata	*Siganus sutor*	*Dentex angolensis*	*Sphyraena forsteri*
Pronotogrammus	*Siganus unimaculatus*	*Dentex barnardi*	*Sphyraena helleri*
Pronotogrammus eos	*Siganus vermiculatus*	*Dentex canariensis*	*Sphyraena idiastes*
Pronotogrammus martinicensis	*Siganus virgatus*	*Dentex congoensis*	*Sphyraena jello*
Pronotogrammus multifasciatus	*Siganus vulpinus*	*Dentex dentex*	*Sphyraena novaehollandiae*
Pseudanthias	**Sillaginidae**	*Dentex gibbosus*	*Sphyraena obtusata*
Pseudanthias bartlettorum	***Sillaginodes***	*Dentex macrophthalmus*	*Sphyraena picudilla*
Pseudanthias bicolor	*Sillaginodes punctatus*	*Dentex maroccanus*	*Sphyraena qenie*
Pseudanthias cooperi	***Sillaginopodys***	*Dentex tumifrons*	*Sphyraena sphyraena*
Pseudanthias dispar	*Sillaginopodys chondropus*	***Diplodus***	*Sphyraena tome*
Pseudanthias huchtii	***Sillaginops***	*Diplodus annularis*	**Stichaeidae**
Pseudanthias hypselosoma	*Sillaginops macrolepis*	*Diplodus argenteus*	***Alectridium***
Pseudanthias lori	***Sillaginopsis***	*Diplodus bellottii*	*Alectridium aurantiacum*
Pseudanthias pascalus	*Sillaginopsis panijus*	*Diplodus cervinus*	***Anisarchus***
Pseudanthias pleurotaenia	***Sillago***	*Diplodus holbrookii*	*Anisarchus medius*
Pseudanthias randalli	*Sillago aeolus*	*Diplodus puntazzo*	***Anoplarchus***
Pseudanthias smithvanizi	*Sillago analis*	*Diplodus sargus*	*Anoplarchus purpurescens*
Pseudanthias squamipinnis	*Sillago arabica*	*Diplodus vulgaris*	***Cebidichthys***
Pseudanthias tuka	*Sillago asiatica*	***Evynnis***	*Cebidichthys violaceus*
Pseudanthias ventralis	*Sillago bassensis*	*Evynnis cardinalis*	***Chirolophis***
Pseudogramma	*Sillago burrus*	***Lagodon***	*Chirolophis ascanii*
Pseudogramma gregoryi	*Sillago ciliata*	*Lagodon rhomboides*	***Eumesogrammus***
Pseudogramma polyacantha	*Sillago flindersi*	***Lithognathus***	*Eumesogrammus praecisus*
Pseudogramma thaumasia	*Sillago indica*	*Lithognathus lithognathus*	***Leptoclinus***
Rypticus	*Sillago ingenuua*	*Lithognathus mormyrus*	*Leptoclinus maculatus*
Rypticus maculatus	*Sillago intermedius*	***Oblada***	***Lumpenella***
Rypticus saponaceus	*Sillago japonica*	*Oblada melanura*	*Lumpenella longirostris*
Saloptia	*Sillago lutea*	***Pachymetopon***	***Lumpenus***
Saloptia powelli	*Sillago maculata*	*Pachymetopon aeneum*	*Lumpenus fabricii*
Serraniculus	*Sillago parvisquamis*	***Pagellus***	*Lumpenus lampretaeformis*
Serraniculus pumilio	*Sillago robusta*	*Pagellus acarne*	*Lumpenus sagitta*
Serranocirrhitus	*Sillago schomburgkii*	*Pagellus bellottii*	***Opisthocentrus***
Serranocirrhitus latus	*Sillago sihama*	*Pagellus bogaraveo*	*Opisthocentrus ocellatus*
Serranus	*Sillago vincenti*	*Pagellus erythrinus*	***Phytichthys***
Serranus annularis	*Sillago vittata*	***Pagrus***	*Phytichthys chirus*
Serranus atricauda	**Sparidae**	*Pagrus africanus*	***Plectobranchus***
Serranus atrobranchus	***Acanthopagrus***	*Pagrus auriga*	*Plectobranchus evides*
Serranus baldwini	*Acanthopagrus australis*	*Pagrus caeruleostictus*	***Stichaeus***
Serranus cabrilla	*Acanthopagrus berda*	*Pagrus major*	*Stichaeus punctatus punctatus*
Serranus chionaraia	*Acanthopagrus bifasciatus*	*Pagrus pagrus*	***Ulvaria***
Serranus flaviventris	*Acanthopagrus butcheri*	***Petrus***	*Ulvaria subbifurcata*
Serranus hepatus	*Acanthopagrus latus*	*Petrus rupestris*	***Xiphister***
Serranus phoebe	*Acanthopagrus schlegelii*	***Polysteganus***	*Xiphister atropurpureus*
Serranus psittacinus	***Archosargus***	*Polysteganus coeruleopunctatus*	*Xiphister mucosus*
Serranus scriba	*Archosargus probatocephalus*	*Polysteganus praeorbitalis*	**Stromateidae**
Serranus subligarius	*Archosargus rhomboidalis*	***Pterogymnus***	***Pampus***
Serranus tabacarius	***Argyrops***	*Pterogymnus laniarius*	*Pampus argenteus*
Serranus tigrinus	*Argyrops spinifer*	***Rhabdosargus***	*Pampus chinensis*
Triso	***Argyrozona***	*Rhabdosargus globiceps*	***Peprilus***
Triso dermopterus	*Argyrozona argyrozona*	*Rhabdosargus sarba*	*Peprilus burti*
Variola	***Boops***	*Rhabdosargus thorpei*	*Peprilus medius*
Variola albimarginata	*Boops boops*	***Sarpa***	*Peprilus simillimus*
Variola louti	***Calamus***	*Sarpa salpa*	*Peprilus triacanthus*
Siganidae	*Calamus arctifrons*	***Sparidentex***	***Stromateus***
Siganus	*Calamus brachysomus*	*Sparidentex hasta*	*Stromateus fiatola*
Siganus argenteus	*Calamus calamus*	***Spicara***	**Symphysanodontidae**
Siganus canaliculatus	*Calamus leucosteus*	*Spicara maena*	***Symphysanodon***
Siganus corallinus	*Calamus nodosus*	*Spicara melanurus*	*Symphysanodon maunaloae*
Siganus doliatus	*Calamus penna*	*Spicara smaris*	**Terapontidae**
Siganus fuscescens	*Calamus pennatula*	***Spondyliosoma***	***Mesopristes***
Siganus guttatus	*Calamus proridens*	*Spondyliosoma cantharus*	*Mesopristes argenteus*
Siganus javus	***Centracanthus***	*Spondyliosoma emarginatum*	*Mesopristes cancellatus*
Siganus labyrinthodes	*Centracanthus cirrus*	***Stenotomus***	***Rhynchopelates***
Siganus lineatus	***Cheimerius***	*Stenotomus caprinus*	*Rhynchopelates oxyrhynchus*
Siganus luridus	*Cheimerius nufar*	*Stenotomus chrysops*	***Terapon***
Siganus magnificus	***Chrysoblephus***	**Sphyraenidae**	*Terapon jarbua*
Siganus puellus	*Chrysoblephus anglicus*	***Sphyraena***	*Terapon theraps*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Tetragonuridae	*Astroscopus guttatus*	**Achiridae**	*Cynoglossus lida*
Tetragonurus	*Astroscopus sexspinosus*	***Achirus***	*Cynoglossus lingua*
Tetragonurus atlanticus	*Astroscopus y-graecum*	*Achirus klunzingeri*	*Cynoglossus monodi*
Trachinidae	***Kathetostoma***	*Achirus lineatus*	*Cynoglossus senegalensis*
Echiichthys	*Kathetostoma albigutta*	*Achirus mazatlanus*	*Cynoglossus sinusarabici*
Echiichthys vipera	*Kathetostoma averruncus*	*Achirus scutum*	*Cynoglossus zanzibarensis*
Trachinus	*Kathetostoma giganteum*	***Gymnachirus***	***Paraplagusia***
Trachinus araneus	***Uranoscopus***	*Gymnachirus melas*	*Paraplagusia bilineata*
Trachinus draco	*Uranoscopus albesca*	***Trinectes***	***Symphurus***
Trichiuridae	*Uranoscopus scaber*	*Trinectes fimbriatus*	*Symphurus arawak*
Aphanopus	*Uranoscopus sulphureus*	*Trinectes fluviatilis*	*Symphurus atramentatus*
Aphanopus capricornis	***Xenocephalus***	*Trinectes fonsecensis*	*Symphurus atricaudus*
Aphanopus carbo	*Xenocephalus egregius*	*Trinectes maculatus*	*Symphurus callopterus*
Aphanopus intermedius	**Xiphiidae**	*Trinectes paulistanus*	*Symphurus caribbeanus*
Aphanopus microphthalmus	***Xiphias***	**Achiropsettidae**	*Symphurus chabanaudi*
Aphanopus mikhailini	*Xiphias gladius*	***Achiropsetta***	*Symphurus civitatium*
Assurger	**Zanclidae**	*Achiropsetta tricholepis*	*Symphurus diomedeanus*
Assurger anzac	***Zanclus***	***Mancopsetta***	*Symphurus fasciolaris*
Benthodesmus	*Zanclus cornutus*	*Mancopsetta maculata*	*Symphurus ginsburgi*
Benthodesmus elongatus	**Zaproridae**	***Pseudomancopsetta***	*Symphurus gorgonae*
Benthodesmus macrophthalmus	***Zaprora***	*Pseudomancopsetta andriashevi*	*Symphurus insularis*
Benthodesmus neglectus	*Zaprora silenus*	**Bothidae**	*Symphurus jenynsi*
Benthodesmus oligoradiatus	**Zoarcidae**	***Arnoglossus***	*Symphurus leei*
Benthodesmus pacificus	***Austrolycus***	*Arnoglossus aspilos*	*Symphurus ligulatus*
Benthodesmus papua	*Austrolycus laticinctus*	*Arnoglossus capensis*	*Symphurus marginatus*
Benthodesmus simonyi	***Dieidolycus***	*Arnoglossus debilis*	*Symphurus melanurus*
Benthodesmus suluensis	*Dieidolycus leptodermatus*	*Arnoglossus imperialis*	*Symphurus melasmatotheca*
Benthodesmus tenuis	***Gymnelus***	*Arnoglossus kessleri*	*Symphurus minor*
Benthodesmus tuckeri	*Gymnelus viridis*	*Arnoglossus laterna*	*Symphurus nebulosus*
Benthodesmus vityazi	***Iluocoetes***	*Arnoglossus rueppelii*	*Symphurus nigrescens*
Eupleurogrammus	*Iluocoetes fimbriatus*	*Arnoglossus thori*	*Symphurus oculellus*
Eupleurogrammus glossodon	***Lycenchelys***	***Asterorhombus***	*Symphurus oligomerus*
Eupleurogrammus muticus	*Lycenchelys antarctica*	*Asterorhombus intermedius*	*Symphurus ommaspilus*
Evoxymetopon	*Lycenchelys aratrirostris*	***Bothus***	*Symphurus parvus*
Evoxymetopon taeniatus	*Lycenchelys bachmanni*	*Bothus guibei*	*Symphurus pelicanus*
Lepidopus	*Lycenchelys bellingshauseni*	*Bothus leopardinus*	*Symphurus piger*
Lepidopus caudatus	*Lycenchelys crotalinus*	*Bothus lunatus*	*Symphurus plagiusa*
Lepidopus dubius	*Lycenchelys hureaui*	*Bothus mancus*	*Symphurus plagusia*
Lepidopus fitchi	*Lycenchelys sarsii*	*Bothus myriaster*	*Symphurus prolatinaris*
Lepturacanthus	*Lycenchelys verrillii*	*Bothus ocellatus*	*Symphurus pusillus*
Lepturacanthus savala	***Lycodapus***	*Bothus pantherinus*	*Symphurus stigmosus*
Tentoriceps	*Lycodapus antarcticus*	*Bothus podas*	*Symphurus tessellatus*
Tentoriceps cristatus	*Lycodapus pachysoma*	*Bothus robinsi*	*Symphurus thermophilus*
Trichiurus	***Lycodes***	***Chascanopsetta***	*Symphurus trewavasae*
Trichiurus auriga	*Lycodes eudipleurostictus*	*Chascanopsetta lugubris*	*Symphurus undecimplerus*
Trichiurus lepturus	*Lycodes lavalaei*	***Engyophrys***	*Symphurus urospilus*
Trichodontidae	*Lycodes pallidus*	*Engyophrys sanctilaurentii*	*Symphurus varius*
Arctoscopus	*Lycodes reticulatus*	***Grammatobothus***	*Symphurus williamsi*
Arctoscopus japonicus	*Lycodes turneri*	*Grammatobothus pennatus*	**Paralichthyidae**
Trichodon	***Lycodichthys***	***Monolene***	***Ancylopsetta***
Trichodon trichodon	*Lycodichthys antarcticus*	*Monolene antillarum*	*Ancylopsetta dendritica*
Tripterygiidae	*Lycodichthys dearborni*	*Monolene asaedae*	*Ancylopsetta dilecta*
Acanthanectes	***Melanostigma***	*Monolene dubiosa*	*Ancylopsetta ommata*
Acanthanectes hystrix	*Melanostigma atlanticum*	*Monolene maculipinna*	***Citharichthys***
Acanthanectes rufus	*Melanostigma gelatinosum*	*Monolene mertensi*	*Citharichthys arctifrons*
Enneapterygius	*Melanostigma pammelas*	*Monolene microstoma*	*Citharichthys cornutus*
Enneapterygius atrogulare	*Melanostigma vitiazi*	*Monolene sessilicauda*	*Citharichthys gilberti*
Enneapterygius hemimelas	***Ophthalmolycus***	***Perissias***	*Citharichthys gymnorhinus*
Enneapterygius minutus	*Ophthalmolycus amberensis*	*Perissias taeniopterus*	*Citharichthys macrops*
Enneapterygius nanus	*Ophthalmolycus bothriocephalus*	***Trichopsetta***	*Citharichthys platophrys*
Enneapterygius qirmiz	***Pachycara***	*Trichopsetta caribbaea*	*Citharichthys sordidus*
Enneapterygius similis	*Pachycara brachycephalum*	*Trichopsetta ventralis*	*Citharichthys spilopterus*
Helcogramma	*Pachycara bulbiceps*	**Citharidae**	*Citharichthys stampflii*
Helcogramma hudsoni	*Pachycara crassiceps*	***Citharoides***	*Citharichthys stigmaeus*
Helcogramma striata	***Puzanovia***	*Citharoides macrolepis*	*Citharichthys xanthostigma*
Norfolkia	*Puzanovia rubra*	**Cynoglossidae**	***Cyclopsetta***
Norfolkia brachylepis	***Seleniolycus***	***Cynoglossus***	*Cyclopsetta chittendeni*
Tripterygion	*Seleniolycus laevifasciatus*	*Cynoglossus acutirostris*	*Cyclopsetta fimbriata*
Tripterygion delaisi	***Zoarces***	*Cynoglossus arel*	*Cyclopsetta panamensis*
Tripterygion tripteronotum	*Zoarces americanus*	*Cynoglossus browni*	*Cyclopsetta querna*
Uranoscopidae	*Zoarces viviparus*	*Cynoglossus cadenati*	***Etropus***
Astroscopus	**Pleuronectiformes**	*Cynoglossus canariensis*	*Etropus crossotus*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Etropus microstomus	***Nematops***	***Heteromycteris***	*Agonopsis vulsa*
Etropus rimosus	*Nematops macrochirus*	*Heteromycteris capensis*	***Agonus***
Gastropsetta	***Oncopterus***	*Heteromycteris proboscideus*	*Agonus cataphractus*
Gastropsetta frontalis	*Oncopterus darwinii*	***Microchirus***	***Aspidophoroides***
Hippoglossina	***Paralichthodes***	*Microchirus azevia*	*Aspidophoroides monopterygius*
Hippoglossina bollmani	*Paralichthodes algoensis*	*Microchirus boscanion*	*Aspidophoroides olrikii*
Hippoglossina oblonga	***Parophrys***	*Microchirus frechkopi*	***Bathyagonus***
Hippoglossina stomata	*Parophrys vetulus*	*Microchirus ocellatus*	*Bathyagonus alascanus*
Hippoglossina tetrophthalma	***Platichthys***	*Microchirus theophila*	*Bathyagonus infraspinatus*
Paralichthys	*Platichthys flesus*	*Microchirus variegatus*	*Bathyagonus nigripinnis*
Paralichthys adspersus	*Platichthys stellatus*	*Microchirus wittei*	*Bathyagonus pentacanthus*
Paralichthys aestuarius	***Pleuronectes***	***Monochirus***	***Bothragonus***
Paralichthys albigutta	*Pleuronectes platessa*	*Monochirus hispidus*	*Bothragonus swanii*
Paralichthys brasiliensis	*Pleuronectes putnami*	***Pardachirus***	***Hypsagonus***
Paralichthys californicus	*Pleuronectes quadrituberculatus*	*Pardachirus pavoninus*	*Hypsagonus quadricornis*
Paralichthys dentatus	***Pleuronichthys***	***Pegusa***	***Leptagonus***
Paralichthys isosceles	*Pleuronichthys ocellatus*	*Pegusa impar*	*Leptagonus decagonus*
Paralichthys lethostigma	***Poecilopsetta***	*Pegusa lascaris*	***Occella***
Paralichthys olivaceus	*Poecilopsetta beanii*	*Pegusa nasuta*	*Occella dodecaedron*
Paralichthys orbignyanus	*Poecilopsetta inermis*	*Pegusa triophthalma*	***Odontopyxis***
Paralichthys squamilentus	***Psettichthys***	***Solea***	*Odontopyxis trispinosa*
Paralichthys triocellatus	*Psettichthys melanostictus*	*Solea elongata*	***Sarritor***
Paralichthys woolmani	***Pseudopleuronectes***	*Solea senegalensis*	*Sarritor frenatus*
Pseudorhombus	*Pseudopleuronectes americanus*	*Solea solea*	***Stellerina***
Pseudorhombus cinnamoneus	*Pseudopleuronectes herzensteini*	***Soleichthys***	*Stellerina xyosterna*
Pseudorhombus elevatus	***Reinhardtius***	*Soleichthys heterorhinos*	***Xeneretmus***
Syacium	*Reinhardtius hippoglossoides*	*Soleichthys microcephalus*	*Xeneretmus latifrons*
Syacium latifrons	***Taratretis***	***Synapturichthys***	*Xeneretmus triacanthus*
Syacium ovale	*Taratretis derwentensis*	*Synapturichthys kleinii*	**Anoplopomatidae**
Syacium papillosum	**Psettodidae**	***Vanstraelenia***	***Anoplopoma***
Thysanopsetta	***Psettodes***	*Vanstraelenia chirophthalma*	*Anoplopoma fimbria*
Thysanopsetta naresi	*Psettodes belcheri*	**Polymixiiformes**	***Erilepis***
Xystreurys	*Psettodes bennettii*	**Polymixiidae**	*Erilepis zonifer*
Xystreurys liolepis	*Psettodes erumei*	***Polymixia***	**Aploactinidae**
Pleuronectidae	**Samaridae**	*Polymixia japonica*	***Aploactisoma***
Acanthopsetta	***Samaris***	*Polymixia lowei*	*Aploactisoma milesii*
Acanthopsetta nadeshnyi	*Samaris cristatus*	**Saccopharyngiformes**	***Kanekonia***
Atheresthes	***Samariscus***	**Saccopharyngidae**	*Kanekonia queenslandica*
Atheresthes evermanni	*Samariscus triocellatus*	***Saccopharynx***	***Pseudopataecus***
Atheresthes stomias	**Scophthalmidae**	*Saccopharynx ampullaceus*	*Pseudopataecus carnatobarbatus*
Clidoderma	***Lepidorhombus***	**Salmoniformes**	**Congiopodidae**
Clidoderma asperrimum	*Lepidorhombus boscii*	**Salmonidae**	***Congiopodus***
Embassichthys	*Lepidorhombus whiffiagonis*	***Coregonus***	*Congiopodus peruvianus*
Embassichthys bathybius	***Phrynorhombus***	*Coregonus albula*	*Congiopodus spinifer*
Eopsetta	*Phrynorhombus norvegicus*	*Coregonus autumnalis*	***Zanclorhynchus***
Eopsetta jordani	***Scophthalmus***	*Coregonus maraena*	*Zanclorhynchus spinifer*
Glyptocephalus	*Scophthalmus aquosus*	*Coregonus sardinella*	**Cottidae**
Glyptocephalus cynoglossus	*Scophthalmus maximus*	***Oncorhynchus***	***Archistes***
Glyptocephalus stelleri	*Scophthalmus rhombus*	*Oncorhynchus clarkii*	*Archistes biseriatus*
Glyptocephalus zachirus	***Zeugopterus***	*Oncorhynchus gorbuscha*	***Artediellus***
Hippoglossoides	*Zeugopterus punctatus*	*Oncorhynchus keta*	*Artediellus atlanticus*
Hippoglossoides dubius	*Zeugopterus regius*	*Oncorhynchus kisutch*	*Artediellus uncinatus*
Hippoglossoides elassodon	**Soleidae**	*Oncorhynchus masou*	***Artedius***
Hippoglossoides platessoides	***Aseraggodes***	*Oncorhynchus mykiss*	*Artedius fenestralis*
Hippoglossus	*Aseraggodes heemstrai*	*Oncorhynchus nerka*	*Artedius harringtoni*
Hippoglossus hippoglossus	*Aseraggodes melanostictus*	*Oncorhynchus tshawytscha*	*Artedius lateralis*
Hippoglossus stenolepis	*Aseraggodes normani*	***Parahucho***	*Artedius notospilotus*
Isopsetta	*Aseraggodes whitakeri*	*Parahucho perryi*	***Ascelichthys***
Isopsetta isolepis	***Austroglossus***	***Salmo***	*Ascelichthys rhodorus*
Lepidopsetta	*Austroglossus microlepis*	*Salmo salar*	***Chitonotus***
Lepidopsetta bilineata	*Austroglossus pectoralis*	*Salmo trutta*	*Chitonotus pugetensis*
Limanda	***Bathysolea***	***Salvelinus***	***Clinocottus***
Limanda aspera	*Bathysolea profundicola*	*Salvelinus alpinus*	*Clinocottus acuticeps*
Limanda ferruginea	***Brachirus***	*Salvelinus fontinalis*	*Clinocottus embryum*
Limanda limanda	*Brachirus orientalis*	*Salvelinus leucomaenis*	*Clinocottus globiceps*
Lyopsetta	***Buglossidium***	*Salvelinus malma*	***Enophrys***
Lyopsetta exilis	*Buglossidium luteum*	**Scorpaeniformes**	*Enophrys bison*
Marleyella	***Dexillus***	**Agonidae**	*Enophrys taurina*
Marleyella bicolorata	*Dexillus muelleri*	***Agonomalus***	***Gymnocanthus***
Microstomus	***Dicologlossa***	*Agonomalus mozinoi*	*Gymnocanthus tricuspis*
Microstomus kitt	*Dicologlossa cuneata*	***Agonopsis***	***Hemilepidotus***
Microstomus pacificus	*Dicologlossa hexophthalma*	*Agonopsis chiloensis*	*Hemilepidotus gilberti*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Hemilepidotus hemilepidotus	***Hemitripterus***	*Normanichthys crockeri*	*Parascorpaena mcadamsi*
Hemilepidotus jordani	*Hemitripterus americanus*	**Parabembridae**	***Phenacoscorpius***
Hemilepidotus spinosus	*Hemitripterus villosus*	***Parabembras***	*Phenacoscorpius megalops*
Hemilepidotus zapus	***Nautichthys***	*Parabembras curtus*	***Pontinus***
Icelinus	*Nautichthys oculofasciatus*	**Pataecidae**	*Pontinus castor*
Icelinus cavifrons	**Hexagrammidae**	***Pataecus***	*Pontinus furcirhinus*
Icelinus tenuis	***Hexagrammos***	*Pataecus fronto*	*Pontinus kuhlii*
Icelus	*Hexagrammos decagrammus*	**Peristediidae**	*Pontinus leda*
Icelus bicornis	*Hexagrammos lagocephalus*	***Gargariscus***	*Pontinus longispinis*
Icelus spatula	*Hexagrammos octogrammus*	*Gargariscus prionocephalus*	*Pontinus nematophthalmus*
Icelus stenosomus	*Hexagrammos otakii*	***Peristedion***	*Pontinus rathbuni*
Jordania	*Hexagrammos stelleri*	*Peristedion cataphractum*	***Pterois***
Jordania zonope	***Ophiodon***	*Peristedion gracile*	*Pterois antennata*
Leptocottus	*Ophiodon elongatus*	*Peristedion miniatum*	*Pterois miles*
Leptocottus armatus	***Oxylebius***	*Peristedion thompsoni*	*Pterois radiata*
Micrenophrys	*Oxylebius pictus*	**Platycephalidae**	*Pterois russelii*
Micrenophrys lilljeborgii	***Pleurogrammus***	***Ambiserrula***	*Pterois volitans*
Myoxocephalus	*Pleurogrammus azonus*	*Ambiserrula jugosa*	***Rhinopias***
Myoxocephalus aenaeus	*Pleurogrammus monopterygius*	***Cymbacephalus***	*Rhinopias frondosa*
Myoxocephalus octodecemspinosus	***Zaniolepis***	*Cymbacephalus beauforti*	***Scorpaena***
Myoxocephalus polyacanthocephalus	*Zaniolepis latipinnis*	***Onigocia***	*Scorpaena agassizii*
Myoxocephalus quadricornis	**Liparidae**	*Onigocia oligolepis*	*Scorpaena angolensis*
Myoxocephalus scorpioides	***Acantholiparis***	***Platycephalus***	*Scorpaena bergii*
Myoxocephalus scorpius	*Acantholiparis opercularis*	*Platycephalus bassensis*	*Scorpaena brasiliensis*
Oligocottus	***Careproctus***	*Platycephalus conatus*	*Scorpaena calcarata*
Oligocottus maculosus	*Careproctus comus*	*Platycephalus fuscus*	*Scorpaena dispar*
Oligocottus rubellio	*Careproctus faunus*	*Platycephalus grandispinis*	*Scorpaena elachys*
Oligocottus snyderi	*Careproctus ranula*	*Platycephalus indicus*	*Scorpaena elongata*
Paricelinus	*Careproctus reinhardti*	*Platycephalus laevigatus*	*Scorpaena grandicornis*
Paricelinus hopliticus	*Careproctus simus*	*Platycephalus marmoratus*	*Scorpaena guttata*
Radulinus	***Eutelichthys***	*Platycephalus richardsoni*	*Scorpaena histrio*
Radulinus asprellus	*Eutelichthys leptochirus*	***Ratabulus***	*Scorpaena inermis*
Radulinus boleoides	***Genioliparis***	*Ratabulus diversidens*	*Scorpaena isthmensis*
Ruscarius	*Genioliparis lindbergi*	***Rogadius***	*Scorpaena loppei*
Ruscarius creaseri	***Liparis***	*Rogadius welanderi*	*Scorpaena maderensis*
Ruscarius meanyi	*Liparis atlanticus*	***Solitas***	*Scorpaena mystes*
Scorpaenichthys	*Liparis coheni*	*Solitas gruveli*	*Scorpaena notata*
Scorpaenichthys marmoratus	*Liparis fabricii*	***Sunagocia***	*Scorpaena plumieri*
Synchirus	*Liparis gibbus*	*Sunagocia otaitensis*	*Scorpaena porcus*
Synchirus gilli	*Liparis inquilinus*	***Thysanophrys***	*Scorpaena russula*
Taurulus	*Liparis liparis*	*Thysanophrys chiltonae*	*Scorpaena scrofa*
Taurulus bubalis	*Liparis montagui*	*Thysanophrys cirronasa*	*Scorpaena sonorae*
Triglops	*Liparis pulchellus*	**Psychrolutidae**	***Scorpaenodes***
Triglops jordani	*Liparis tanakae*	***Cottunculus***	*Scorpaenodes caribbaeus*
Triglops macellus	*Liparis tunicatus*	*Cottunculus granulosus*	*Scorpaenodes englerti*
Triglops metopias	***Nectoliparis***	*Cottunculus microps*	*Scorpaenodes guamensis*
Triglops murrayi	*Nectoliparis pelagicus*	*Cottunculus sadko*	*Scorpaenodes hirsutus*
Triglops nybelini	***Paraliparis***	***Dasycottus***	*Scorpaenodes kelloggi*
Triglops pingelii	*Paraliparis antarcticus*	*Dasycottus setiger*	*Scorpaenodes minor*
Triglops scepticus	*Paraliparis australis*	***Malacocottus***	*Scorpaenodes parvipinnis*
Triglops xenostethus	*Paraliparis gracilis*	*Malacocottus kincaidi*	*Scorpaenodes xyris*
Zesticelus	*Paraliparis leobergi*	*Malacocottus zonurus*	***Scorpaenopsis***
Zesticelus profundorum	*Paraliparis meganchus*	***Psychrolutes***	*Scorpaenopsis cacopsis*
Cyclopteridae	*Paraliparis monoporus*	*Psychrolutes marcidus*	*Scorpaenopsis diabolus*
Aptocyclus	*Paraliparis operculosus*	*Psychrolutes marmoratus*	*Scorpaenopsis furneauxi*
Aptocyclus ventricosus	*Paraliparis penicillus*	*Psychrolutes paradoxus*	*Scorpaenopsis macrochir*
Cyclopterus	*Paraliparis thalassobathyalis*	*Psychrolutes sigalutes*	*Scorpaenopsis oxycephala*
Cyclopterus lumpus	***Rhinoliparis***	**Rhamphocottidae**	***Sebastapistes***
Eumicrotremus	*Rhinoliparis barbulifer*	***Rhamphocottus***	*Sebastapistes cyanostigma*
Eumicrotremus derjugini	***Temnocora***	*Rhamphocottus richardsonii*	*Sebastapistes fowleri*
Eumicrotremus orbis	*Temnocora candida*	**Scorpaenidae**	*Sebastapistes mauritiana*
Eumicrotremus spinosus	**Neosebastidae**	***Caracanthus***	*Sebastapistes strongia*
Dactylopteridae	***Maxillicosta***	*Caracanthus maculatus*	***Taenianotus***
Dactyloptena	*Maxillicosta scabriceps*	*Caracanthus unipinna*	*Taenianotus triacanthus*
Dactyloptena orientalis	*Maxillicosta whitleyi*	***Dendrochirus***	**Sebastidae**
Dactylopterus	***Neosebastes***	*Dendrochirus bellus*	***Helicolenus***
Dactylopterus volitans	*Neosebastes bougainvillii*	*Dendrochirus biocellatus*	*Helicolenus dactylopterus*
Hemitripteridae	*Neosebastes incisipinnis*	*Dendrochirus brachypterus*	*Helicolenus lengerichi*
Blepsias	*Neosebastes nigropunctatus*	*Dendrochirus zebra*	*Helicolenus percoides*
Blepsias bilobus	*Neosebastes pandus*	***Neomerinthe***	***Sebastes***
Blepsias cirrhosus	**Normanichthyidae**	*Neomerinthe hemingwayi*	*Sebastes aleutianus*
	Normanichthys	***Parascorpaena***	*Sebastes alutus*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Sebastes atrovirens	***Lioscorpius***	*Prionotus stephanophrys*	*Scopelogadus beanii*
Sebastes auriculatus	*Lioscorpius trifasciatus*	*Prionotus teaguei*	*Scopelogadus bispinosus*
Sebastes aurora	***Setarches***	*Prionotus tribulus*	*Scopelogadus mizolepis*
Sebastes babcocki	*Setarches guentheri*	***Pterygotrigla***	***Sio***
Sebastes borealis	**Synanceiidae**	*Pterygotrigla polyommata*	*Sio nordenskjoldii*
Sebastes brevispinis	***Inimicus***	***Trigla***	**Stephanoberycidae**
Sebastes capensis	*Inimicus didactylus*	*Trigla lyra*	***Acanthochaenus***
Sebastes carnatus	***Minous***	**Siluriformes**	*Acanthochaenus luetkenii*
Sebastes caurinus	*Minous versicolor*	**Ariidae**	**Stomiiformes**
Sebastes chlorostictus	***Synanceia***	***Amphiarius***	**Gonostomatidae**
Sebastes chrysomelas	*Synanceia nana*	*Amphiarius phrygiatus*	***Bonapartia***
Sebastes ciliatus	*Synanceia verrucosa*	*Amphiarius rugispinis*	*Bonapartia pedaliota*
Sebastes constellatus	**Tetrarogidae**	***Ariopsis***	***Cyclothone***
Sebastes cortezi	***Ablabys***	*Ariopsis felis*	*Cyclothone acclinidens*
Sebastes crameri	*Ablabys macracanthus*	*Ariopsis guatemalensis*	*Cyclothone alba*
Sebastes dallii	*Ablabys taenianotus*	***Arius***	*Cyclothone atraria*
Sebastes diploproa	***Centropogon***	*Arius maculatus*	*Cyclothone braueri*
Sebastes elongatus	*Centropogon australis*	***Aspistor***	*Cyclothone kobayashii*
Sebastes emphaeus	***Glyptauchen***	*Aspistor quadriscutis*	*Cyclothone livida*
Sebastes ensifer	*Glyptauchen panduratus*	***Bagre***	*Cyclothone microdon*
Sebastes entomelas	***Gymnapistes***	*Bagre bagre*	*Cyclothone obscura*
Sebastes eos	*Gymnapistes marmoratus*	*Bagre marinus*	*Cyclothone pallida*
Sebastes fasciatus	***Liocranium***	*Bagre pinnimaculatus*	*Cyclothone pseudopallida*
Sebastes flavidus	*Liocranium praepositum*	***Carlarius***	*Cyclothone pygmaea*
Sebastes gilli	***Neovespicula***	*Carlarius heudelotii*	***Diplophos***
Sebastes goodei	*Neovespicula depressifrons*	***Cathorops***	*Diplophos taenia*
Sebastes helvomaculatus	***Tetraroge***	*Cathorops spixii*	***Gonostoma***
Sebastes hopkinsi	*Tetraroge barbata*	***Galeichthys***	*Gonostoma atlanticum*
Sebastes inermis	**Triglidae**	*Galeichthys feliceps*	*Gonostoma denudatum*
Sebastes jordani	***Bellator***	***Nemapteryx***	***Manducus***
Sebastes lentiginosus	*Bellator brachychir*	*Nemapteryx caelata*	*Manducus maderensis*
Sebastes levis	*Bellator egretta*	***Neoarius***	***Margrethia***
Sebastes macdonaldi	*Bellator gymnostethus*	*Neoarius graeffei*	*Margrethia obtusirostra*
Sebastes maliger	*Bellator loxias*	*Neoarius leptaspis*	***Sigmops***
Sebastes melanops	*Bellator militaris*	***Netuma***	*Sigmops bathyphilus*
Sebastes melanostomus	*Bellator ribeiroi*	*Netuma thalassina*	*Sigmops elongatus*
Sebastes mentella	*Bellator xenisma*	***Notarius***	*Sigmops gracilis*
Sebastes miniatus	***Chelidonichthys***	*Notarius grandicassis*	**Phosichthyidae**
Sebastes mystinus	*Chelidonichthys capensis*	*Notarius troschelii*	***Ichthyococcus***
Sebastes nebulosus	*Chelidonichthys cuculus*	***Occidentarius***	*Ichthyococcus elongatus*
Sebastes nigrocinctus	*Chelidonichthys kumu*	*Occidentarius platypogon*	*Ichthyococcus intermedius*
Sebastes norvegicus	*Chelidonichthys lucerna*	***Sciades***	*Ichthyococcus irregularis*
Sebastes ovalis	*Chelidonichthys obscurus*	*Sciades parkeri*	*Ichthyococcus ovatus*
Sebastes paucispinis	*Chelidonichthys queketti*	*Sciades proops*	*Ichthyococcus polli*
Sebastes pinniger	***Eutrigla***	**Plotosidae**	***Phosichthys***
Sebastes proriger	*Eutrigla gurnardus*	***Cnidoglanis***	*Phosichthys argenteus*
Sebastes rastrelliger	***Lepidotrigla***	*Cnidoglanis macrocephalus*	***Pollichthys***
Sebastes reedi	*Lepidotrigla brachyoptera*	***Plotosus***	*Pollichthys mauli*
Sebastes rosaceus	*Lepidotrigla cadmani*	*Plotosus lineatus*	***Polymetme***
Sebastes rosenblatti	*Lepidotrigla calodactyla*	**Stephanoberyciformes**	*Polymetme corythaeola*
Sebastes ruberrimus	*Lepidotrigla carolae*	**Gibberichthyidae**	***Vinciguerria***
Sebastes rubrivinctus	*Lepidotrigla cavillone*	***Gibberichthys***	*Vinciguerria attenuata*
Sebastes rufus	*Lepidotrigla dieuzeidei*	*Gibberichthys pumilus*	*Vinciguerria nimbaria*
Sebastes saxicola	*Lepidotrigla modesta*	**Melamphaidae**	*Vinciguerria poweriae*
Sebastes semicinctus	*Lepidotrigla mulhalli*	***Melamphaes***	***Woodsia***
Sebastes serranoides	*Lepidotrigla papilio*	*Melamphaes danae*	*Woodsia nonsuchae*
Sebastes serriceps	*Lepidotrigla vanessa*	*Melamphaes hubbsi*	***Yarrella***
Sebastes simulator	***Prionotus***	*Melamphaes leprus*	*Yarrella blackfordi*
Sebastes sinensis	*Prionotus alatus*	*Melamphaes lugubris*	**Sternoptychidae**
Sebastes umbrosus	*Prionotus albirostris*	*Melamphaes macrocephalus*	***Argyropelecus***
Sebastes variegatus	*Prionotus birostratus*	*Melamphaes microps*	*Argyropelecus aculeatus*
Sebastes viviparus	*Prionotus carolinus*	*Melamphaes polylepis*	*Argyropelecus affinis*
Sebastes zacentrus	*Prionotus evolans*	*Melamphaes pumilus*	*Argyropelecus gigas*
Sebastolobus	*Prionotus longispinosus*	*Melamphaes suborbitalis*	*Argyropelecus hemigymnus*
Sebastolobus alascanus	*Prionotus ophryas*	*Melamphaes typhlops*	*Argyropelecus olfersii*
Sebastolobus altivelis	*Prionotus paralatus*	***Poromitra***	*Argyropelecus sladeni*
Sebastolobus macrochir	*Prionotus punctatus*	*Poromitra capito*	***Danaphos***
Trachyscorpia	*Prionotus roseus*	*Poromitra crassa*	*Danaphos oculatus*
Trachyscorpia cristulata cristulata	*Prionotus rubio*	*Poromitra oscitans*	***Maurolicus***
Trachyscorpia cristulata echinata	*Prionotus ruscarius*	***Scopeloberyx***	*Maurolicus muelleri*
Trachyscorpia eschmeyeri	*Prionotus scitulus*	*Scopeloberyx microlepis*	*Maurolicus stehmanni*
Setarchidae	*Prionotus stearnsi*	***Scopelogadus***	*Maurolicus walvisensis*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Polyipnus	*Eustomias melanonema*	***Thysanactis***	*Hippocampus breviceps*
Polyipnus polli	*Eustomias melanostigma*	*Thysanactis dentex*	*Hippocampus camelopardalis*
Sternoptyx	*Eustomias monoclonus*	***Trigonolampa***	*Hippocampus comes*
Sternoptyx diaphana	*Eustomias obscurus*	*Trigonolampa miriceps*	*Hippocampus erectus*
Sternoptyx pseudobscura	*Eustomias patulus*	**Syngnathiformes**	*Hippocampus guttulatus*
Valenciennellus	*Eustomias satterleei*	**Aulostomidae**	*Hippocampus hippocampus*
Valenciennellus tripunctulatus	*Eustomias schmidti*	***Aulostomus***	*Hippocampus histrix*
Stomiidae	*Eustomias simplex*	*Aulostomus chinensis*	*Hippocampus kuda*
Aristostomias	*Eustomias spherulifer*	*Aulostomus maculatus*	*Hippocampus reidi*
Aristostomias grimaldii	*Eustomias tenisoni*	**Centriscidae**	*Hippocampus spinosissimus*
Aristostomias lunifer	*Eustomias tetranema*	***Aeoliscus***	*Hippocampus trimaculatus*
Aristostomias polydactylus	*Eustomias trewavasae*	*Aeoliscus strigatus*	*Hippocampus whitei*
Aristostomias scintillans	***Flagellostomias***	***Macroramphosus***	*Hippocampus zebra*
Aristostomias tittmanni	*Flagellostomias boureei*	*Macroramphosus gracilis*	*Hippocampus zosterae*
Aristostomias xenostoma	***Grammatostomias***	*Macroramphosus scolopax*	***Ichthyocampus***
Astronesthes	*Grammatostomias circularis*	**Fistulariidae**	*Ichthyocampus carce*
Astronesthes bilobatus	***Heterophotus***	***Fistularia***	***Micrognathus***
Astronesthes boulengeri	*Heterophotus ophistoma*	*Fistularia commersonii*	*Micrognathus andersonii*
Astronesthes caulophorus	***Idiacanthus***	*Fistularia corneta*	*Micrognathus crinitus*
Astronesthes cyaneus	*Idiacanthus antrostomus*	*Fistularia petimba*	*Micrognathus micronotopterus*
Astronesthes gemmifer	*Idiacanthus atlanticus*	*Fistularia tabacaria*	***Microphis***
Astronesthes illuminatus	*Idiacanthus fasciola*	**Syngnathidae**	*Microphis argulus*
Astronesthes indopacificus	***Leptostomias***	***Amphelikturus***	*Microphis brachyurus*
Astronesthes leucopogon	*Leptostomias gladiator*	*Amphelikturus dendriticus*	***Minyichthys***
Astronesthes lucifer	*Leptostomias gracilis*	***Anarchopterus***	*Minyichthys myersi*
Astronesthes macropogon	*Leptostomias haplocaulus*	*Anarchopterus tectus*	***Nannocampus***
Astronesthes micropogon	*Leptostomias longibarba*	***Bhanotia***	*Nannocampus elegans*
Astronesthes neopogon	***Malacosteus***	*Bhanotia nuda*	***Nerophis***
Astronesthes niger	*Malacosteus australis*	***Bryx***	*Nerophis lumbriciformis*
Astronesthes richardsoni	*Malacosteus niger*	*Bryx dunckeri*	*Nerophis ophidion*
Astronesthes similus	***Melanostomias***	***Bulbonaricus***	***Phoxocampus***
Astronesthes splendidus	*Melanostomias bartonbeani*	*Bulbonaricus brauni*	*Phoxocampus diacanthus*
Bathophilus	*Melanostomias biseriatus*	***Choeroichthys***	***Phycodurus***
Bathophilus ater	*Melanostomias macrophotus*	*Choeroichthys brachysoma*	*Phycodurus eques*
Bathophilus brevis	*Melanostomias melanopogon*	*Choeroichthys sculptus*	***Pugnaso***
Bathophilus digitatus	*Melanostomias melanops*	***Corythoichthys***	*Pugnaso curtirostris*
Bathophilus flemingi	*Melanostomias niger*	*Corythoichthys amplexus*	***Stigmatopora***
Bathophilus longipinnis	*Melanostomias tentaculatus*	*Corythoichthys flavofasciatus*	*Stigmatopora nigra*
Bathophilus nigerrimus	*Melanostomias valdiviae*	*Corythoichthys haematopterus*	***Syngnathoides***
Bathophilus pawneei	***Neonesthes***	*Corythoichthys intestinalis*	*Syngnathoides biaculeatus*
Bathophilus schizochirus	*Neonesthes capensis*	*Corythoichthys nigripectus*	***Syngnathus***
Bathophilus vaillanti	***Odontostomias***	*Corythoichthys ocellatus*	*Syngnathus abaster*
Borostomias	*Odontostomias micropogon*	*Corythoichthys schultzi*	*Syngnathus acus*
Borostomias antarcticus	***Opostomias***	***Cosmocampus***	*Syngnathus floridae*
Borostomias elucens	*Opostomias mitsuii*	*Cosmocampus albirostris*	*Syngnathus fuscus*
Chauliodus	***Pachystomias***	*Cosmocampus banneri*	*Syngnathus leptorhynchus*
Chauliodus danae	*Pachystomias microdon*	*Cosmocampus darrosanus*	*Syngnathus louisianae*
Chauliodus macouni	***Photonectes***	*Cosmocampus elucens*	*Syngnathus rostellatus*
Chauliodus minimus	*Photonectes albipennis*	*Cosmocampus maxweberi*	*Syngnathus springeri*
Chauliodus pammelas	*Photonectes braueri*	***Doryrhamphus***	***Trachyrhamphus***
Chauliodus schmidti	*Photonectes caerulescens*	*Doryrhamphus excisus excisus*	*Trachyrhamphus bicoarctatus*
Chauliodus sloani	*Photonectes dinema*	*Doryrhamphus janssi*	***Urocampus***
Chirostomias	*Photonectes leucospilus*	*Doryrhamphus negrosensis*	*Urocampus carinirostris*
Chirostomias pliopterus	*Photonectes margarita*	***Dunckerocampus***	**Tetraodontiformes**
Echiostoma	*Photonectes mirabilis*	*Dunckerocampus dactyliophorus*	**Balistidae**
Echiostoma barbatum	*Photonectes parvimanus*	***Entelurus***	***Abalistes***
Eustomias	*Photonectes phyllopogon*	*Entelurus aequoreus*	*Abalistes stellaris*
Eustomias achirus	***Photostomias***	***Halicampus***	*Abalistes stellatus*
Eustomias arborifer	*Photostomias guernei*	*Halicampus brocki*	***Balistapus***
Eustomias bibulbosus	***Rhadinesthes***	*Halicampus dunckeri*	*Balistapus undulatus*
Eustomias bigelowi	*Rhadinesthes decimus*	*Halicampus nitidus*	***Balistes***
Eustomias bimargaritatus	***Stomias***	***Haliichthys***	*Balistes capriscus*
Eustomias braueri	*Stomias affinis*	*Haliichthys taeniophorus*	*Balistes polylepis*
Eustomias bulbornatus	*Stomias atriventer*	***Hippichthys***	*Balistes punctatus*
Eustomias dendriticus	*Stomias boa boa*	*Hippichthys penicillus*	*Balistes vetula*
Eustomias enbarbatus	*Stomias boa ferox*	*Hippichthys spicifer*	***Balistoides***
Eustomias filifer	*Stomias brevibarbatus*	***Hippocampus***	*Balistoides conspicillum*
Eustomias fissibarbis	*Stomias gracilis*	*Hippocampus abdominalis*	*Balistoides viridescens*
Eustomias kreffti	*Stomias lampropeltis*	*Hippocampus algiricus*	***Canthidermis***
Eustomias lipochirus	*Stomias longibarbatus*	*Hippocampus angustus*	*Canthidermis maculata*
Eustomias longibarba	***Tactostoma***	*Hippocampus barbouri*	*Canthidermis sufflamen*
Eustomias macrurus	*Tactostoma macropus*	*Hippocampus bargibanti*	***Melichthys***

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Melichthys niger	***Paramonacanthus***	*Sphoeroides lobatus*	*Carcharhinus altimus*
Melichthys vidua	*Paramonacanthus cryptodon*	*Sphoeroides maculatus*	*Carcharhinus amblyrhynchoides*
Odonus	*Paramonacanthus japonicus*	*Sphoeroides marmoratus*	*Carcharhinus amblyrhynchos*
Odonus niger	*Paramonacanthus sulcatus*	*Sphoeroides nephelus*	*Carcharhinus amboinensis*
Pseudobalistes	***Pervagor***	*Sphoeroides pachygaster*	*Carcharhinus borneensis*
Pseudobalistes flavimarginatus	*Pervagor aspricaudus*	*Sphoeroides parvus*	*Carcharhinus brachyurus*
Pseudobalistes fuscus	*Pervagor janthinosoma*	*Sphoeroides sechurae*	*Carcharhinus brevipinna*
Pseudobalistes naufragium	*Pervagor melanocephalus*	*Sphoeroides spengleri*	*Carcharhinus cautus*
Rhinecanthus	*Pervagor nigrolineatus*	*Sphoeroides testudineus*	*Carcharhinus dussumieri*
Rhinecanthus aculeatus	*Pervagor randalli*	***Takifugu***	*Carcharhinus falciformis*
Rhinecanthus rectangulus	*Pervagor spilosoma*	*Takifugu porphyreus*	*Carcharhinus fitzroyensis*
Rhinecanthus verrucosus	***Rudarius***	*Takifugu rubripes*	*Carcharhinus galapagensis*
Sufflamen	*Rudarius minutus*	*Takifugu vermicularis*	*Carcharhinus hemiodon*
Sufflamen bursa	***Stephanolepis***	***Torquigener***	*Carcharhinus isodon*
Sufflamen chrysopterum	*Stephanolepis cirrhifer*	*Torquigener perlevis*	*Carcharhinus leucas*
Sufflamen fraenatum	*Stephanolepis diaspros*	**Triacanthidae**	*Carcharhinus limbatus*
Sufflamen verres	*Stephanolepis hispidus*	***Triacanthus***	*Carcharhinus longimanus*
Xanthichthys	*Stephanolepis setifer*	*Triacanthus biaculeatus*	*Carcharhinus macloti*
Xanthichthys auromarginatus	**Ostraciidae**	*Triacanthus nieuhofii*	*Carcharhinus melanopterus*
Xanthichthys caeruleolineatus	***Acanthostracion***	**Triacanthodidae**	*Carcharhinus obscurus*
Xanthichthys mento	*Acanthostracion guineensis*	***Hollardia***	*Carcharhinus perezi*
Xanthichthys ringens	*Acanthostracion polygonius*	*Hollardia hollardi*	*Carcharhinus plumbeus*
Diodontidae	*Acanthostracion quadricornis*	*Hollardia meadi*	*Carcharhinus porosus*
Chilomycterus	***Lactophrys***	***Parahollardia***	*Carcharhinus sealei*
Chilomycterus schoepfii	*Lactophrys bicaudalis*	*Parahollardia lineata*	*Carcharhinus signatus*
Cyclichthys	*Lactophrys trigonus*	**Zeiformes**	*Carcharhinus sorrah*
Cyclichthys orbicularis	*Lactophrys triqueter*	**Grammicolepididae**	*Carcharhinus tilstoni*
Diodon	***Lactoria***	***Grammicolepis***	***Galeocerdo***
Diodon eydouxii	*Lactoria cornuta*	*Grammicolepis brachiusculus*	*Galeocerdo cuvier*
Diodon holocanthus	*Lactoria diaphana*	***Xenolepidichthys***	***Glyphis***
Diodon hystrix	*Lactoria fornasini*	*Xenolepidichthys dalgleishi*	*Glyphis gangeticus*
Diodon liturosus	***Ostracion***	**Oreosomatidae**	***Isogomphodon***
Molidae	*Ostracion cubicus*	***Allocyttus***	*Isogomphodon oxyrhynchus*
Masturus	*Ostracion meleagris*	*Allocyttus guineensis*	***Lamiopsis***
Masturus lanceolatus	*Ostracion solorensis*	*Allocyttus niger*	*Lamiopsis temminckii*
Mola	***Rhynchostracion***	*Allocyttus verrucosus*	***Loxodon***
Mola mola	*Rhynchostracion nasus*	***Neocyttus***	*Loxodon macrorhinus*
Ranzania	***Tetrosomus***	*Neocyttus helgae*	***Nasolamia***
Ranzania laevis	*Tetrosomus concatenatus*	*Neocyttus rhomboidalis*	*Nasolamia velox*
Monacanthidae	**Tetraodontidae**	***Pseudocyttus***	***Negaprion***
Acanthaluteres	***Arothron***	*Pseudocyttus maculatus*	*Negaprion acutidens*
Acanthaluteres brownii	*Arothron hispidus*	**Zeidae**	*Negaprion brevirostris*
Acanthaluteres spilomelanurus	*Arothron immaculatus*	***Zenopsis***	***Prionace***
Acanthaluteres vittiger	*Arothron manilensis*	*Zenopsis conchifer*	*Prionace glauca*
Acreichthys	*Arothron mappa*	*Zenopsis nebulosa*	***Rhizoprionodon***
Acreichthys tomentosus	*Arothron meleagris*	***Zeus***	*Rhizoprionodon acutus*
Aluterus	*Arothron nigropunctatus*	*Zeus capensis*	*Rhizoprionodon lalandii*
Aluterus heudelotii	*Arothron stellatus*	*Zeus faber*	*Rhizoprionodon longurio*
Aluterus monoceros	***Canthigaster***	**Zeniontidae**	*Rhizoprionodon oligolinx*
Aluterus schoepfii	*Canthigaster amboinensis*	***Zenion***	*Rhizoprionodon porosus*
Aluterus scriptus	*Canthigaster bennetti*	*Zenion hololepis*	*Rhizoprionodon taylori*
Amanses	*Canthigaster compressa*	**Cephalaspidomorphi**	*Rhizoprionodon terraenovae*
Amanses scopas	*Canthigaster coronata*	**Petromyzontiformes**	***Scoliodon***
Brachaluteres	*Canthigaster epilampra*	**Mordaciidae**	*Scoliodon laticaudus*
Brachaluteres taylori	*Canthigaster figueiredoi*	***Mordacia***	***Triaenodon***
Cantherhines	*Canthigaster jactator*	*Mordacia mordax*	*Triaenodon obesus*
Cantherhines dumerilii	*Canthigaster janthinoptera*	**Petromyzontidae**	**Hemigaleidae**
Cantherhines fronticinctus	*Canthigaster leoparda*	***Entosphenus***	***Chaenogaleus***
Cantherhines macrocerus	*Canthigaster papua*	*Entosphenus tridentatus*	*Chaenogaleus macrostoma*
Cantherhines pardalis	*Canthigaster punctatissima*	***Lampetra***	***Hemigaleus***
Cantherhines pullus	*Canthigaster rostrata*	*Lampetra ayresii*	*Hemigaleus microstoma*
Meuschenia	*Canthigaster solandri*	*Lampetra fluviatilis*	***Hemipristis***
Meuschenia scaber	*Canthigaster valentini*	***Lethenteron***	*Hemipristis elongata*
Monacanthus	***Chelonodon***	*Lethenteron camtschaticum*	***Paragaleus***
Monacanthus ciliatus	*Chelonodon patoca*	***Petromyzon***	*Paragaleus pectoralis*
Monacanthus tuckeri	***Ephippion***	*Petromyzon marinus*	*Paragaleus tengi*
Nelusetta	*Ephippion guttifer*	**Elasmobranchii**	**Leptochariidae**
Nelusetta ayraud	***Lagocephalus***	**Carcharhiniformes**	***Leptocharias***
Oxymonacanthus	*Lagocephalus laevigatus*	**Carcharhinidae**	*Leptocharias smithii*
Oxymonacanthus longirostris	***Sphoeroides***	***Carcharhinus***	**Proscylliidae**
Paraluteres	*Sphoeroides annulatus*	*Carcharhinus acronotus*	***Eridacnis***
Paraluteres prionurus	*Sphoeroides dorsalis*	*Carcharhinus albimarginatus*	*Eridacnis radcliffei*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Eridacnis sinuans	*Schroederichthys maculatus*	*Heterodontus zebra*	*Pteroplatytrygon violacea*
Proscyllium	***Scyliorhinus***	**Hexanchiformes**	***Taeniura***
Proscyllium habereri	*Scyliorhinus besnardi*	**Chlamydoselachidae**	*Taeniura grabata*
Pseudotriakidae	*Scyliorhinus boa*	***Chlamydoselachus***	*Taeniura lymma*
Pseudotriakis	*Scyliorhinus canicula*	*Chlamydoselachus anguineus*	***Taeniurops***
Pseudotriakis microdon	*Scyliorhinus capensis*	**Hexanchidae**	*Taeniurops meyeni*
Scyliorhinidae	*Scyliorhinus cervigoni*	***Heptranchias***	***Urogymnus***
Apristurus	*Scyliorhinus garmani*	*Heptranchias perlo*	*Urogymnus granulatus*
Apristurus brunneus	*Scyliorhinus haeckelii*	***Hexanchus***	**Gymnuridae**
Apristurus canutus	*Scyliorhinus hesperius*	*Hexanchus griseus*	***Gymnura***
Apristurus herklotsi	*Scyliorhinus meadi*	*Hexanchus nakamurai*	*Gymnura altavela*
Apristurus indicus	*Scyliorhinus retifer*	***Notorynchus***	*Gymnura australis*
Apristurus kampae	*Scyliorhinus stellaris*	*Notorynchus cepedianus*	*Gymnura marmorata*
Apristurus laurussonii	*Scyliorhinus torrei*	**Lamniformes**	**Hexatrygonidae**
Apristurus longicephalus	**Sphyrnidae**	**Alopiidae**	***Hexatrygon***
Apristurus macrorhynchus	***Eusphyra***	***Alopias***	*Hexatrygon bickelli*
Apristurus manis	*Eusphyra blochii*	*Alopias pelagicus*	**Myliobatidae**
Apristurus microps	***Sphyrna***	*Alopias superciliosus*	***Aetomylaeus***
Apristurus parvipinnis	*Sphyrna corona*	*Alopias vulpinus*	*Aetomylaeus bovinus*
Apristurus platyrhynchus	*Sphyrna couardi*	**Cetorhinidae**	*Aetomylaeus maculatus*
Apristurus profundorum	*Sphyrna lewini*	***Cetorhinus***	*Aetomylaeus nichofii*
Apristurus riveri	*Sphyrna mokarran*	*Cetorhinus maximus*	*Aetomylaeus vespertilio*
Apristurus saldanha	*Sphyrna tiburo*	**Lamnidae**	***Mobula***
Asymbolus	*Sphyrna tudes*	***Carcharodon***	*Mobula alfredi*
Asymbolus analis	*Sphyrna zygaena*	*Carcharodon carcharias*	*Mobula birostris*
Asymbolus vincenti	**Triakidae**	***Isurus***	*Mobula eregoodootenkee*
Atelomycterus	***Furgaleus***	*Isurus oxyrinchus*	*Mobula hypostoma*
Atelomycterus fasciatus	*Furgaleus macki*	*Isurus paucus*	*Mobula japanica*
Atelomycterus macleayi	***Galeorhinus***	***Lamna***	*Mobula mobular*
Bythaelurus	*Galeorhinus galeus*	*Lamna ditropis*	*Mobula thurstoni*
Bythaelurus canescens	***Hemitriakis***	*Lamna nasus*	***Myliobatis***
Bythaelurus hispidus	*Hemitriakis japanica*	**Megachasmidae**	*Myliobatis aquila*
Bythaelurus lutarius	*Hemitriakis leucoperiptera*	***Megachasma***	*Myliobatis australis*
Cephaloscyllium	***Hypogaleus***	*Megachasma pelagios*	*Myliobatis californica*
Cephaloscyllium fasciatum	*Hypogaleus hyugaensis*	**Mitsukurinidae**	*Myliobatis freminvillei*
Cephaloscyllium isabellum	***Iago***	***Mitsukurina***	*Myliobatis goodei*
Cephaloscyllium laticeps	*Iago garricki*	*Mitsukurina owstoni*	*Myliobatis peruvianus*
Cephaloscyllium sufflans	*Iago omanensis*	**Odontaspididae**	***Rhinoptera***
Cephaloscyllium ventriosum	***Mustelus***	***Carcharias***	*Rhinoptera bonasus*
Cephalurus	*Mustelus antarcticus*	*Carcharias taurus*	*Rhinoptera marginata*
Cephalurus cephalus	*Mustelus asterias*	***Odontaspis***	**Plesiobatidae**
Figaro	*Mustelus californicus*	*Odontaspis ferox*	***Plesiobatis***
Figaro boardmani	*Mustelus canis*	*Odontaspis noronhai*	*Plesiobatis daviesi*
Galeus	*Mustelus dorsalis*	**Pseudocarchariidae**	**Urolophidae**
Galeus arae	*Mustelus fasciatus*	***Pseudocarcharias***	***Trygonoptera***
Galeus eastmani	*Mustelus griseus*	*Pseudocarcharias kamoharai*	*Trygonoptera ovalis*
Galeus gracilis	*Mustelus henlei*	**Myliobatiformes**	*Trygonoptera testacea*
Galeus melastomus	*Mustelus higmani*	**Aetobatidae**	***Urolophus***
Galeus murinus	*Mustelus lenticulatus*	***Aetobatus***	*Urolophus bucculentus*
Galeus nipponensis	*Mustelus lunulatus*	*Aetobatus narinari*	*Urolophus cruciatus*
Galeus piperatus	*Mustelus manazo*	**Dasyatidae**	*Urolophus expansus*
Galeus polli	*Mustelus mento*	***Dasyatis***	*Urolophus flavomosaicus*
Galeus sauteri	*Mustelus mustelus*	*Dasyatis brevis*	*Urolophus halleri*
Halaelurus	*Mustelus norrisi*	*Dasyatis hypostigma*	*Urolophus neocaledoniensis*
Halaelurus boesemani	*Mustelus palumbes*	*Dasyatis pastinaca*	*Urolophus paucimaculatus*
Halaelurus buergeri	*Mustelus punctulatus*	*Dasyatis thetidis*	*Urolophus sufflavus*
Halaelurus lineatus	*Mustelus schmitti*	*Dasyatis tortonesei*	*Urolophus viridis*
Halaelurus natalensis	*Mustelus whitneyi*	***Himantura***	*Urolophus westraliensis*
Haploblepharus	***Triakis***	*Himantura uarnak*	**Urotrygonidae**
Haploblepharus edwardsii	*Triakis megalopterus*	*Himantura undulata*	***Urobatis***
Haploblepharus fuscus	*Triakis scyllium*	***Hypanus***	*Urobatis concentricus*
Holohalaelurus	*Triakis semifasciata*	*Hypanus americanus*	*Urobatis jamaicensis*
Holohalaelurus punctatus	**Heterodontiformes**	*Hypanus longus*	***Urotrygon***
Holohalaelurus regani	**Heterodontidae**	***Neotrygon***	*Urotrygon chilensis*
Parmaturus	***Heterodontus***	*Neotrygon annotata*	*Urotrygon munda*
Parmaturus xaniurus	*Heterodontus francisci*	*Neotrygon kuhlii*	*Urotrygon nana*
Poroderma	*Heterodontus galeatus*	*Neotrygon leylandi*	*Urotrygon rogersi*
Poroderma africanum	*Heterodontus japonicus*	***Pastinachus***	**Orectolobiformes**
Poroderma pantherinum	*Heterodontus mexicanus*	*Pastinachus sephen*	**Brachaeluridae**
Schroederichthys	*Heterodontus portusjacksoni*	***Pateobatis***	***Brachaelurus***
Schroederichthys bivius	*Heterodontus quoyi*	*Pateobatis fai*	*Brachaelurus colcloughi*
Schroederichthys chilensis	*Heterodontus ramalheira*	***Pteroplatytrygon***	*Brachaelurus waddi*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Ginglymostomatidae	*Bathyraja meridionalis*	*Raja equatorialis*	***Deania***
Ginglymostoma	*Bathyraja murrayi*	*Raja herwigi*	*Deania calcea*
Ginglymostoma cirratum	*Bathyraja richardsoni*	*Raja microocellata*	*Deania hystricosa*
Nebrius	*Bathyraja scaphiops*	*Raja miraletus*	*Deania profundorum*
Nebrius ferrugineus	*Bathyraja spinicauda*	*Raja montagui*	*Deania quadrispinosa*
Hemiscylliidae	*Bathyraja trachura*	*Raja radula*	**Dalatiidae**
Chiloscyllium	***Irolita***	*Raja rouxi*	***Dalatias***
Chiloscyllium arabicum	*Irolita waitii*	*Raja straeleni*	*Dalatias licha*
Chiloscyllium griseum	***Pavoraja***	*Raja texana*	***Euprotomicrus***
Chiloscyllium hasseltii	*Pavoraja alleni*	*Raja undulata*	*Euprotomicrus bispinatus*
Chiloscyllium indicum	*Pavoraja nitida*	***Rajella***	***Isistius***
Chiloscyllium plagiosum	***Psammobatis***	*Rajella bathyphila*	*Isistius brasiliensis*
Chiloscyllium punctatum	*Psammobatis lentiginosa*	*Rajella bigelowi*	*Isistius plutodus*
Hemiscyllium	***Sympterygia***	*Rajella caudaspinosa*	***Squaliolus***
Hemiscyllium freycineti	*Sympterygia acuta*	*Rajella dissimilis*	*Squaliolus laticaudus*
Hemiscyllium ocellatum	*Sympterygia bonapartii*	*Rajella fyllae*	**Echinorhinidae**
Hemiscyllium trispeculare	*Sympterygia brevicaudata*	*Rajella lintea*	***Echinorhinus***
Orectolobidae	**Gurgesiellidae**	***Rostroraja***	*Echinorhinus brucus*
Eucrossorhinus	***Cruriraja***	*Rostroraja alba*	*Echinorhinus cookei*
Eucrossorhinus dasypogon	*Cruriraja parcomaculata*	***Spiniraja***	**Etmopteridae**
Orectolobus	***Gurgesiella***	*Spiniraja whitleyi*	***Aculeola***
Orectolobus japonicus	*Gurgesiella dorsalifera*	***Zearaja***	*Aculeola nigra*
Orectolobus maculatus	**Rajidae**	*Zearaja chilensis*	***Centroscyllium***
Orectolobus ornatus	***Amblyraja***	**Rhinopristiformes**	*Centroscyllium fabricii*
Orectolobus wardi	*Amblyraja georgiana*	**Glaucostegidae**	*Centroscyllium granulatum*
Sutorectus	*Amblyraja hyperborea*	***Glaucostegus***	*Centroscyllium kamoharai*
Sutorectus tentaculatus	*Amblyraja jenseni*	*Glaucostegus granulatus*	*Centroscyllium nigrum*
Parascylliidae	*Amblyraja radiata*	*Glaucostegus typus*	*Centroscyllium ornatum*
Cirrhoscyllium	*Amblyraja taaf*	**Pristidae**	***Etmopterus***
Cirrhoscyllium expolitum	***Beringraja***	***Anoxypristis***	*Etmopterus benchleyi*
Cirrhoscyllium japonicum	*Beringraja inornata*	*Anoxypristis cuspidata*	*Etmopterus brachyurus*
Parascyllium	*Beringraja rhina*	***Pristis***	*Etmopterus gracilispinis*
Parascyllium collare	*Beringraja stellulata*	*Pristis microdon*	*Etmopterus granulosus*
Parascyllium ferrugineum	***Breviraja***	*Pristis pectinata*	*Etmopterus hillianus*
Parascyllium variolatum	*Breviraja claramaculata*	*Pristis perotteti*	*Etmopterus lucifer*
Rhincodontidae	*Breviraja marklei*	*Pristis pristis*	*Etmopterus molleri*
Rhincodon	*Breviraja nigriventralis*	*Pristis zijsron*	*Etmopterus polli*
Rhincodon typus	***Dentiraja***	**Rhinidae**	*Etmopterus princeps*
Stegostomatidae	*Dentiraja lemprieri*	***Rhina***	*Etmopterus pusillus*
Stegostoma	***Dipturus***	*Rhina ancylostoma*	*Etmopterus schultzi*
Stegostoma fasciatum	*Dipturus batis*	***Rhynchobatus***	*Etmopterus sentosus*
Pristiophoriformes	*Dipturus campbelli*	*Rhynchobatus djiddensis*	*Etmopterus spinax*
Pristiophoridae	*Dipturus doutrei*	*Rhynchobatus luebberti*	*Etmopterus virens*
Pliotrema	*Dipturus gudgeri*	**Rhinobatidae**	**Oxynotidae**
Pliotrema warreni	*Dipturus innominatus*	***Acroteriobatus***	***Oxynotus***
Pristiophorus	*Dipturus laevis*	*Acroteriobatus blochii*	*Oxynotus bruniensis*
Pristiophorus cirratus	*Dipturus leptocauda*	***Aptychotrema***	*Oxynotus caribbaeus*
Pristiophorus japonicus	*Dipturus nidarosiensis*	*Aptychotrema rostrata*	*Oxynotus centrina*
Pristiophorus nudipinnis	*Dipturus oxyrinchus*	*Aptychotrema vincentiana*	**Somniosidae**
Pristiophorus schroederi	*Dipturus pullopunctatus*	***Platyrhinoidis***	***Centroscymnus***
Rajiformes	***Leucoraja***	*Platyrhinoidis triseriata*	*Centroscymnus coelolepis*
Anacanthobatidae	*Leucoraja circularis*	***Pseudobatos***	*Centroscymnus crepidater*
Indobatis	*Leucoraja erinacea*	*Pseudobatos lentiginosus*	*Centroscymnus owstonii*
Indobatis ori	*Leucoraja fullonica*	***Rhinobatos***	*Centroscymnus plunketi*
Schroederobatis	*Leucoraja garmani*	*Rhinobatos albomaculatus*	***Scymnodalatias***
Schroederobatis americana	*Leucoraja leucosticta*	*Rhinobatos irvinei*	*Scymnodalatias albicauda*
Springeria	*Leucoraja melitensis*	*Rhinobatos rhinobatos*	***Scymnodon***
Springeria folirostris	*Leucoraja naevus*	***Trygonorrhina***	*Scymnodon ringens*
Arhynchobatidae	*Leucoraja ocellata*	*Trygonorrhina fasciata*	***Somniosus***
Atlantoraja	***Malacoraja***	***Zanobatus***	*Somniosus microcephalus*
Atlantoraja castelnaui	*Malacoraja senta*	*Zanobatus schoenleinii*	*Somniosus pacificus*
Atlantoraja cyclophora	*Malacoraja spinacidermis*	***Zapteryx***	*Somniosus rostratus*
Atlantoraja platana	***Neoraja***	*Zapteryx exasperata*	***Zameus***
Bathyraja	*Neoraja africana*	**Squaliformes**	*Zameus squamulosus*
Bathyraja abyssicola	*Neoraja caerulea*	**Centrophoridae**	**Squalidae**
Bathyraja brachyurops	*Neoraja carolinensis*	***Centrophorus***	***Cirrhigaleus***
Bathyraja eatonii	*Neoraja stehmanni*	*Centrophorus granulosus*	*Cirrhigaleus asper*
Bathyraja griseocauda	***Raja***	*Centrophorus harrissoni*	*Cirrhigaleus barbifer*
Bathyraja interrupta	*Raja asterias*	*Centrophorus lusitanicus*	***Squalus***
Bathyraja irrasa	*Raja brachyura*	*Centrophorus moluccensis*	*Squalus acanthias*
Bathyraja maccaini	*Raja clavata*	*Centrophorus squamosus*	*Squalus blainville*
Bathyraja maculata	*Raja eglanteria*	*Centrophorus uyato*	*Squalus cubensis*

Table A3.1 (continued). Taxonomic levels of 5619 marine fish used in this thesis.

Squalus japonicus	**Holocephali**	**Myxini**	**Sarcopterygii**
Squalus megalops	**Chimaeriformes**	**Myxiniformes**	**Coelacanthiformes**
Squalus mitsukurii	**Callorhinchidae**	**Myxinidae**	**Latimeriidae**
Squatiniformes	***Callorhinchus***	***Eptatretus***	***Latimeria***
Squatinidae	*Callorhinchus capensis*	*Eptatretus deani*	*Latimeria chalumnae*
Squatina	*Callorhinchus milii*	*Eptatretus hexatrema*	
Squatina aculeata	**Chimaeridae**	*Eptatretus polytrema*	
Squatina africana	***Chimaera***	*Eptatretus stoutii*	
Squatina argentina	*Chimaera argiloba*	***Myxine***	
Squatina australis	*Chimaera jordani*	*Myxine australis*	
Squatina californica	*Chimaera monstrosa*	*Myxine glutinosa*	
Squatina guggenheim	*Chimaera opalescens*	*Myxine ios*	
Squatina japonica	***Hydrolagus***		
Squatina nebulosa	*Hydrolagus affinis*		
Squatina oculata	*Hydrolagus alberti*		
Squatina squatina	*Hydrolagus colliei*		
Squatina tergocellata	*Hydrolagus lemures*		
Torpediniformes	*Hydrolagus melanophasma*		
Hypnidae	*Hydrolagus mirabilis*		
Hypnos	*Hydrolagus novaezealandiae*		
Hypnos monopterygius	*Hydrolagus ogilbyi*		
Narcinidae	**Rhinochimaeridae**		
Benthobatis	***Harriotta***		
Benthobatis kreffti	*Harriotta haeckeli*		
Diplobatis	*Harriotta raleighana*		
Diplobatis ommata	***Rhinochimaera***		
Narcine	*Rhinochimaera atlantica*		
Narcine brasiliensis	*Rhinochimaera pacifica*		
Narcine entemedor			
Narcine vermiculata			
Narcinops			
Narcinops tasmaniensis			
Narcinops westraliensis			
Platyrhinidae			
Platyrhina			
Platyrhina sinensis			
Torpedinidae			
Torpedo			
Torpedo mackayana			
Torpedo marmorata			
Torpedo torpedo			

Table A3.2. Species richness, average phylogenetic diversity (AvPD), sum of the higher taxonomic levels (STL), and sum of the higher taxonomic levels divided by the number of species (STL/spp) of all fish in 5-degree latitude bands in depth zones. – indicates not analysed.

Latitude (°)	Whole water column				Surface zone (0 -200 m)				Middle zone (201 - 1000 m)				Deep zone (1001 - 6000 m)			
	Species richness	AvPD	STL	STL/spp	Species richness	AvPD	STL	STL/spp	Species richness	AvPD	STL	STL/spp	Species richness	AvPD	STL	STL/spp
-75	72	46.1	190	2.6	8	–	–	–	50	41.8	130	2.6	14	60.0	81	5.8
-70	95	45.8	252	2.7	13	46.0	55	4.2	61	39.3	159	2.6	21	60.0	120	5.7
-65	120	46.8	325	2.7	16	48.0	73	4.6	74	41.8	196	2.6	30	59.3	153	5.1
-60	177	47.1	511	2.9	24	56.5	122	5.1	97	46.3	331	3.4	56	52.7	238	4.3
-55	265	46.2	776	2.9	59	60.8	313	5.3	135	48.2	489	3.6	71	51.6	287	4.0
-50	396	44.5	1078	2.7	112	54.6	527	4.7	193	47.1	636	3.3	91	51.1	352	3.9
-45	581	41.9	1481	2.5	231	51.5	867	3.8	246	44.6	732	3.0	104	48.5	379	3.6
-40	828	39.3	1864	2.3	402	44.9	1189	3.0	303	42.5	824	2.7	123	47.9	441	3.6
-35	1462	36.0	2571	1.8	908	38.2	1781	2.0	403	40.4	1011	2.5	151	47.4	508	3.4
-30	1997	33.7	2942	1.5	1406	33.6	2109	1.5	441	40.3	1071	2.4	150	47.8	517	3.4
-25	2543	32.5	3206	1.3	1931	31.7	2351	1.2	460	39.6	1084	2.4	152	47.2	519	3.4
-20	2777	31.2	3277	1.2	2129	30.1	2387	1.1	482	38.6	1078	2.2	166	46.1	541	3.3
-15	2914	30.6	3300	1.1	2264	29.5	2431	1.1	487	38.0	1067	2.2	163	45.6	531	3.3
-10	3090	30.2	3355	1.1	2419	29.2	2482	1.0	502	37.3	1066	2.1	169	45.2	544	3.2
-5	3147	29.9	3319	1.1	2467	28.8	2449	1.0	507	37.2	1054	2.1	173	45.1	547	3.2
0	3188	29.7	3312	1.0	2511	28.6	2452	1.0	501	37.1	1047	2.1	176	44.4	533	3.0
5	3299	29.6	3372	1.0	2595	28.5	2478	1.0	525	37.1	1085	2.1	179	43.8	534	3.0
10	3461	29.5	3466	1.0	2714	28.4	2564	0.9	558	36.7	1110	2.0	189	43.3	554	2.9
15	3480	29.4	3499	1.0	2715	28.6	2591	1.0	571	36.4	1125	2.0	194	43.2	563	2.9
20	3532	29.6	3601	1.0	2719	28.8	2665	1.0	606	36.3	1193	2.0	207	42.7	605	2.9
25	3533	29.8	3674	1.0	2679	29.2	2698	1.0	638	36.2	1234	1.9	216	43.0	620	2.9
30	3397	30.2	3688	1.1	2517	29.7	2653	1.1	666	36.2	1297	1.9	214	42.8	615	2.9
35	2341	33.2	3240	1.4	1527	33.9	2249	1.5	607	37.4	1246	2.1	207	43.8	594	2.9
40	1656	35.2	2756	1.7	952	36.7	1795	1.9	525	38.8	1193	2.3	179	44.9	566	3.2
45	1291	36.8	2377	1.8	711	38.0	1519	2.1	425	40.7	1059	2.5	155	46.2	516	3.3
50	897	38.1	1803	2.0	423	39.9	1023	2.4	340	42.2	914	2.7	134	46.4	451	3.4
55	750	39.2	1596	2.1	345	40.8	881	2.6	288	42.8	815	2.8	117	49.3	417	3.6
60	633	40.4	1429	2.3	292	41.6	764	2.6	253	43.4	750	3.0	88	51.4	363	4.1
65	434	43.9	1158	2.7	176	44.8	541	3.1	187	47.8	652	3.5	71	57.1	343	4.8
70	216	49.7	713	3.3	98	47.3	337	3.4	97	54.4	444	4.6	21	76.3	154	7.3
75	113	50.9	413	3.7	48	50.2	195	4.1	56	57.0	279	5.0	9	–	–	–

Table A3.3. Species richness, average phylogenetic diversity (AvPD), sum of the higher taxonomic levels (STL), and sum of the higher taxonomic levels divided by the number of species (STL/spp) of bony fish in 5-degree latitude bands in depth zones. – indicates not analysed.

Latitude (°)	Whole water column				Surface zone (0 -200 m)				Middle zone (201 - 1000 m)				Deep zone (1001 - 6000 m)			
	Species richness	AvPD	STL	STL/spp	Species richness	AvPD	STL	STL/spp	Species richness	AvPD	STL	STL/spp	Species richness	AvPD	STL	STL/spp
-75	69	22.6	167	2.4	7	–	–	–	48	24.0	116	2.4	14	44.7	77	5.5
-70	91	22.5	233	2.6	12	25.2	41	3.4	58	21.8	145	2.5	21	44.9	120	5.7
-65	115	24.4	292	2.5	14	28.1	45	3.2	71	24.8	182	2.6	30	43.0	153	5.1
-60	161	25.2	415	2.6	21	33.3	81	3.9	86	28.7	260	3.0	54	34.7	215	4.0
-55	217	26.0	599	2.8	46	39.8	212	4.6	106	29.9	357	3.4	65	33.0	247	3.8
-50	328	24.9	842	2.6	91	35.1	390	4.3	155	28.5	474	3.1	82	32.2	284	3.5
-45	480	23.9	1185	2.5	192	32.9	689	3.6	194	26.0	546	2.8	94	29.7	314	3.3
-40	672	22.0	1479	2.2	325	26.9	914	2.8	238	24.9	628	2.6	109	28.6	352	3.2
-35	1238	19.1	2091	1.7	786	20.7	1442	1.8	317	23.2	766	2.4	135	27.6	404	3.0
-30	1741	16.5	2441	1.4	1267	16.5	1763	1.4	341	23.0	811	2.4	133	28.0	408	3.1
-25	2293	15.3	2698	1.2	1788	15.0	2006	1.1	370	22.2	830	2.2	135	27.4	410	3.0
-20	2523	14.2	2790	1.1	1981	13.8	2057	1.0	393	21.2	837	2.1	149	26.5	432	2.9
-15	2672	13.9	2841	1.1	2121	13.4	2123	1.0	405	20.7	839	2.1	146	26.1	422	2.9
-10	2843	13.6	2905	1.0	2270	13.2	2182	1.0	421	20.2	845	2.0	152	26.0	440	2.9
-5	2904	13.4	2874	1.0	2319	12.9	2154	0.9	430	20.0	840	2.0	155	26.0	441	2.8
0	2949	13.2	2876	1.0	2363	12.7	2151	0.9	430	19.9	851	2.0	156	25.3	427	2.7
5	3055	13.1	2930	1.0	2446	12.7	2176	0.9	451	19.8	882	2.0	158	24.9	426	2.7
10	3196	13.0	3009	0.9	2556	12.6	2249	0.9	475	19.7	903	1.9	165	24.7	444	2.7
15	3202	13.1	3042	1.0	2550	12.7	2276	0.9	486	19.6	922	1.9	166	24.9	451	2.7
20	3243	13.2	3119	1.0	2550	12.9	2348	0.9	515	19.3	960	1.9	178	24.4	479	2.7
25	3245	13.4	3185	1.0	2516	13.2	2386	0.9	543	19.0	981	1.8	186	24.5	492	2.6
30	3122	13.8	3204	1.0	2366	13.6	2357	1.0	571	19.0	1038	1.8	185	24.2	487	2.6
35	2103	16.1	2782	1.3	1403	16.8	1958	1.4	523	20.0	996	1.9	177	24.8	470	2.7
40	1453	17.8	2327	1.6	849	19.4	1520	1.8	449	21.2	958	2.1	155	26.0	448	2.9
45	1139	18.8	2006	1.8	640	20.6	1290	2.0	367	22.5	837	2.3	132	27.0	398	3.0
50	791	19.7	1501	1.9	389	21.7	861	2.2	291	23.8	713	2.5	111	27.3	344	3.1
55	659	20.5	1322	2.0	318	22.2	730	2.3	246	24.4	644	2.6	95	30.4	310	3.3
60	552	21.3	1175	2.1	271	22.9	642	2.4	212	25.0	581	2.7	69	32.5	263	3.8
65	377	24.1	941	2.5	165	25.8	453	2.7	155	28.8	490	3.2	57	37.1	249	4.4
70	186	27.1	554	3.0	93	28.0	285	3.1	79	34.2	320	4.1	14	63.0	105	7.5
75	99	29.7	329	3.3	45	30.9	163	3.6	48	37.7	214	4.5	6	–	–	–

Table A3.4. Species richness, average phylogenetic diversity (AvPD), sum of the higher taxonomic levels (STL), and sum of the higher taxonomic levels divided by the number of species (STL/spp) of cartilaginous fish in 5-degree latitude bands in depth zones. – indicates not analysed.

Latitude (°)	Whole water column				Surface zone (0 -200 m)				Middle zone (201 - 1000 m)				Deep zone (1001 - 6000 m)			
	Species richness	AvPD	STL	STL/spp	Species richness	AvPD	STL	STL/spp	Species richness	AvPD	STL	STL/spp	Species richness	AvPD	STL	STL/spp
-75	3	–	–	–	1	–	–	–	2	–	–	–	0	–	–	–
-70	4	–	–	–	1	–	–	–	3	–	–	–	0	–	–	–
-65	4	–	–	–	1	–	–	–	3	–	–	–	0	–	–	–
-60	15	43.0	82	5.5	2	–	–	–	11	45.0	67	6.1	2	–	–	–
-55	47	30.0	155	3.3	12	52.1	75	6.3	29	35.3	124	4.3	6	–	–	–
-50	63	27.7	193	3.1	19	41.3	97	5.1	35	34.2	140	4.0	7	–	–	–
-45	93	26.3	244	2.6	37	38.3	136	3.7	46	31.3	159	3.5	7	–	–	–
-40	145	22.8	326	2.2	74	27.9	217	2.9	57	27.0	176	3.1	10	47.3	70	7.0
-35	210	20.0	405	1.9	117	23.1	281	2.4	77	24.6	209	2.7	12	50.6	81	6.8
-30	244	19.9	442	1.8	136	23.0	306	2.3	91	23.3	218	2.4	13	47.6	86	6.6
-25	240	19.6	447	1.9	141	22.4	311	2.2	82	23.5	212	2.6	13	47.6	86	6.6
-20	245	19.2	444	1.8	147	21.5	312	2.1	81	23.2	201	2.5	13	47.6	86	6.6
-15	235	18.6	418	1.8	143	20.3	302	2.1	75	22.6	187	2.5	13	47.6	86	6.6
-10	241	18.0	405	1.7	149	19.7	290	1.9	75	22.3	185	2.5	14	45.2	81	5.8
-5	237	18.1	402	1.7	148	19.9	287	1.9	71	22.7	178	2.5	15	43.6	83	5.5
0	234	18.4	407	1.7	148	19.9	293	2.0	66	23.7	174	2.6	17	43.6	83	4.9
5	239	18.3	415	1.7	149	19.8	294	2.0	69	23.9	183	2.7	18	40.4	85	4.7
10	259	17.9	428	1.7	158	19.8	307	1.9	77	22.4	187	2.4	20	35.0	85	4.3
15	272	17.6	431	1.6	165	19.7	310	1.9	79	21.7	183	2.3	24	33.0	87	3.6
20	281	17.6	446	1.6	169	19.6	318	1.9	84	21.5	199	2.4	24	33.0	87	3.6
25	276	17.6	437	1.6	163	19.5	311	1.9	85	22.2	198	2.3	23	31.9	87	3.8
30	260	17.7	425	1.6	151	19.6	290	1.9	82	22.6	198	2.4	21	31.9	87	4.1
35	222	19.5	396	1.8	122	22.5	274	2.2	72	24.5	189	2.6	23	35.7	87	3.8
40	186	19.9	359	1.9	100	23.6	246	2.5	64	25.3	174	2.7	17	34.3	81	4.8
45	136	20.9	297	2.2	68	25.0	193	2.8	47	28.7	161	3.4	17	35.8	83	4.9
50	89	24.2	228	2.6	31	36.0	125	4.0	37	30.5	146	3.9	16	35.7	74	4.6
55	75	25.3	205	2.7	24	42.2	119	5.0	31	29.3	112	3.6	15	35.7	74	4.9
60	68	25.7	185	2.7	18	43.8	94	5.2	33	28.7	112	3.4	14	38.7	69	4.9
65	47	29.0	150	3.2	9	–	–	–	25	32.2	99	4.0	11	48.7	70	6.4
70	26	39.4	111	4.3	4	–	–	–	15	42.6	74	4.9	7	–	–	–
75	13	40.6	70	5.4	3	–	–	–	7	–	–	–	3	–	–	–

Table A3.5. Species richness, average phylogenetic diversity (AvPD), sum of the higher taxonomic levels (STL), and sum of the higher taxonomic levels divided by the number of species (STL/spp) of all, bony and cartilaginous fish in 100 m depth bands from 0 m to 3500 m. – indicates not analysed.

Depth (m)	All fish				Bony fish				Cartilaginous fish			
	Specires richness	AvPD	STL	STL/spp	Specires richness	AvPD	STL	STL/spp	Specires richness	AvPD	STL	STL/spp
0 - 100	4224	12.75	3857	0.91	3920	12.43	3388	0.86	294	16.03	413	1.40
101 - 200	1153	17.76	1918	1.66	999	17.23	1583	1.58	143	19.35	272	1.90
201 - 300	904	18.59	1617	1.79	777	17.82	1300	1.67	118	21.02	254	2.15
301 - 400	736	19.10	1373	1.87	621	18.57	1109	1.79	106	20.25	216	2.04
401 - 500	636	19.75	1248	1.96	537	19.02	995	1.85	89	21.65	200	2.25
501 - 600	517	20.93	1106	2.14	432	20.09	870	2.01	76	22.54	181	2.38
601 - 700	444	21.40	981	2.21	372	20.50	772	2.08	62	23.66	158	2.55
701 - 800	401	21.56	896	2.23	341	20.72	719	2.11	50	23.47	126	2.52
801 - 900	360	22.11	834	2.32	309	20.84	657	2.13	41	26.83	124	3.02
901 - 1000	278	24.15	729	2.62	235	22.67	564	2.40	33	29.29	112	3.39
1001 - 1100	242	25.54	685	2.83	209	24.34	554	2.65	26	30.77	94	3.62
1101 - 1200	206	26.57	615	2.99	175	25.26	488	2.79	25	31.20	92	3.68
1201 - 1300	163	27.81	517	3.17	142	26.71	427	3.01	19	33.33	76	4.00
1301 - 1400	131	29.31	445	3.40	112	28.45	366	3.27	17	32.16	65	3.82
1401 - 1500	138	27.29	427	3.09	120	26.17	351	2.93	16	32.50	62	3.88
1501 - 1600	129	27.86	410	3.18	114	26.43	338	2.96	13	33.85	53	4.08
1601 - 1700	112	29.64	386	3.45	100	27.73	316	3.16	10	40.67	51	5.10
1701 - 1800	100	31.13	367	3.67	88	29.17	297	3.38	10	40.67	51	5.10
1801 - 1900	92	31.30	340	3.70	84	28.65	277	3.30	7	–	–	–
1901 - 2000	82	31.38	304	3.71	76	28.68	251	3.30	5	–	–	–
2001 - 2100	77	31.34	285	3.70	72	29.44	246	3.42	5	–	–	–
2101 - 2200	63	30.90	229	3.63	62	29.78	215	3.47	1	–	–	–
2201 - 2300	59	32.09	225	3.81	58	30.92	211	3.64	1	–	–	–
2301 - 2400	36	39.07	175	4.86	36	39.07	175	4.86	0	–	–	–
2401 - 2500	32	42.50	172	5.38	32	42.50	172	5.38	0	–	–	–
2501 - 2600	23	48.41	144	6.26	23	48.41	144	6.26	0	–	–	–
2601 - 2700	13	53.33	98	7.00	13	53.33	98	7.00	0	–	–	–
2701 - 2800	14	56.67	105	7.50	14	56.67	105	7.50	0	–	–	–
2801 - 2900	15	51.11	100	6.67	15	51.11	100	6.67	0	–	–	–
2901 - 3000	14	50.00	91	6.50	14	50.00	91	6.50	0	–	–	–
3001 - 3100	14	50.95	93	6.64	14	50.95	93	6.64	0	–	–	–
3101 - 3200	12	46.67	72	6.00	12	46.67	72	6.00	0	–	–	–
3201 - 3300	10	48.67	63	6.30	10	48.67	63	6.30	0	–	–	–
3301 - 3400	8	–	–	–	8	–	–	–	0	–	–	–
3401 - 3500	6	–	–	–	6	–	–	–	0	–	–	–

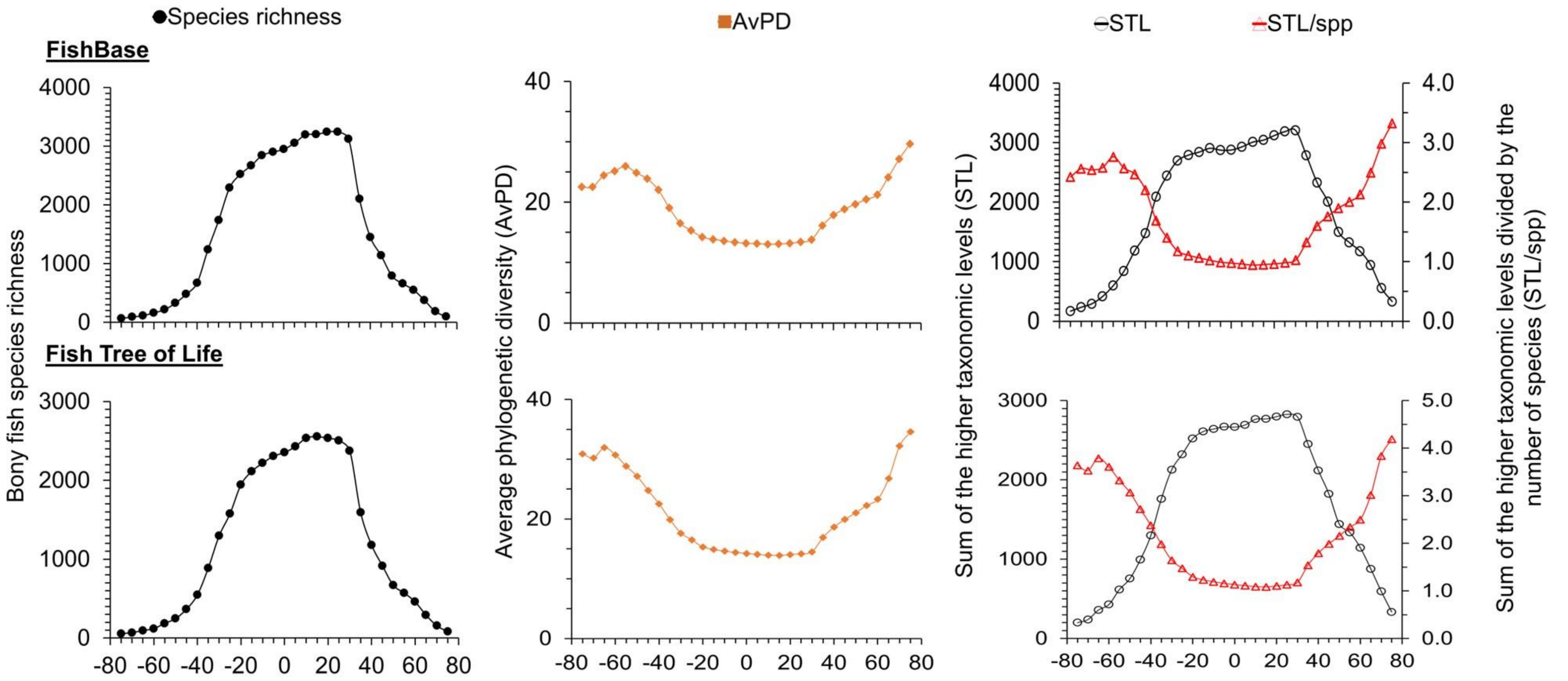


Figure A3.1. For fish taxonomy of bony fish from FishBase and Fish Tree of Life, latitudinal gradients of species richness, average phylogenetic diversity (AvPD), the sum of the higher taxonomic levels (STL) and the sum of the higher taxonomic levels divided by the number of species (STL/spp) between 75°S and 75°N in the whole water column.

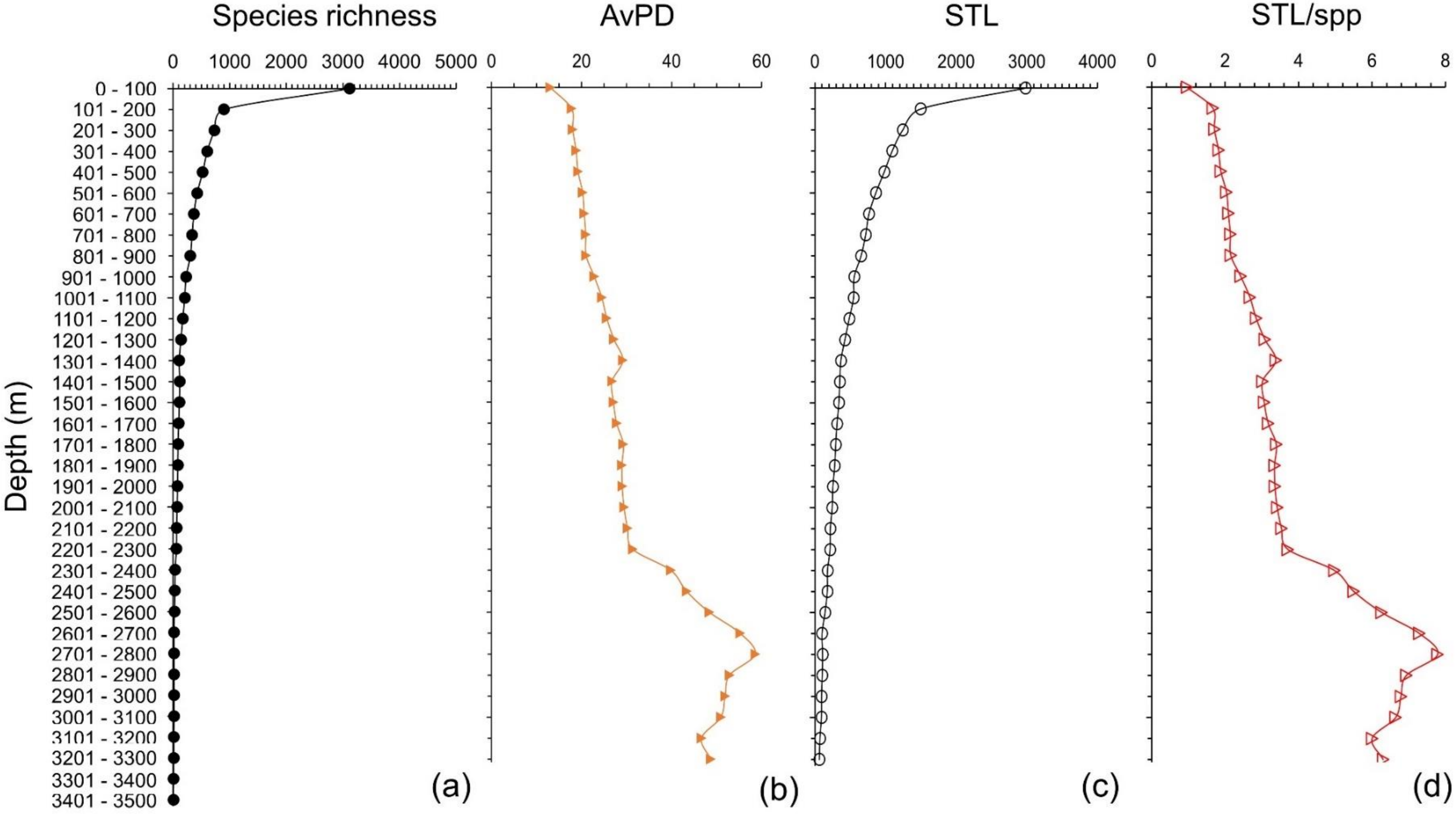


Figure A3.2. For fish taxonomy of bony fish from Fish Tree of Life, gradients of (a) species richness, (b) average phylogenetic diversity (AvPD), (c) the sum of the higher taxonomic levels (STL), and (d) the sum of the higher taxonomic levels divided by the number of species (STL/spp) in 100 m depth bands from 0 m to 3500 m.

Table A4.1. Comparison of species number between FishBase and this study

Fish group	FishBase	This Study	
	Species number	Species number	%
All fish	15195	5619	37
With body size records	13894	5619	40
With trophic level records	15194	5619	37

In traits group

Maximum body size (cm)	FishBase		This Study		
	Species number	% of all records	Species number	% of 5619 species	% of FishBase species
< 30	8644	62	2743	49	32
30 - 100	4402	32	2260	40	51
> 100	848	6	616	11	73
Trophic level					
< 2.20	468	3	242	4	52
2.20 - 2.80	621	4	286	5	46
2.81 - 3.70	10203	67	3234	58	32
> 3.7	3902	26	1857	33	48

Table A4.2. Species richness for groups of three body sizes and four trophic levels in the 5-degree latitude band in the whole water column.

Latitude (°)	All fish	Maximum body size (cm)			Trophic level			
		< 30	30 - 100	> 100	< 2.20	2.21 - 2.80	2.81 - 3.70	> 3.70
-75	72	39	32	1	0	1	58	13
-70	95	52	40	3	0	1	72	22
-65	120	63	52	5	0	1	94	25
-60	177	81	74	22	2	3	118	54
-55	265	95	110	60	2	4	143	116
-50	396	152	151	93	5	7	209	175
-45	581	212	234	135	10	13	301	257
-40	828	298	342	188	15	25	402	386
-35	1462	550	634	278	45	66	740	611
-30	1997	845	831	321	100	111	1035	751
-25	2543	1197	988	358	155	158	1325	905
-20	2777	1343	1063	371	156	167	1470	984
-15	2914	1418	1119	377	173	172	1543	1026
-10	3090	1549	1159	382	181	188	1655	1066
-5	3147	1572	1188	387	183	180	1690	1094
0	3188	1590	1206	392	187	188	1706	1107
5	3299	1661	1248	390	192	189	1781	1137
10	3461	1743	1323	395	196	189	1894	1182
15	3480	1722	1353	405	197	193	1895	1195
20	3532	1721	1393	418	196	187	1946	1203
25	3533	1664	1438	431	180	181	1940	1232
30	3397	1551	1426	420	171	158	1865	1203
35	2341	931	1021	389	66	81	1281	913
40	1656	610	716	330	33	40	907	676
45	1291	478	552	261	18	29	726	518
50	897	325	394	178	4	17	522	354
55	750	268	334	148	1	12	452	285
60	633	222	277	134	1	11	367	254
65	434	147	190	97	0	5	253	176
70	216	67	82	67	0	1	123	92
75	113	37	43	33	0	1	66	46

Table A4.3. Species richness for groups of three body sizes and four trophic levels in the 5-degree latitude band in the surface zone (0 – 200 m).

Latitude (°)	All fish	Maximum body size (cm)			Trophic level			
		< 30	30 - 100	> 100	< 2.20	2.21 - 2.80	2.81 - 3.70	> 3.70
-75	8	4	4	0	0	0	7	1
-70	13	6	7	0	0	0	9	4
-65	16	7	9	0	0	0	12	4
-60	24	11	10	3	1	2	13	8
-55	59	17	29	13	1	3	27	28
-50	112	34	50	28	4	6	55	47
-45	231	72	104	55	9	12	116	94
-40	402	125	181	96	14	25	186	177
-35	908	314	430	164	44	66	462	336
-30	1406	589	614	203	99	111	745	451
-25	1931	922	768	241	154	158	1032	587
-20	2129	1042	830	257	155	167	1152	655
-15	2264	1110	883	271	172	172	1217	703
-10	2419	1221	921	277	180	188	1313	738
-5	2467	1237	945	285	183	180	1341	763
0	2511	1254	965	292	187	188	1357	779
5	2595	1308	995	292	192	189	1413	801
10	2714	1376	1044	294	196	189	1502	827
15	2715	1350	1068	297	197	192	1495	831
20	2719	1323	1095	301	196	186	1511	826
25	2679	1263	1111	305	180	180	1484	835
30	2517	1149	1080	288	171	156	1400	790
35	1527	576	702	249	66	80	842	539
40	952	313	436	203	33	39	514	366
45	711	248	318	145	18	28	398	267
50	423	151	192	80	4	16	256	147
55	345	127	155	63	1	11	217	116
60	292	108	132	52	1	11	179	101
65	176	63	80	33	0	5	107	64
70	98	34	41	23	0	1	63	34
75	48	17	21	10	0	1	30	17

Table A4.4. Species richness for groups of three body sizes and four trophic levels in the 5-degree latitude band in the middle zone (201 – 1000 m).

Latitude (°)	All fish	Maximum body size (cm)			Trophic level			
		< 30	30 - 100	> 100	< 2.20	2.21 - 2.80	2.81 - 3.70	> 3.70
-75	50	28	21	1	0	1	40	9
-70	61	36	22	3	0	1	47	13
-65	74	40	30	4	0	1	59	14
-60	97	41	44	12	1	1	63	32
-55	135	40	59	36	1	1	64	69
-50	193	72	70	51	1	1	92	99
-45	246	88	94	64	1	1	117	127
-40	303	115	115	73	1	0	143	159
-35	403	163	146	94	1	0	189	213
-30	441	183	160	98	1	0	204	236
-25	460	203	162	95	1	0	208	251
-20	482	219	171	92	1	0	224	257
-15	487	229	173	85	1	0	234	252
-10	502	246	173	83	1	0	243	258
-5	507	252	173	82	0	0	245	262
0	501	254	167	80	0	0	245	256
5	525	269	176	80	0	0	262	263
10	558	283	193	82	0	0	281	277
15	571	288	196	87	0	1	286	284
20	606	307	204	95	0	1	309	296
25	638	305	231	102	0	1	325	312
30	666	308	252	106	0	2	337	327
35	607	269	225	113	0	1	317	289
40	525	223	198	104	0	1	284	240
45	425	171	161	93	0	1	235	189
50	340	130	134	76	0	1	189	150
55	288	102	122	64	0	1	166	121
60	253	82	108	63	0	0	141	112
65	187	57	81	49	0	0	108	79
70	97	27	34	36	0	0	53	44
75	56	15	21	20	0	0	31	25

Table A4.5. Species richness for groups of three body sizes and four trophic levels in the 5-degree latitude band in the deep zone (1001 – 6000 m).

Latitude (°)	All fish	Maximum body size (cm)			Trophic level			
		< 30	30 - 100	> 100	< 2.20	2.21 - 2.80	2.81 - 3.70	> 3.70
-75	14	7	7	0	0	0	11	3
-70	21	10	11	0	0	0	16	5
-65	30	16	13	1	0	0	23	7
-60	56	29	20	7	0	0	42	14
-55	71	38	22	11	0	0	52	19
-50	91	46	31	14	0	0	62	29
-45	104	52	36	16	0	0	68	36
-40	123	58	46	19	0	0	73	50
-35	151	73	58	20	0	0	89	62
-30	150	73	57	20	0	0	86	64
-25	152	72	58	22	0	0	85	67
-20	166	82	62	22	0	0	94	72
-15	163	79	63	21	0	0	92	71
-10	169	82	65	22	0	0	99	70
-5	173	83	70	20	0	0	104	69
0	176	82	74	20	0	0	104	72
5	179	84	77	18	0	0	106	73
10	189	84	86	19	0	0	111	78
15	194	84	89	21	0	0	114	80
20	207	91	94	22	0	0	126	81
25	216	96	96	24	0	0	131	85
30	214	94	94	26	0	0	128	86
35	207	86	94	27	0	0	122	85
40	179	74	82	23	0	0	109	70
45	155	59	73	23	0	0	93	62
50	134	44	68	22	0	0	77	57
55	117	39	57	21	0	0	69	48
60	88	32	37	19	0	0	47	41
65	71	27	29	15	0	0	38	33
70	21	6	7	8	0	0	7	14
75	9	5	1	3	0	0	5	4

Table A4.6. Mean and standard error (± SE) of maximum body size (cm) and trophic level for all fish in 5-degree latitude bands.

Latitude (°)	Maximum body size (cm)								Trophic level							
	Whole water column		0 - 200 m		201 - 1000 m		1001 - 6000 m		Whole water column		0 - 200 m		201 - 1000 m		1001 - 6000 m	
	Mean	Standard error	Mean	Standard error	Mean	Standard error	Mean	Standard error	Mean	Standard error	Mean	Standard error	Mean	Standard error	Mean	Standard error
-75	33.6	3.2	26.5	9.4	32.6	4.1	35.2	6.2	3.4	0.0	3.4	0.6	3.4	0.0	3.5	0.1
-70	35.5	3.1	33.4	9.3	33.0	3.9	37.6	5.9	3.5	0.0	3.6	1.2	3.5	0.0	3.5	0.1
-65	39.7	4.0	31.8	8.0	38.9	5.4	39.9	7.6	3.5	0.0	3.6	1.1	3.5	0.0	3.5	0.1
-60	66.4	10.4	138.4	28.3	73.3	17.3	47.9	6.9	3.6	0.0	3.5	0.4	3.6	0.0	3.5	0.0
-55	87.5	8.6	151.4	19.7	98.2	14.0	50.0	6.4	3.7	0.0	3.7	0.2	3.7	0.0	3.6	0.0
-50	89.9	8.2	228.9	21.6	89.9	10.6	52.2	7.1	3.7	0.0	3.6	0.3	3.8	0.0	3.6	0.0
-45	86.0	6.0	173.5	11.4	88.4	8.8	52.1	6.4	3.7	0.0	3.6	0.3	3.8	0.0	3.6	0.0
-40	83.2	4.6	150.5	7.5	81.3	7.3	52.5	5.6	3.7	0.0	3.6	0.0	3.8	0.0	3.7	0.0
-35	73.8	3.0	120.6	4.0	78.9	5.8	49.5	4.7	3.6	0.0	3.5	0.1	3.8	0.0	3.7	0.0
-30	65.1	2.3	103.4	2.8	75.0	5.4	48.7	4.6	3.5	0.0	3.4	-0.1	3.8	0.0	3.7	0.0
-25	58.8	1.9	93.0	2.1	71.6	5.2	50.3	4.7	3.5	0.0	3.4	-0.2	3.8	0.0	3.7	0.0
-20	56.8	1.8	91.0	2.0	68.7	5.0	47.9	4.3	3.5	0.0	3.4	-0.2	3.8	0.0	3.7	0.0
-15	56.2	1.7	90.2	1.9	66.6	4.9	48.0	4.4	3.5	0.0	3.4	-0.2	3.7	0.0	3.7	0.0
-10	54.7	1.6	88.2	1.8	64.9	4.8	48.2	4.3	3.5	0.0	3.4	-0.2	3.7	0.0	3.7	0.0
-5	54.7	1.6	87.8	1.8	64.2	4.7	45.8	3.9	3.5	0.0	3.4	-0.2	3.7	0.0	3.7	0.0
0	54.6	1.6	87.3	1.7	63.8	4.8	46.3	3.9	3.5	0.0	3.4	-0.2	3.7	0.0	3.7	0.0
5	53.7	1.5	85.9	1.7	62.2	4.6	45.4	3.7	3.5	0.0	3.4	-0.2	3.7	0.0	3.7	0.0
10	53.0	1.5	84.5	1.6	61.4	4.3	46.5	3.6	3.5	0.0	3.4	-0.2	3.7	0.0	3.7	0.0
15	53.7	1.5	85.0	1.6	62.0	4.3	47.7	3.5	3.5	0.0	3.4	-0.2	3.7	0.0	3.7	0.0
20	54.1	1.4	84.8	1.6	61.2	4.1	47.3	3.4	3.5	0.0	3.4	-0.2	3.7	0.0	3.7	0.0
25	55.1	1.4	85.1	1.6	62.3	3.9	47.6	3.3	3.5	0.0	3.4	-0.2	3.7	0.0	3.7	0.0
30	56.2	1.5	86.6	1.7	62.7	3.7	48.7	3.4	3.5	0.0	3.4	-0.2	3.7	0.0	3.7	0.0
35	66.0	2.0	100.1	2.6	67.9	4.2	50.6	3.5	3.6	0.0	3.5	0.2	3.7	0.0	3.7	0.0
40	74.8	2.7	120.1	3.9	72.0	4.8	51.5	3.9	3.6	0.0	3.6	0.3	3.7	0.0	3.7	0.0
45	76.5	3.3	128.9	4.8	77.0	5.7	55.0	4.4	3.6	0.0	3.6	0.4	3.7	0.0	3.7	0.0
50	76.2	4.2	142.4	6.9	79.3	6.7	59.6	5.0	3.6	0.0	3.6	0.6	3.7	0.0	3.7	0.0
55	76.8	4.8	152.2	8.2	79.5	7.4	61.1	5.5	3.6	0.0	3.6	0.6	3.7	0.0	3.7	0.0
60	75.9	4.5	104.6	6.1	84.7	8.3	64.5	7.0	3.7	0.0	3.6	0.6	3.7	0.0	3.7	0.0
65	82.0	6.0	113.2	8.5	94.4	10.9	64.0	8.2	3.7	0.0	3.6	0.7	3.7	0.0	3.7	0.1
70	98.6	10.4	123.7	12.5	117.8	19.1	79.8	13.5	3.7	0.0	3.7	1.0	3.7	0.0	3.9	0.1
75	97.2	16.4	90.1	13.0	128.7	30.6	57.6	23.0	3.7	0.0	3.7	0.7	3.7	0.1	3.9	0.2

Table A4.7. Mean and standard error (± SE) of maximum body size (cm) and trophic level for all fish along 100 m depth bands

Depth (m)	Maximum body size (cm)		Trophic level	
	Mean	SE	Mean	SE
0 - 100	50.6	1.2	3.4	0.0
101 - 200	69.0	2.8	3.7	0.0
201 - 300	66.9	3.3	3.7	0.0
301 - 400	60.0	3.5	3.7	0.0
401 - 500	62.0	3.9	3.7	0.0
501 - 600	59.6	4.4	3.7	0.0
601 - 700	55.7	4.8	3.7	0.0
701 - 800	55.0	4.9	3.7	0.0
801 - 900	55.6	5.4	3.7	0.0
901 - 1000	52.8	3.8	3.7	0.0
1001 - 1100	50.7	3.4	3.7	0.0
1101 - 1200	52.1	3.8	3.7	0.0
1201 - 1300	48.8	3.4	3.7	0.0
1301 - 1400	46.8	3.6	3.7	0.0
1401 - 1500	42.1	3.3	3.7	0.0
1501 - 1600	40.7	3.4	3.7	0.0
1601 - 1700	39.3	3.4	3.7	0.0
1701 - 1800	40.7	3.6	3.7	0.0
1801 - 1900	41.1	3.8	3.7	0.0
1901 - 2000	39.3	3.5	3.7	0.1
2001 - 2100	40.9	3.9	3.7	0.1
2101 - 2200	35.2	3.9	3.6	0.1
2201 - 2300	35.2	4.2	3.7	0.1
2301 - 2400	42.2	5.7	3.5	0.1
2401 - 2500	39.9	6.1	3.5	0.1
2501 - 2600	40.1	7.0	3.6	0.1
2601 - 2700	40.8	9.6	3.5	0.1
2701 - 2800	43.4	9.0	3.5	0.1
2801 - 2900	45.3	8.0	3.5	0.1
2901 - 3000	48.0	8.1	3.5	0.1
3001 - 3100	49.5	8.1	3.5	0.1
3101 - 3200	42.8	5.0	3.4	0.1
3201 - 3300	43.9	4.9	3.4	0.1
3301 - 3400	41.2	4.6	3.4	0.1
3401 - 3500	39.6	6.0	3.3	0.1

Table A4.8. Species richness for all fish, three body sizes and four trophic levels along 100 m depth bands.

Depth (m)	All fish	Maximum body size (cm)			Trophic level			
		< 30	30 -100	> 100	< 2.20	2.21 - 2.80	2.81 - 3.70	> 3.70
0 - 100	4224	2104	1666	454	241	285	2443	1255
101 - 200	1153	428	525	200	3	13	597	540
201 - 300	904	386	358	160	1	4	477	422
301 - 400	736	344	277	115	1	2	392	341
401 - 500	636	294	233	109	1	1	332	302
501 - 600	517	247	187	83	1	1	273	242
601 - 700	444	219	164	61	0	0	253	191
701 - 800	401	192	155	54	0	0	240	161
801 - 900	360	170	143	47	0	0	226	134
901 - 1000	278	125	114	39	0	0	166	112
1001 - 1100	242	107	99	36	0	0	141	101
1101 - 1200	206	87	88	31	0	0	115	91
1201 - 1300	163	70	69	24	0	0	90	73
1301 - 1400	131	59	54	18	0	0	74	57
1401 - 1500	138	75	48	15	0	0	79	59
1501 - 1600	129	72	46	11	0	0	74	55
1601 - 1700	112	63	41	8	0	0	66	46
1701 - 1800	100	54	38	8	0	0	56	44
1801 - 1900	92	49	36	7	0	0	54	38
1901 - 2000	82	44	33	5	0	0	47	35
2001 - 2100	77	43	28	6	0	0	47	30
2101 - 2200	63	39	20	4	0	0	40	23
2201 - 2300	59	37	18	4	0	0	36	23
2301 - 2400	36	17	16	3	0	0	26	10
2401 - 2500	32	15	14	3	0	0	23	9
2501 - 2600	23	12	9	2	0	0	16	7
2601 - 2700	13	6	6	1	0	0	10	3
2701 - 2800	14	6	7	1	0	0	11	3
2801 - 2900	15	5	9	1	0	0	12	3
2901 - 3000	14	4	9	1	0	0	11	3
3001 - 3100	14	4	9	1	0	0	12	2
3101 - 3200	12	3	9	0	0	0	11	1
3201 - 3300	10	2	8	0	0	0	9	1
3301 - 3400	8	2	6	0	0	0	7	1
3401 - 3500	6	2	4	0	0	0	5	1

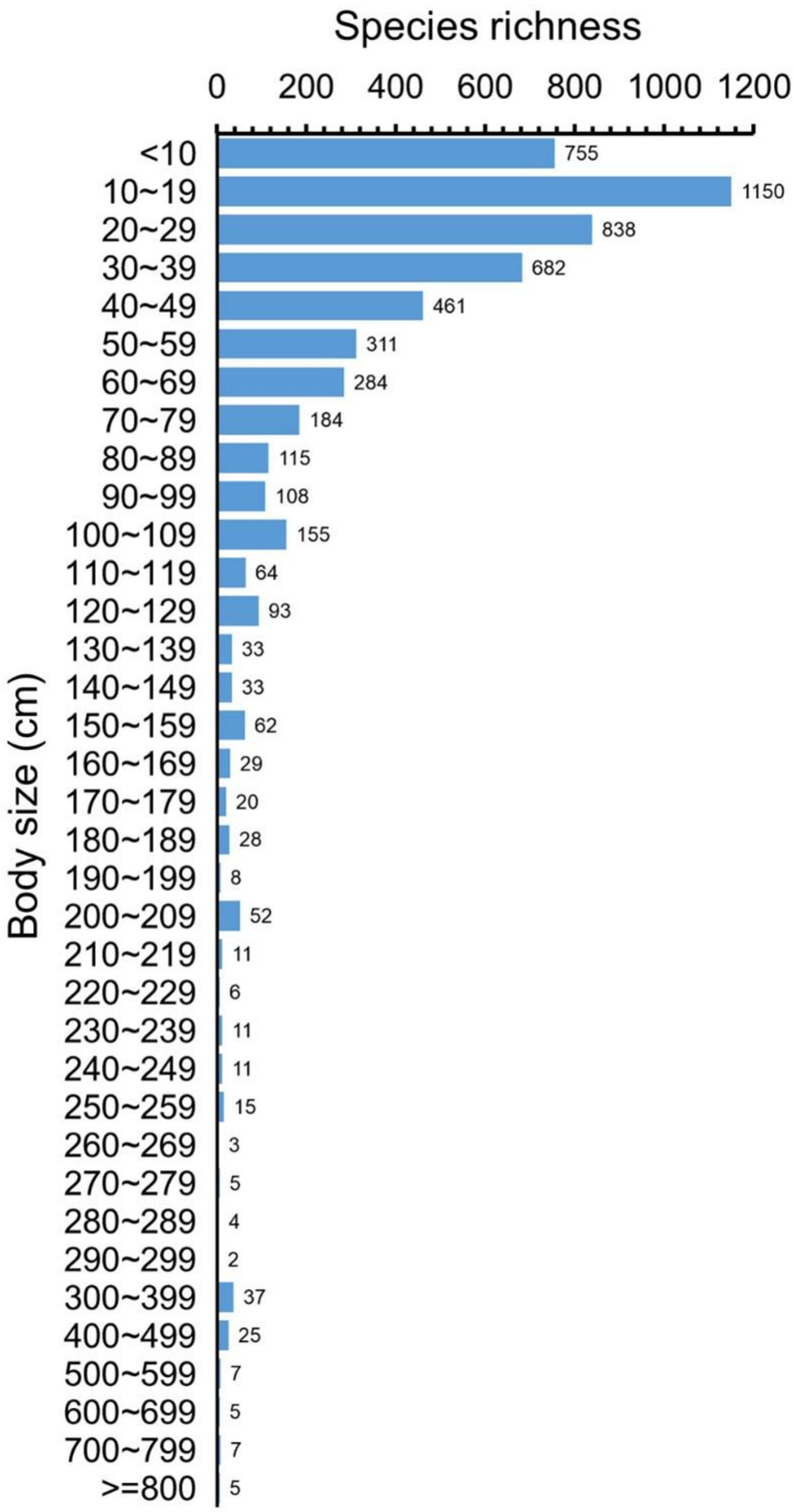


Figure A4.1. Species richness of marine fish in different body size groups.

Appendices: GAM

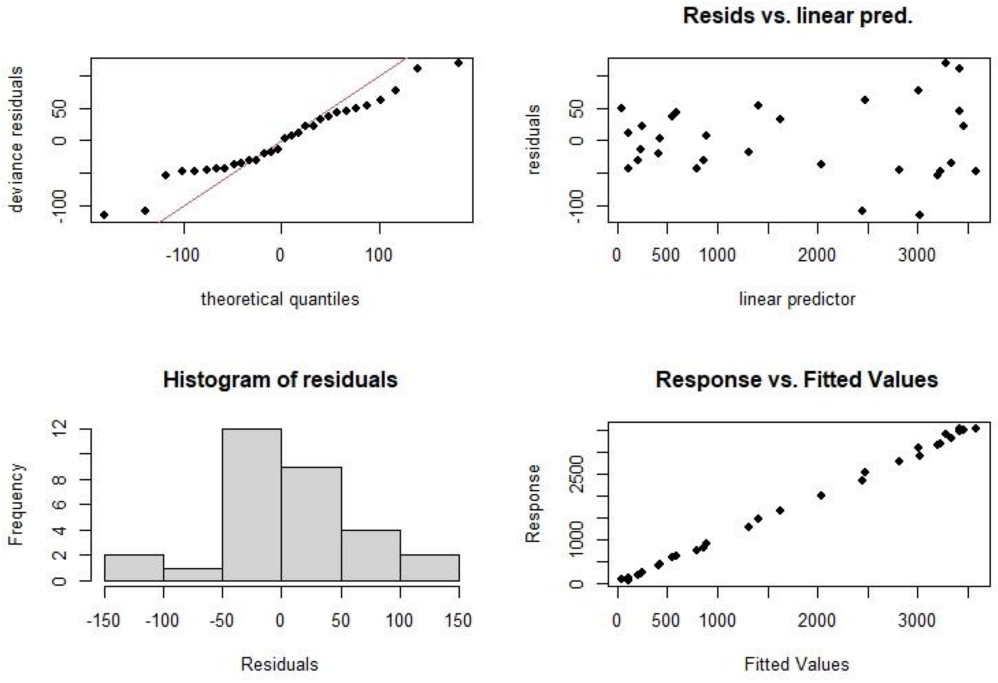
Chapter 2:
Correlations of species richness and environmental variables

Table of abbreviation:

Fish group	Abbreviation	Environmental variable	Abbreviation
All fish	AF	Sea surface temperature	SST
Pelagic fish	PF	Sea bottom temperature	SBT
Demersal fish	DF	Sea surface salinity	Salinity
Bony fish	BF	Primary productivity	Primary.productivity
Cartilaginous fish	CF		

(a) All fish

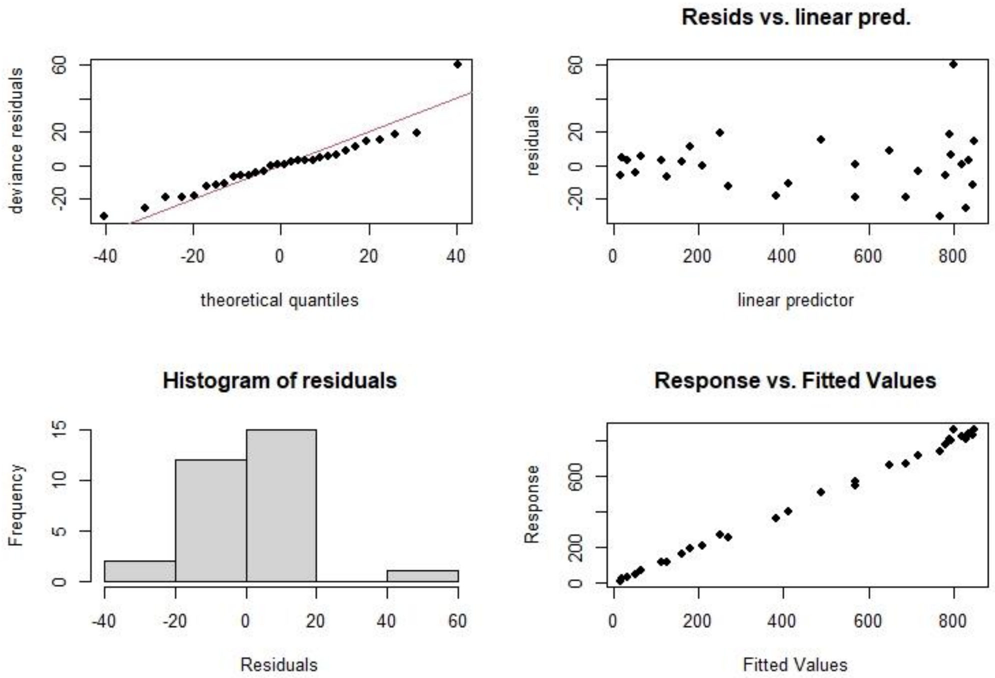
```
> Gam_AF_species <- gam(Species.AF ~ s(SST) + s(SBT, k=3) + s(Salinity) + s
(Primary.productivity), data = Data)
> gam.check(Gam_AF_species, pch =19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 21 iterations.
The RMS GCV score gradient at convergence was 0.0007185314 .
The Hessian was positive definite.
Model rank =  30 / 30

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

                        k'  edf k-index p-value
s(SST)                9.00 8.49    1.08    0.61
s(SBT)                2.00 2.00    1.25    0.91
s(Salinity)           9.00 4.62    0.96    0.41
s(Primary.productivity) 9.00 1.00    1.32    0.94
```




```
> summary(Gam_AF_species)

Family: gaussian
Link function: identity

Formula:
Species.AF ~ s(SST) + s(SBT, k = 3) + s(Salinity) + s(Primary.productivity)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   1752.4       15.5   113.1   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
                        edf Ref.df      F  p-value
s(SST)                8.492  8.857 81.855  < 2e-16 ***
s(SBT)                2.000  2.000 14.685 0.000326 ***
s(Salinity)           4.623  5.679  3.777 0.021665 *
s(Primary.productivity) 1.000  1.000  1.515 0.240224
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.996   Deviance explained = 99.8%
GCV =  16771  Scale est. = 7203.4    n = 30
```

(b) Pelagic fish

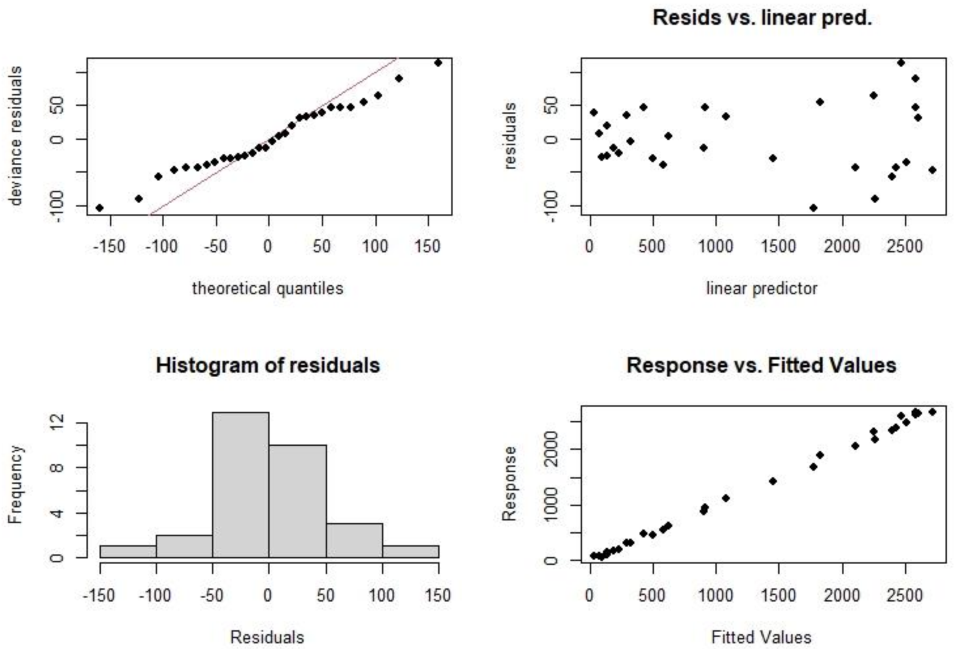
```
> Gam_PF_species <- gam(Species.PF ~ s(SST) + s(SBT, k=3) + s(Salinity) + s
(Primary.productivity), data = Data)
> gam.check(Gam_PF_species, pch =19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 19 iterations.
The RMS GCV score gradient at convergence was 1.318425e-05 .
The Hessian was positive definite.
Model rank =  30 / 30

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

                       k'  edf k-index p-value
s(SST)               9.00 2.39    1.39    0.98
s(SBT)               2.00 1.76    1.11    0.68
s(Salinity)          9.00 1.00    1.41    0.99
s(Primary.productivity) 9.00 1.00    1.06    0.60
```




```
> summary(Gam_PF_species)

Family: gaussian
Link function: identity

Formula:
Species.PF ~ s(SST) + s(SBT, k = 3) + s(Salinity) + s(Primary.productivity)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  469.167      3.459   135.6   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
                       edf Ref.df       F  p-value
s(SST)               2.389  3.030 226.853  < 2e-16 ***
s(SBT)               1.757  1.921  37.528 1.66e-09 ***
s(Salinity)          1.000  1.000   0.107    0.747
s(Primary.productivity) 1.000  1.000   1.014    0.324
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.996   Deviance explained = 99.7%
GCV =  471.2  Scale est. = 358.95    n = 30
```

(c) Demersal fish

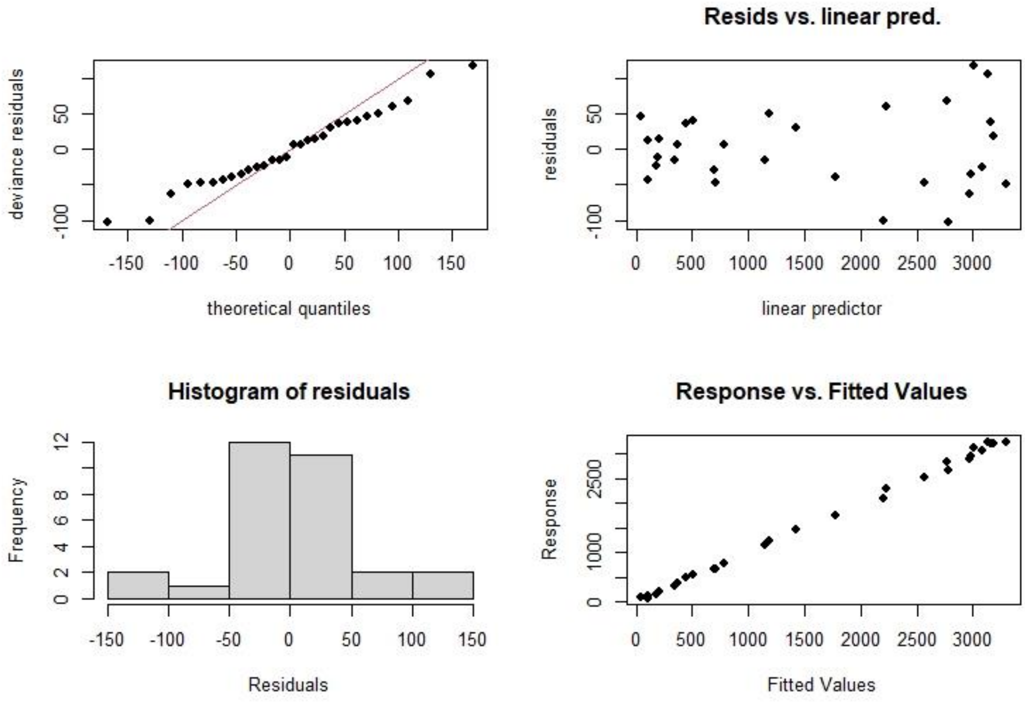
```
> Gam_DF_species <- gam(Species.DF ~ s(SST) + s(SBT, k=3) + s(Salinity) +
s(Primary.productivity), data = Data)
> gam.check(Gam_DF_species, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 21 iterations.
The RMS GCV score gradient at convergence was 0.000350048 .
The Hessian was positive definite.
Model rank =  30 / 30

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

                          k'  edf k-index p-value
s(SST)                  9.00 8.37    1.08    0.56
s(SBT)                  2.00 2.00    1.28    0.92
s(Salinity)             9.00 4.37    0.98    0.36
s(Primary.productivity) 9.00 1.00    1.38    0.97
```




```
> summary(Gam_DF_species)

Family: gaussian
Link function: identity

Formula:
Species.DF ~ s(SST) + s(SBT, k = 3) + s(Salinity) + s(Primary.productivity)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  1283.23      13.65   94.04   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
                          edf Ref.df      F  p-value
s(SST)                  8.368  8.803 75.865  < 2e-16 ***
s(SBT)                  2.000  2.000 12.881 0.000596 ***
s(Salinity)             4.369  5.391  3.706 0.023194 *
s(Primary.productivity) 1.000  1.000  1.420 0.254159
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.995   Deviance explained = 99.8%
GCV =  12636  Scale est. = 5586.1    n = 30
```

(d) Bony fish

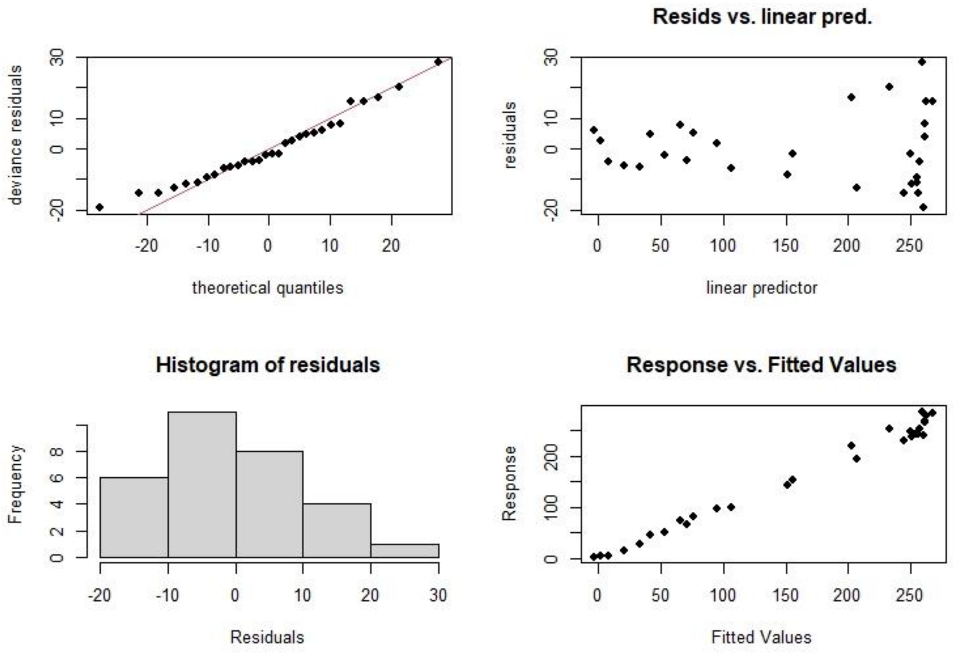
```
> Gam_BF_species <- gam(Species.BF ~ s(SST) + s(SBT, k=3) + s(Salinity) +
s(Primary.productivity), data = Data)
> gam.check(Gam_BF_species, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 20 iterations.
The RMS GCV score gradient at convergence was 0.000684484 .
The Hessian was positive definite.
Model rank =  30 / 30

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

                          k'  edf k-index p-value
s(SST)                  9.00 8.42    1.06    0.57
s(SBT)                  2.00 2.00    1.27    0.87
s(Salinity)             9.00 4.34    0.96    0.28
s(Primary.productivity) 9.00 1.00    1.33    0.95
```




```
> summary(Gam_BF_species)
Family: gaussian
Link function: identity

Formula:
Species.BF ~ s(SST) + s(SBT, k = 3) + s(Salinity) + s(Primary.productivity)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  1587.53      14.46   109.8   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
                          edf Ref.df      F  p-value
s(SST)                  8.422  8.842 90.648  < 2e-16 ***
s(SBT)                  2.000  2.000 15.702 0.000204 ***
s(Salinity)             4.343  5.365  3.578 0.026583 *
s(Primary.productivity) 1.000  1.000  1.723 0.211431
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.996   Deviance explained = 99.8%
GCV =  14218  Scale est. = 6272.7    n = 30
```

(e) Cartilaginous fish

```
> Gam_CF_species <- gam(Species.CF ~ s(SST) + s(SBT, k=3) + s(Salinity) +
s(Primary.productivity), data = Data)
> gam.check(Gam_CF_species, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 17 iterations.
The RMS GCV score gradient at convergence was 5.08585e-06 .
The Hessian was positive definite.
Model rank =  30 / 30

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

                          k'  edf k-index p-value
s(SST)                  9.00 4.07    1.63   1.000
s(SBT)                  2.00 1.00    0.95   0.310
s(Salinity)             9.00 1.00    1.28   0.895
s(Primary.productivity) 9.00 1.00    0.70   0.025 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```




```
> summary(Gam_CF_species)

Family: gaussian
Link function: identity

Formula:
Species.CF ~ s(SST) + s(SBT, k = 3) + s(Salinity) + s(Primary.productivity)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  161.967      2.382   67.99   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
                          edf Ref.df      F p-value
s(SST)                  4.072  5.103 49.574  <2e-16 ***
s(SBT)                  1.000  1.000  3.620  0.0701 .
s(Salinity)             1.000  1.000  1.211  0.2829
s(Primary.productivity) 1.000  1.000  1.729  0.2019
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.984   Deviance explained = 98.8%
GCV = 232.94  Scale est. = 170.26    n = 30
```

Apendices: GAM

Chapter 3:

Correlations of phylogenetic indices and sea temperatures

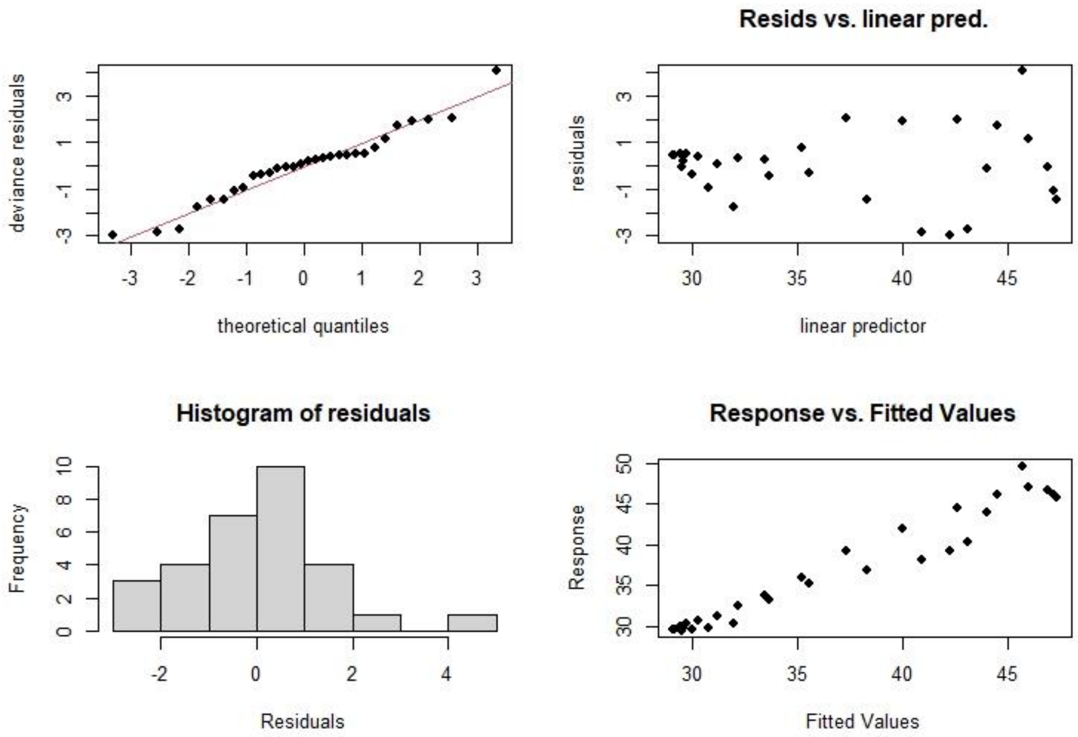
Table of abbreviation:

Phylogenetic indices	Abbreviation
Average phylogenetic diversity	AvPD
Sum of the higher taxonomic levels (STL)	STL
Sum of the higher taxonomic levels divided by the number of species (STL/spp)	STL_spp
Environmental variable	**Abbreviation**
Sea surface temperature	SST
Sea bottom temperature	SBT

Sea Surface Temperature

(a) AvPD

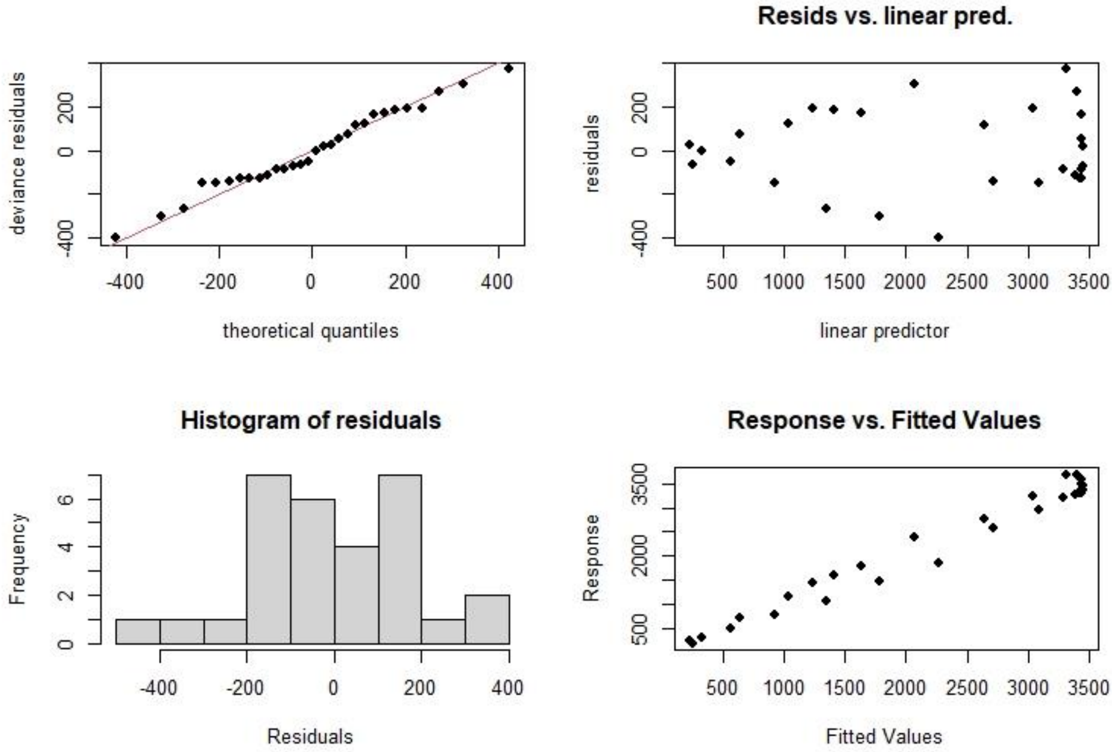
```
> AvPD_SST <- gam(AvPD ~ s(SST), data = Data)
> gam.check(AvPD_SST, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 13 iterations.
The RMS GCV score gradient at convergence was 2.787815e-07 .
The Hessian was positive definite.
Model rank = 10 / 10
Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

       k' edf k-index p-value
s(SST) 9   1    1.06    0.56
```




```
> summary(AvPD_SST)

Family: gaussian
Link function: identity
Formula:
AvPD ~ s(SST)
Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 36.8700     0.2843   129.7   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
       edf Ref.df   F p-value
s(SST)  1       1 529  <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
R-sq.(adj) = 0.948   Deviance explained =   95%
GCV = 2.5979 Scale est. = 2.4247    n = 30
```

(b) STL

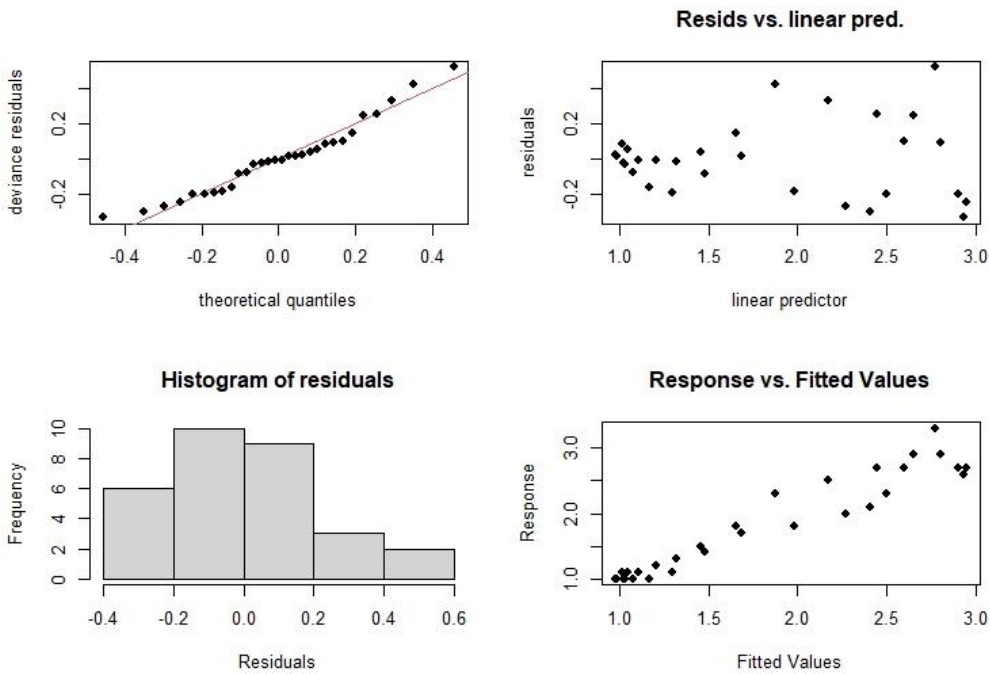
```
> STL_SST <- gam(STL ~ s(SST), data = Data)
> gam.check(STL_SST, pch=19)
Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 5 iterations.
The RMS GCV score gradient at convergence was 0.2082459 .
The Hessian was positive definite.
Model rank = 10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

         k’  edf k-index p-value
s(SST) 9.00 4.21    1.69       1
```




```
> summary(STL_SST)

Family: gaussian
Link function: identity
Formula:
STL ~ s(SST)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  2271.03      36.19   62.74   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
         edf Ref.df     F p-value
s(SST) 4.207  5.151 205.7  <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.973   Deviance explained = 97.7%
GCV =  47556  Scale est. = 39301     n = 30
```

(c) STL/spp

```
> STL_spp_SST <- gam(STL_spp ~ s(SST), data = Data)
> gam.check(STL_spp_SST, pch=19)
Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 7 iterations.
The RMS GCV score gradient at convergence was 5.385002e-07 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

        k' edf k-index p-value
s(SST) 9.0 1.1    0.98     0.4
```

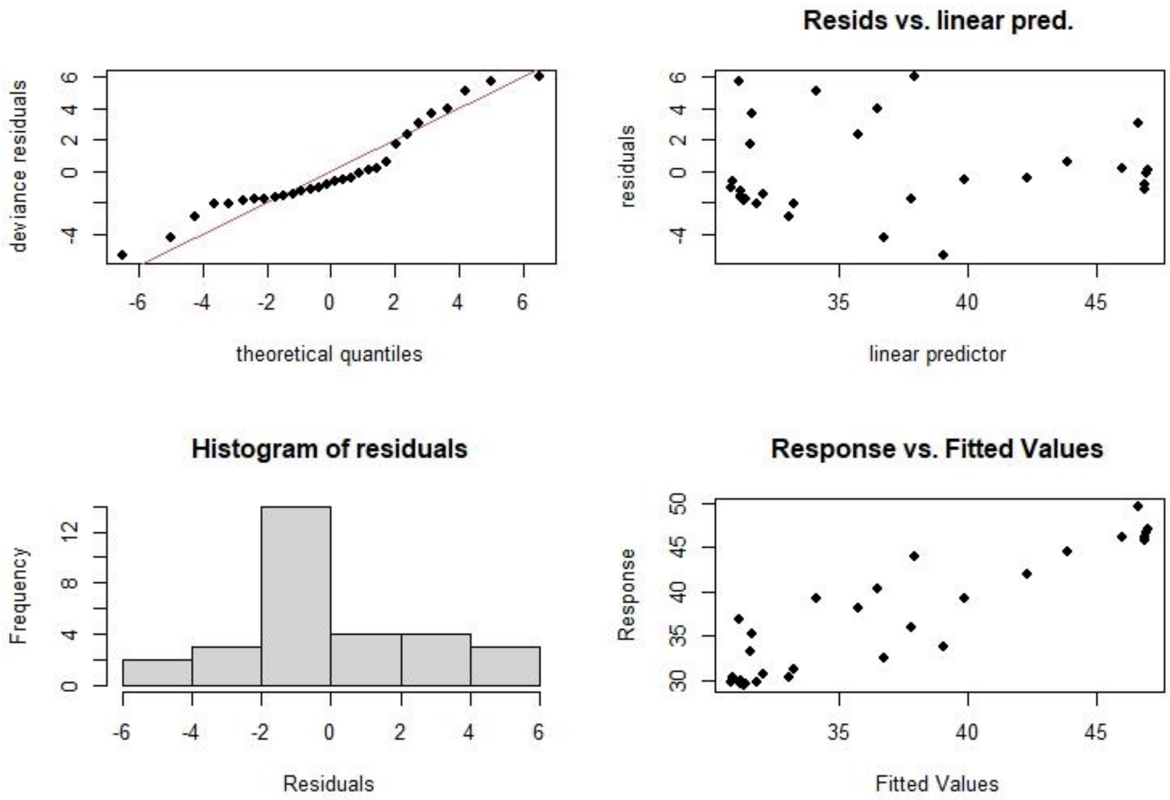



```
> summary(STL_spp_SST)

Family: gaussian
Link function: identity

Formula:
STL_spp ~ s(SST)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.82667    0.03906   46.76   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
       edf Ref.df     F p-value
s(SST) 1.1  1.192 272.8  <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.919   Deviance explained = 92.2%
GCV = 0.049222  Scale est. = 0.045777  n = 30
```

Sea Bottom Temperature

(a) AvPD

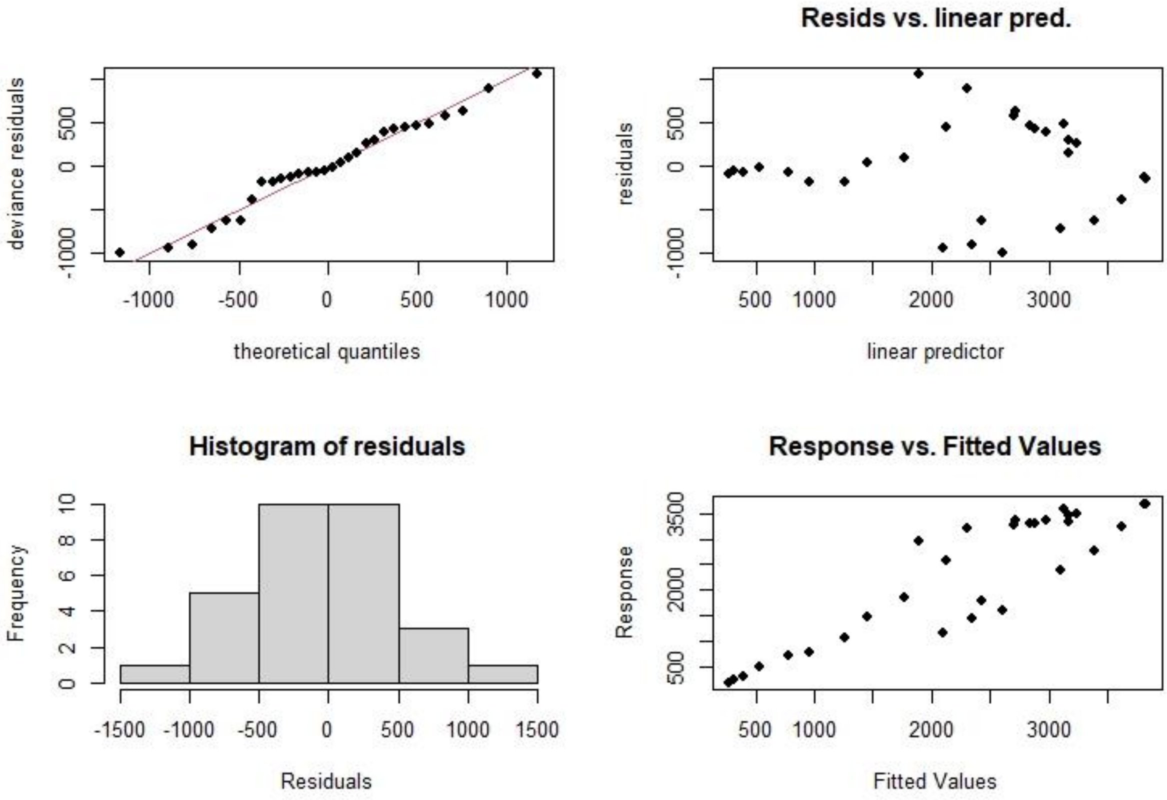
```
> AvPD_SBT <- gam(AvPD ~ s(SBT), data = Data)
> gam.check(AvPD_SBT, pch=19)
Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 4 iterations.
The RMS GCV score gradient at convergence was 4.553241e-06 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

         k'  edf k-index p-value
s(SBT) 9.00 4.73    1.18    0.78
```




```
> summary(AvPD_SBT)


Family: gaussian
Link function: identity

Formula:
AvPD ~ s(SBT)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  36.8700     0.5569   66.21   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
         edf Ref.df     F p-value
s(SBT) 4.733   5.75 20.61  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =    0.8   Deviance explained = 83.3%
GCV = 11.501  Scale est. = 9.3033    n = 30
```

(b) STL

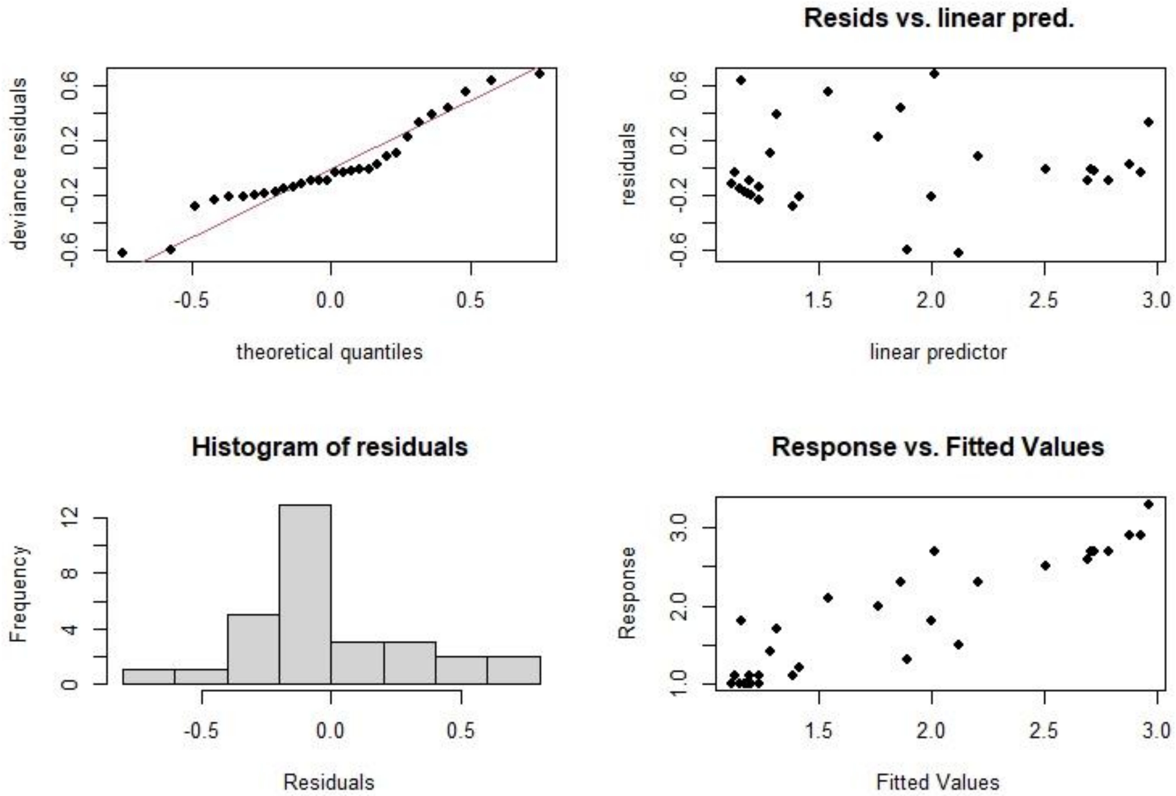
```
> STL_SBT <- gam(STL ~ s(SBT), data = Data)
> gam.check(STL_SBT, pch=19)
Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 7 iterations.
The RMS GCV score gradient at convergence was 1.934022 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

          k'  edf k-index p-value
s(SBT) 9.00 1.69    1.07    0.56
```




```
> summary(STL_SBT)


Family: gaussian
Link function: identity

Formula:
STL ~ s(SBT)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  2271.03      99.86   22.74   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
         edf Ref.df     F p-value
s(SBT) 1.692  2.102 54.56  <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.797   Deviance explained = 80.9%
GCV = 3.2868e+05  Scale est. = 2.9918e+05  n = 30
```

(c) STL/spp

```
> STL_spp_SBT <- gam(STL_spp ~ s(SBT), data = Data)
> gam.check(STL_spp_SBT, pch=19)
Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 6 iterations.
The RMS GCV score gradient at convergence was 8.766752e-06 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

         k'  edf k-index p-value
s(SBT) 9.00 5.65    1.27    0.90
```




```
> summary(STL_spp_SBT)


Family: gaussian
Link function: identity

Formula:
STL_spp ~ s(SBT)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.82667    0.06399   28.55   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
         edf Ref.df     F p-value
s(SBT) 5.653  6.772 15.87  <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.782   Deviance explained = 82.4%
GCV = 0.15784  Scale est. = 0.12283   n = 30
```

Appendices: GAM

Chapter 4:

Correlations of mean body sizes, mean trophic levels and environmental variables

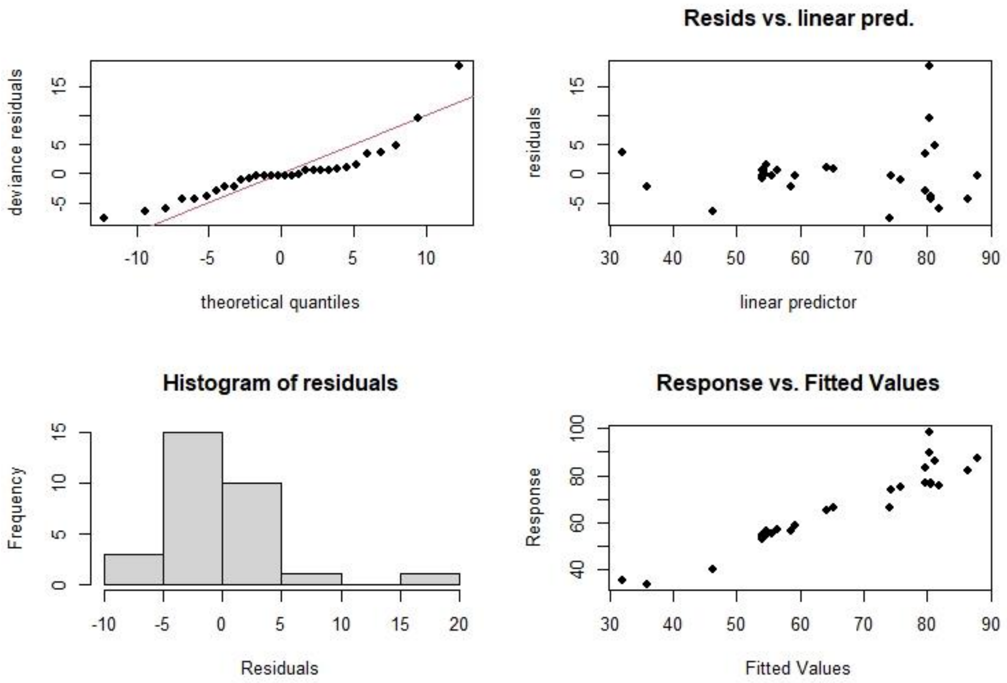
Table of abbreviation:

Functional trait	Abbreviation	Environmental variable	Abbreviation
Mean body size	Mean_body	Sea surface temperature	SST
Mean trophic level	Mean_trophic	Sea surface dissolved oxygen	SDO
		Sea surface salinity	Salinity
		Sea bottom temperature	SBT
		Sea bottom dissolved oxygen	BDO

Mean body size

(a) SST

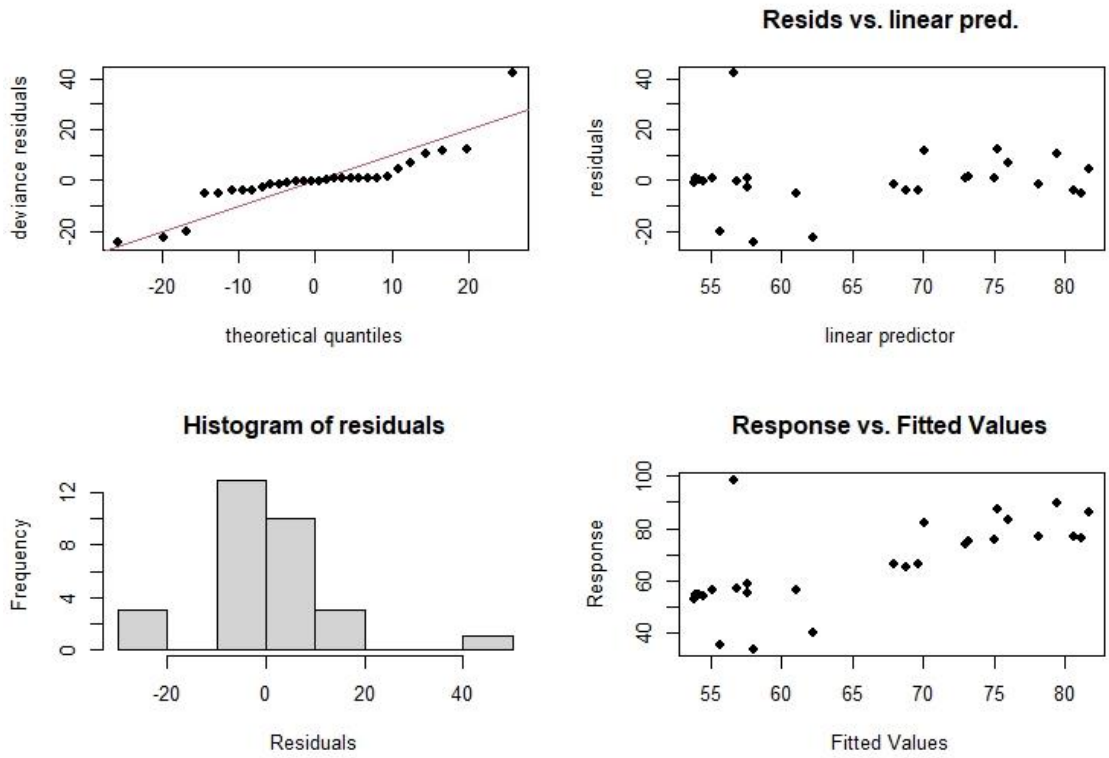
```
> Gam_Mean_body_SST <- gam(Mean_body ~ s(SST), data = Data)

> gam.check(Gam_Mean_body_SST, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 6 iterations.
The RMS GCV score gradient at convergence was 0.003310758 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

         k'  edf k-index p-value
s(SST) 9.00 7.87    1.32    0.96
```




```
> summary(Gam_Mean_body_SST)

Family: gaussian
Link function: identity

Formula:
Mean_body ~ s(SST)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   64.966      1.047   62.03   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
         edf Ref.df     F p-value
s(SST) 7.869  8.658 24.09  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.876   Deviance explained =   91%
GCV = 46.714  Scale est. = 32.904    n = 30
```

(b) SDO

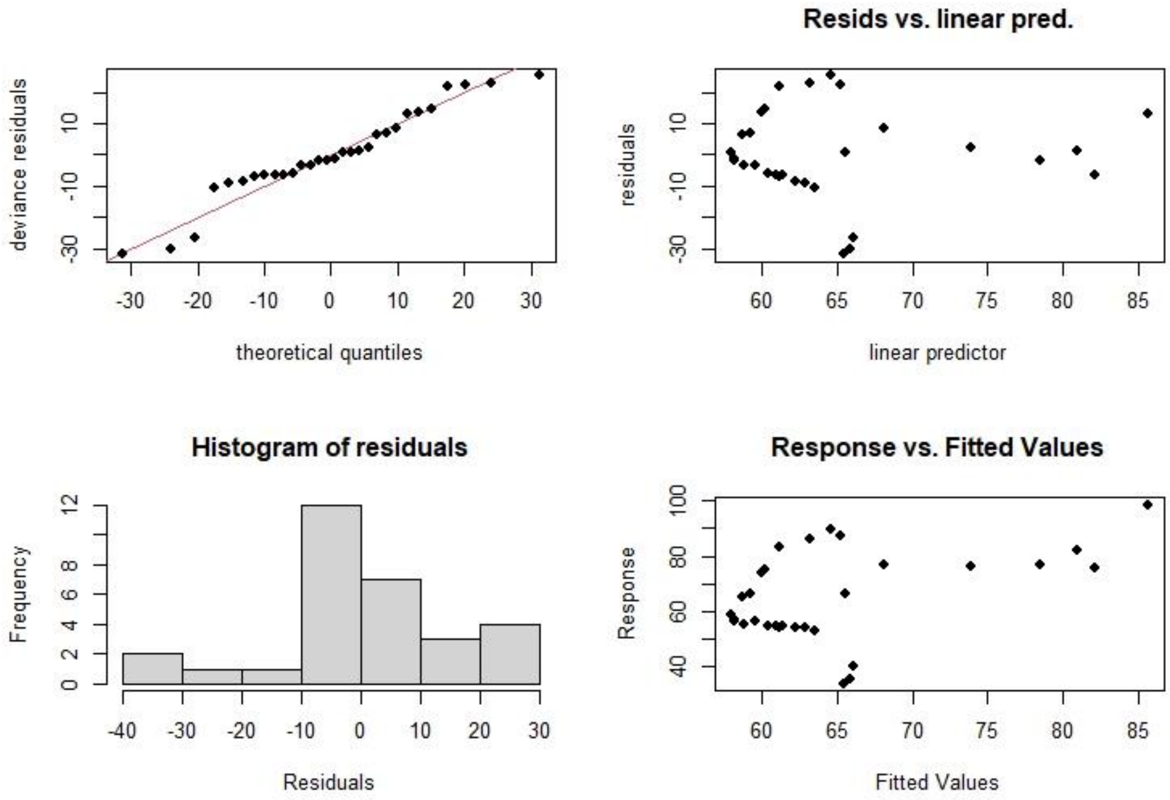
```
> Gam_Mean_body_SDO <- gam(Mean_body ~ s(SDO), data = Data)

> gam.check(Gam_Mean_body_SDO, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 4 iterations.
The RMS GCV score gradient at convergence was 8.409334e-06 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

         k'  edf k-index p-value
s(SDO) 9.00 2.61    1.36    0.96
```




```
> summary(Gam_Mean_body_SDO)

Family: gaussian
Link function: identity

Formula:
Mean_body ~ s(SDO)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   64.966      2.206   29.45   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
         edf Ref.df     F  p-value
s(SDO) 2.607  3.189 7.381 0.000736 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =   0.45   Deviance explained =   50%
GCV = 165.93  Scale est. = 145.98    n = 30
```

(c) Salinity

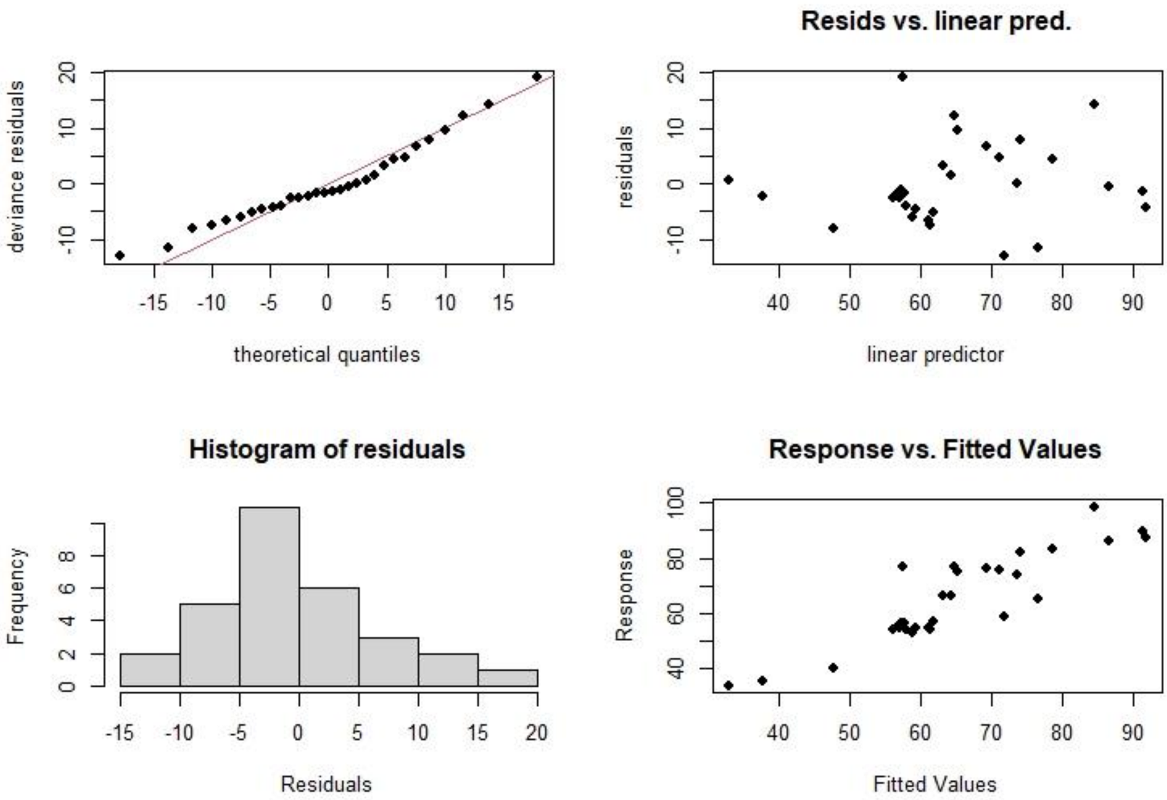
```
> Gam_Mean_body_Salinity <- gam(Mean_body ~ s(Salinity), data = Data)

> gam.check(Gam_Mean_body_Salinity, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 13 iterations.
The RMS GCV score gradient at convergence was 2.123498e-05 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

            k' edf k-index p-value
s(Salinity)  9   1    1.11    0.58
```




```
> summary(Gam_Mean_body_Salinity)

Family: gaussian
Link function: identity

Formula:
Mean_body ~ s(Salinity)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   64.966      2.676   24.27   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
            edf Ref.df     F p-value
s(Salinity)   1      1 7.828 0.00909 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.191   Deviance explained = 21.8%
GCV = 230.22  Scale est. = 214.88    n = 30
```

(d) SBT

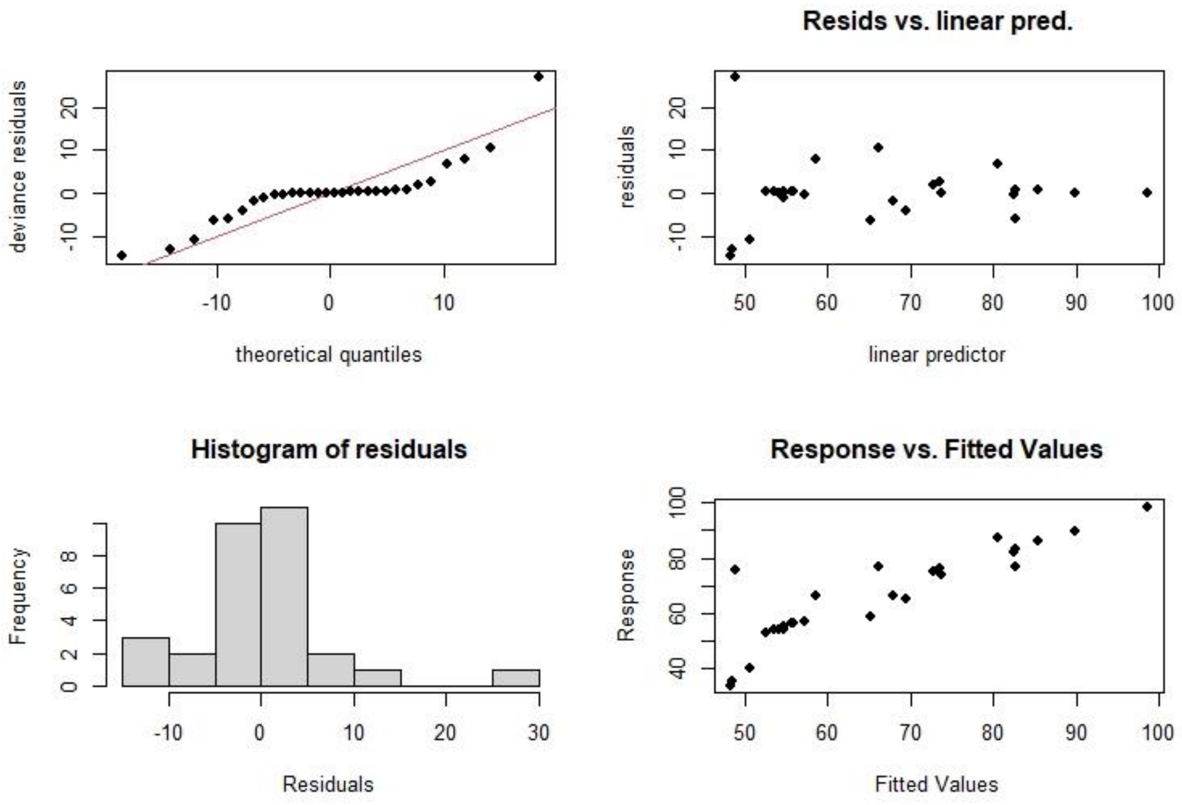
```
> Gam_Mean_body_SBT <- gam(Mean_body ~ s(SBT), data = Data)

> gam.check(Gam_Mean_body_SBT, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 5 iterations.
The RMS GCV score gradient at convergence was 2.280202e-05 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

          k'  edf k-index p-value
s(SBT) 9.00 6.71    1.17    0.76
```




```
> summary(Gam_Mean_body_SBT)

Family: gaussian
Link function: identity

Formula:
Mean_body ~ s(SBT)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   64.966      1.532    42.4   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
        edf Ref.df     F  p-value
s(SBT) 6.71   7.81 10.51 3.82e-07 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.735   Deviance explained = 79.6%
GCV = 94.776  Scale est. = 70.42     n = 30
```

(e) BDO

```
> Gam_Mean_body_BDO <- gam(Mean_body ~ s(BDO), data = Data)

> gam.check(Gam_Mean_body_BDO, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 6 iterations.
The RMS GCV score gradient at convergence was 0.0004117251 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

         k'  edf k-index p-value
s(BDO) 9.00 7.85    1.12    0.68
```

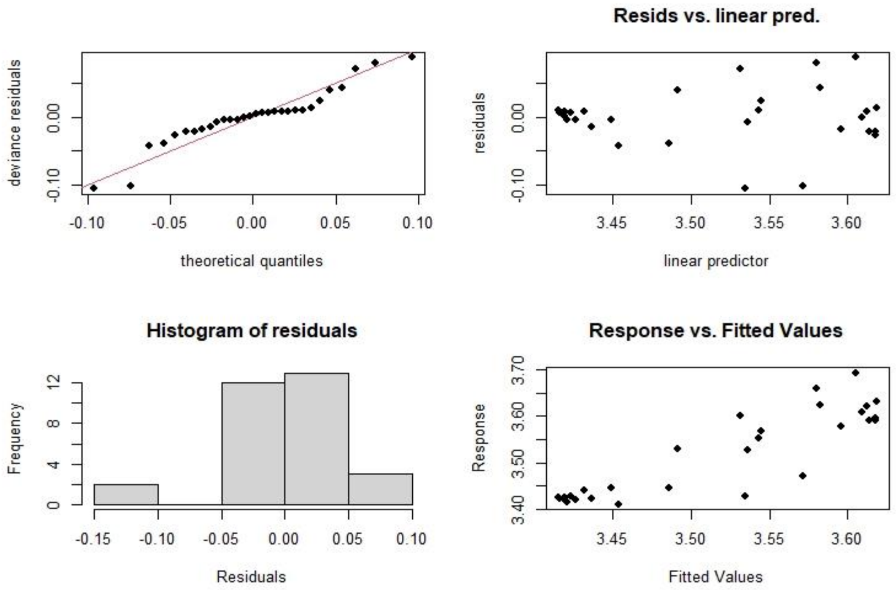



```
> summary(Gam_Mean_body_BDO)

Family: gaussian
Link function: identity

Formula:
Mean_body ~ s(BDO)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   64.966      1.569    41.4   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
         edf Ref.df     F  p-value
s(BDO) 7.847  8.591 9.133 1.63e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.722   Deviance explained = 79.7%
GCV = 104.76  Scale est. = 73.87     n = 30
```

Mean trophic level

(a) SST

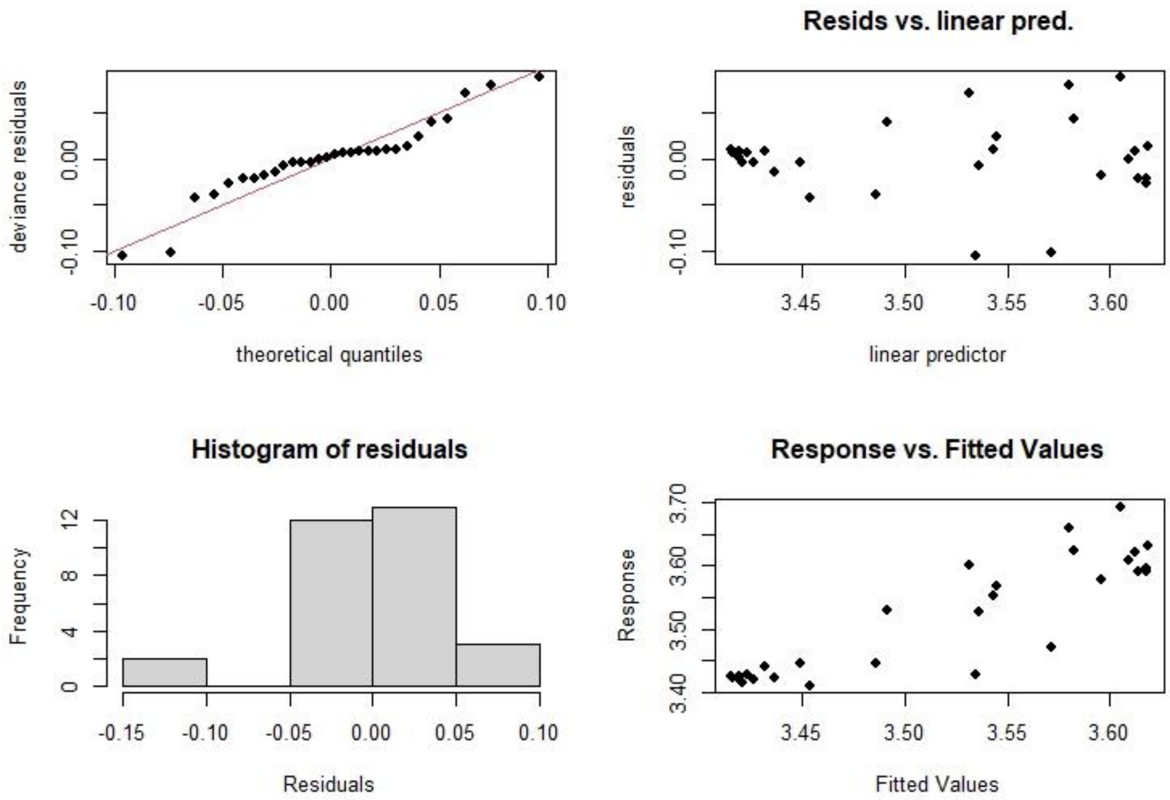
```
> Gam_Mean_trophic_SST <- gam(Mean_trophic ~ s(SST), data = Data)

> gam.check(Gam_Mean_trophic_SST, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 5 iterations.
The RMS GCV score gradient at convergence was 1.01099e-06 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

         k'  edf k-index p-value
s(SST) 9.00 4.08    1.19    0.82
```




```
> summary(Gam_Mean_trophic_SST)

Family: gaussian
Link function: identity

Formula:
Mean_trophic ~ s(SST)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 3.514121   0.008243   426.3   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
         edf Ref.df     F  p-value
s(SST) 4.076  4.994 18.56 8.99e-10 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.758   Deviance explained = 79.2%
GCV = 0.0024538  Scale est. = 0.0020386  n = 30
```

(b) SDO

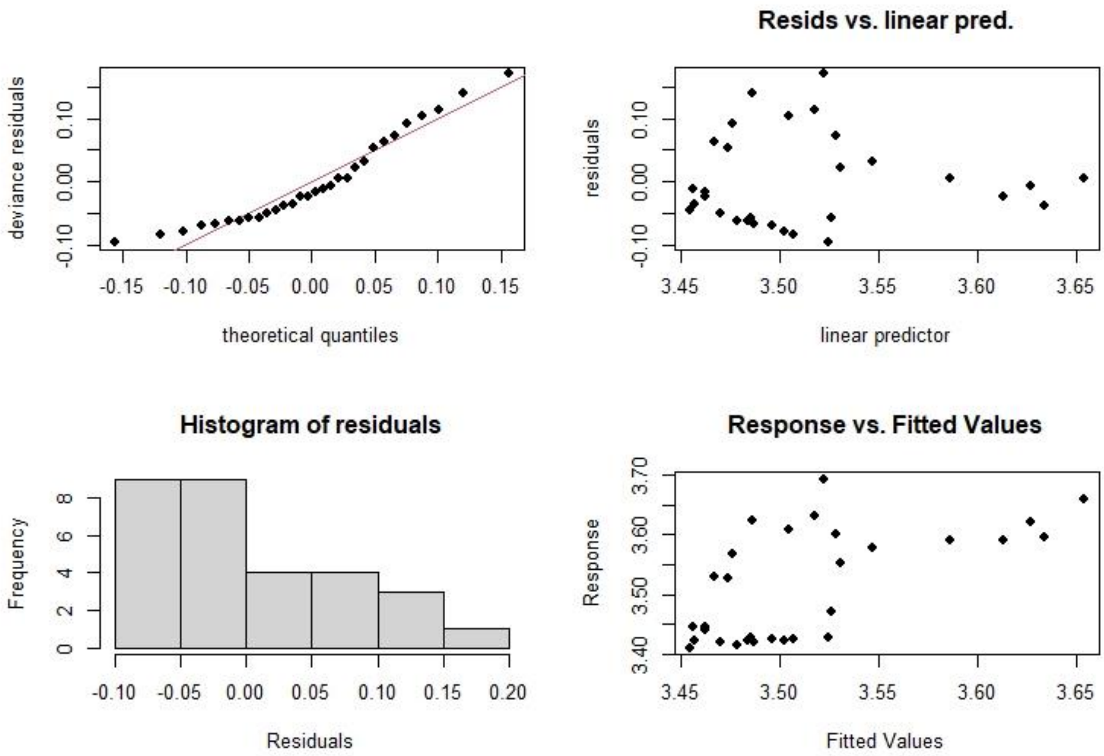
```
> Gam_Mean_trophic_SDO <- gam(Mean_trophic ~ s(SDO), data = Data)

> gam.check(Gam_Mean_trophic_SDO, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 5 iterations.
The RMS GCV score gradient at convergence was 1.01099e-06 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

         k'   edf k-index p-value
s(SST) 9.00 4.08    1.19    0.84
```




```
> summary(Gam_Mean_trophic_SDO)

Family: gaussian
Link function: identity

Formula:
Mean_trophic ~ s(SDO)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 3.514121   0.009131   384.9   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
        edf Ref.df     F  p-value
s(SDO) 2.48  3.038 22.55 1.05e-08 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.704   Deviance explained = 72.9%
GCV = 0.0028295  Scale est. = 0.0025013  n = 30
```

(c) Salinity

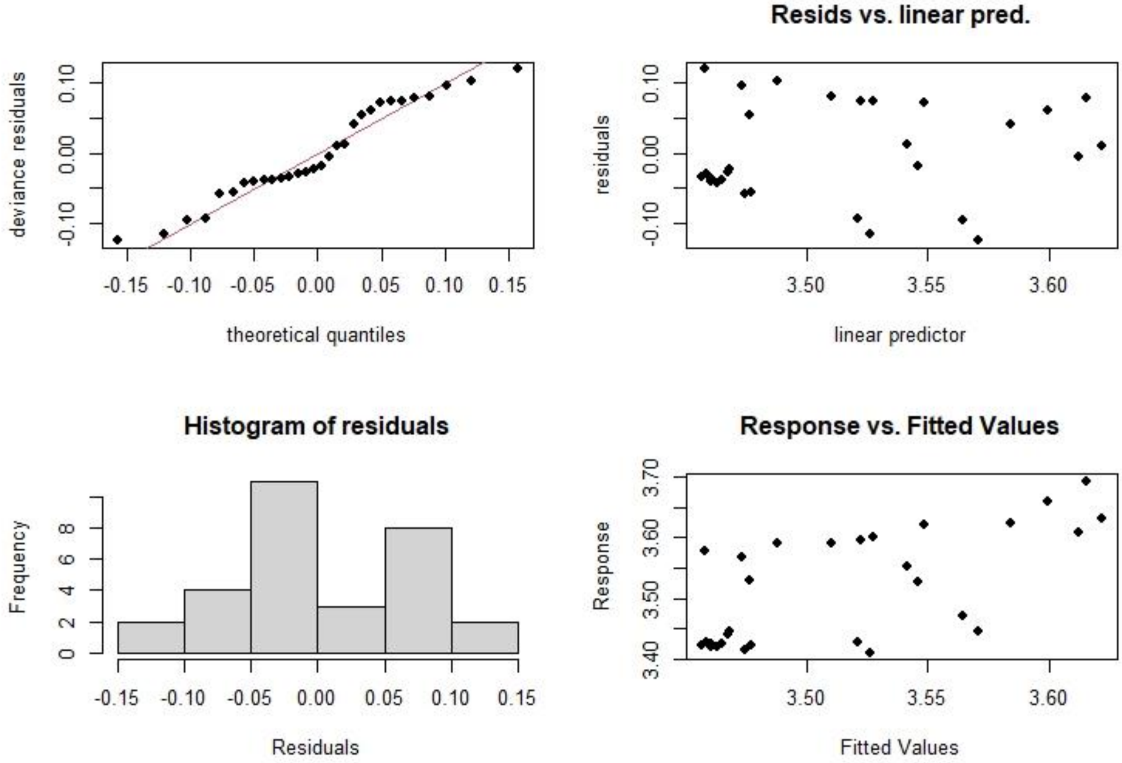
```
> Gam_Mean_trophic_Salinity <- gam(Mean_trophic ~ s(Salinity), data =Data)

> gam.check(Gam_Mean_trophic_Salinity, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 4 iterations.
The RMS GCV score gradient at convergence was 9.807278e-07 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

              k'  edf k-index p-value
s(Salinity) 9.00 1.39     1.2    0.85
```




```
>summary(Gam_Mean_trophic_Salinity)

Family: gaussian
Link function: identity

Formula:
Mean_trophic ~ s(Salinity)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  3.51412    0.01339   262.4   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
              edf Ref.df     F p-value
s(Salinity) 1.393  1.682 9.036 0.00113 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.363   Deviance explained = 39.3%
GCV = 0.0058473  Scale est. = 0.0053809  n = 30
```

(d) SBT

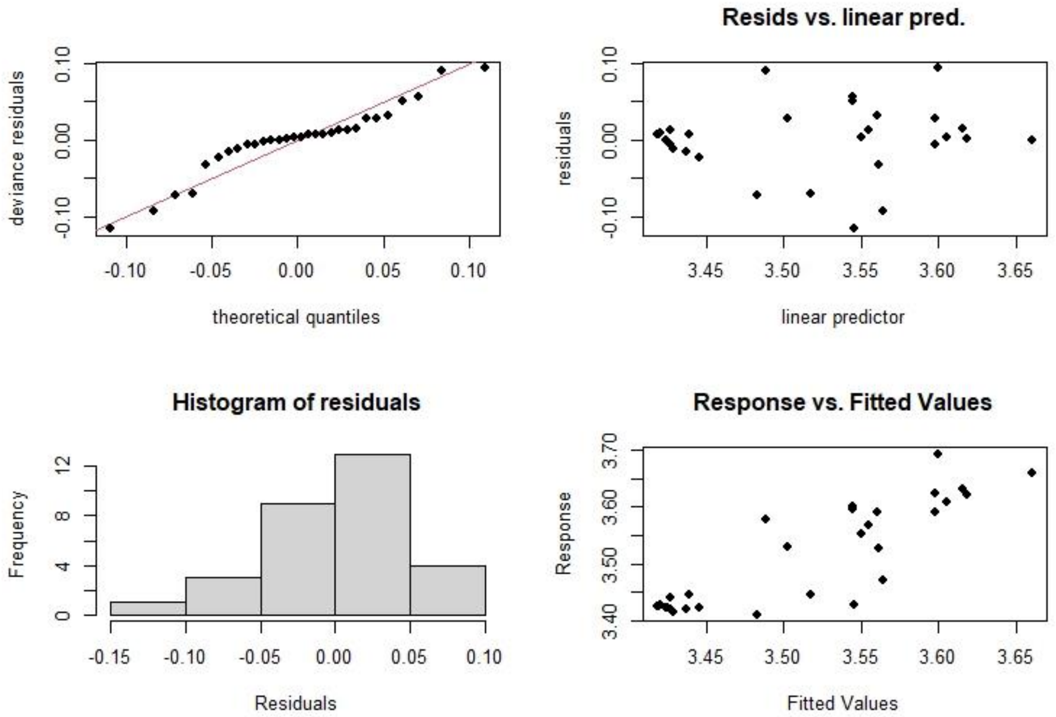
```
> Gam_Mean_trophic_SBT <- gam(Mean_trophic ~ s(SBT), data = Data)

> gam.check(Gam_Mean_trophic_SBT, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 4 iterations.
The RMS GCV score gradient at convergence was 8.222767e-07 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

          k'   edf k-index p-value
s(SBT) 9.00 4.19    1.11    0.62
```




```
> summary(Gam_Mean_trophic_SBT)

Family: gaussian
Link function: identity

Formula:
Mean_trophic ~ s(SBT)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  3.51412    0.01347   260.8   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
         edf Ref.df     F p-value
s(SBT) 4.186  5.114 3.386  0.01 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.355   Deviance explained = 44.8%
GCV = 0.0065833  Scale est. = 0.0054454  n = 30
```

(e) BDO

```
> Gam_Mean_trophic_BDO <- gam(Mean_trophic ~ s(BDO), data = Data)
> gam.check(Gam_Mean_trophic_BDO, pch=19)

Method: GCV   Optimizer: magic
Smoothing parameter selection converged after 7 iterations.
The RMS GCV score gradient at convergence was 6.643937e-07 .
The Hessian was positive definite.
Model rank =  10 / 10

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

         k'  edf k-index p-value
s(BDO) 9.00 5.69    1.35    0.95
```




```
> summary(Gam_Mean_trophic_BDO)

Family: gaussian
Link function: identity

Formula:
Mean_trophic ~ s(BDO)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 3.514121   0.009328   376.7   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
         edf Ref.df     F  p-value
s(BDO) 5.688  6.698 9.993 2.01e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.691   Deviance explained = 75.1%
GCV = 0.003359  Scale est. = 0.0026102  n = 30
```

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