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Assessment of the impacts of ornamental fish export trade on the exploited ichthyofauna of Lake Malawi

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Abstract

Globally there are many documented impacts of ornamental fish export trade elsewhere on the exploited populations, on habitats of fish as well as on unequitable distribution of benefits along the ornamental fish export trade value chain. Capture of live cichlid fish of Lake Malawi for ornamental fish export trade started in the 1970s but there have been no studies of the impacts of the trade on the targeted fish species.

This study investigated the potential impacts of ornamental fish export trade on the exploited ornamental fish species of Lake Malawi focusing on: species exported during the past two decades (with respect to export volumes and value, collection localities, export destinations and conservation status); comparison of ornamental fish populations inside and outside the protected areas of Lake Malawi; size at maturity and fecundity of a sample of exploited ornamental fish species; and assessment of the relative risk of the fish to exploitation based on the productivity sustainability analysis (PSA) risk assessment criteria.

The ornamental fish exported from Malawi between 1998 and 2017 were represented by 257 described and 279 undescribed fish species belonging to a total of 64 genera, with the cichlidae family dominating the export volumes at 98.6%. One potentially negative impact of the trade on fish populations was that of the exported fish species, 21 were near threatened species, 12 were critically endangered species, five were endangered species, and five were vulnerable species according to IUCN conservation threat criteria. Underwater visual census of fish showed no significant difference of overall fish abundance between protected and unprotected areas, but large rocky reefs/islands showed significantly higher fish abundance than small rocky reefs/islands. Fish species' diversity metrics were significantly higher for sites sampled inside protected areas than those in unprotected areas. Fish size at maturity varied between species and between sexes of the fish. Absolute fecundity of fish varied widely amongst the sampled fish species. Some fish species showed significant positive association between absolute fecundity and standard length while other species showed no association between the two variables. Egg sizes significantly varied between fish species and genera. PSA results showed that of the 99 fish species assessed, nine species have high relative risk, 19 species have medium relative risk and 71 species have low relative risk to exploitation for ornamental fish export trade. These results are discussed in relation to management of the ornamental fishery of Lake Malawi and various recommendations are made for further research and fishery management including a proposed framework for the conservation plan for the fishery.

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Chapter 1 General Introduction

1.1 Background

1.1.1 African Rift Valley Lakes

The African Great Lakes region, located in the East African Region between 14° 40' S – 4° 31' N and 28° 50' E – 36° 42' E, is endowed with seven major lake basins including: Victoria (68,800 km^2), Tanganyika (32,600 km^2), Malawi/Nyasa/Niassa (29,500 km^2), Turkana (6,405 km^2), Albert (5,300 km^2), Kivu (2,370 km^2) and Edward (2,325 km^2) (Cowx & Ogutu-Owhayo, 2019). These lakes' ecosystems have a combined catchment area covering more than 850,000 km^2 across 10 countries including: Democratic Republic of Congo, Burundi, Kenya, Mozambique, South Sudan, Rwanda, Uganda, Malawi, Tanzania and Zambia (Cowx & Ogutu-Owhayo, 2019). The African Great Lakes are known for their exceptionally high fish species diversity, dominated by cichlids, with Lakes Tanganyika (250 species), Victoria (700 species) and Malawi/Nyasa/Niassa (1000 species) having the highest fish species diversity (Salzburger, 2018; Cowx & Ogutu-Owhayo, 2019; Ahi *et al*., 2020). Because of the exceptionally high cichlid species diversity and their tendency for adaptive radiations, these fishes are regarded as one of the very important vertebrate model systems for evolutionary biology (Salzburger, 2018; Schedel *et al*., 2019; Ahi *et al*., 2019; 2020).

The African Great Lakes support the livelihoods of more than 50 million people through a diversity of ecosystem services with the fishes of the lake being of great economic, ecological, scientific and biodiversity conservation importance. Additionally, the fishes of the African Great Lakes provide a cheap but high-quality protein food and employment for the surrounding local community (Cowx & Ogutu-Owhayo, 2019). These lakes and their natural resources are threatened by several pressures, including potentially un-sustainable fishing, non-native invasive species, habitat degradation, sedimentation due to deforestation, urban and industrial pollution and eutrophication. Furthermore, high population growth rates in these regions exert pressure on these lakes and their resources (Cowx & Ogutu-Owhayo, 2019).

One of the key issues for sustainable fisheries development in the African Great Lakes is the disruption to biodiversity due to fishing pressure, bait fisheries, ornamental fisheries and environmental degradation (Cowx & Ogutu-Owhayo, 2019). These issues necessitate the need for investigation of the extent and distribution of different fishing sectors and environmental changes on biodiversity and develop plans to mitigate negative effects on endemic fish species

(Cowx & Ogutu-Owhayo, 2019). Currently there is no research about the extent and distribution of the ornamental (aquarium fish species) fisheries in any of the countries that surround the African Great Lakes (Britton *et al*., 2017; Cowx & Ogutu-Owhayo, 2019). This thesis focussed on the research about ornamental fisheries of Lake Malawi as a starting point, which could be replicated for the ornamental fisheries of other African Great Lakes. Lake Malawi was selected because it is in the home country of the researcher making it easier and cheaper to conduct the research.

1.1.2 Lake Malawi and its ichthyofauna

Lake Malawi, the third largest freshwater lake in Africa and eighth largest in the world, is in the southern part of Africa. It is bordered by three countries: Malawi, Tanzania and Mozambique (Figure 1-1). Lake Malawi is approximately 600 km long, with a maximum width of 80 km and a surface area of approximately 31 000 km^2 (Turner *et al.,* 2001). The maximum depth of Lake Malawi is 700 m and its surface is 472 m above sea level with only the upper 200 metres containing sufficient dissolved oxygen to support aerobic organisms (Konings, 2016). The average surface temperature of water ranges from 23 °C to 28 °C (Ribbink *et al.,* 1983; Konings, 2016). The lake is permanently stratified into three thermal layers: the epilimnion - upper layer from surface to 105 m depth, metalimnion -middle layer from 105m to 220 m depth and the hypolimnion - bottom layer from 220 m to the bottom (Vollmer *et al.,* 1999; Bootsma & Hecky, 1999; Bootsma & Jorgensen, 2005). Most algal growth, which supports the food web of Lake Malawi, grows in the epilimnion (Bootsma & Jorgensen, 2005). The metalimnion is cooler (22.9-23.5˚C) than the epilimnion (23.5-25.2 °C) and is characterized by strong gradients of dissolved nutrients and oxygen (Figure 1-2). Amongst the three thermal layers, the hypolimnion is the coolest (22.7-22.9 ˚C) with highest concentrations of the following chemicals: total dissolved nitrogen (6-37 µM N for hypolimnion, 5 -15 µM N for metalimnion and 1-9 µM N for epilimnion), total dissolved phosphorous (1.9-3.3 µMP for hypolimnion, 0.5-1.9 µM P for metalimnion and 0.1 – 0.5 for epilimnion) and silica (125-220 µM Si for hypolimnion, 30-125 µM Si for metalimnion and 12.5 -30 µM Si for epilimnion)[1] but is completely anoxic (Bootsma & Hecky, 1999) and therefore unable to support fish life (Bootsma & Jorgensen, 2005). The three layers do not completely mix vertically but there is some exchange of water between the layers, the rate of which varies with season and location (Bootsma & Jorgensen, 2005). The upward flux of nutrient rich waters from the hypolimnion and metalimnion to the surface mostly occurs during the cool

[1] All quoted values of water temperature and dissolved oxygen have been extrapolated from Figure 4.1 of Vollmer *et al.* (1999) while the values of other chemical concentrations have been extrapolated from Figure 8.3 of Bootsma & Hecky (1999).

windy season facilitated by the southeast trade winds locally known as *mwera* (Bootsma & Jorgensen, 2005). In the southern part of the lake, south easterly winds cause upwelling of the colder water layers between the months of June and August which lowers the surface water temperature to 20 °C from a maximum value of 28.37 °C between the months of October and December (Hamblin *et al.,* 1999). There is an increase in phytoplankton production during or shortly after the windy season (Bootsma & Jorgensen, 2005). According to Guildford *et al.* (1999) Lake Malawi is classified as being oligotrophic with low chlorophyll-a concentrations below 1 μg/L.

The lake experiences both seasonal (i.e. monthly) fluctuations (Ribbink *et al.,* 1983) and longer-term progressive water level changes overtime due to geological history in response to climatic and tectonic events (Neuland, 1984). Seasonally the water level fluctuates between 0.4 m and 2.2 m with the lowest level being in December and the highest level in May (Ribbink *et al.,* 1983). It is also believed that the level of the lake has changed up to a magnitude of 100 m due to past geological events (Ribbink *et al.,* 1983). About 70% of the coastline of Lake Malawi comprises gentle sloping sandy beaches, vegetated areas and swamps, while the remaining 30% are steep rocky shores, 70% of which are replaced by sandy plains in water less than 40 m depth (Ribbink *et al.,* 1983; Weyl *et al.,* 2010).

Figure 1-1. Location of Lake Malawi in Malawi in the southern part of Africa showing the international boundaries

Lake Malawi has a diverse ichthyofauna, estimated at about 1000 species (Lyons *et al.,* 2015; Konings, 2016; Albertson & Pauers, 2019). Fourteen families of fish are represented in the lake but only one family, the Cichlidae, dominates with respect to species richness, diversity and numerical abundance (Weyl *et al.,* 2010). These cichlids are represented by two main phylogenetic lineages - the haplochromines and tilapiines (Weyl *et al.,* 2010). Based on an estimated number of 800 haplochromine fish species belonging to fifty genera in Lake Malawi

(Konings, 2016), at least 80% of Lake Malawi ichthyofauna are haplochromines. Konings (2016) believed more haplochromine fish species remain to be discovered. On the contrary, tilapiines of Lake Malawi are represented by only seven species belonging to the genera; *Oreochromis* {*O. shiranus* Boulenger, 1897; *O. karongae* (Trewavas, 1941); *O. lidole* (Trewavas, 1941); *O. squamipinnis*, (Günther, 1864); and *O. saka* (Lowe, 1953)}, *Tilapia* (*T. sparrmanii*) and *Coptodon* (*C. rendalli*) (Weyl *et al.,* 2010). All but three haplochromine species of Lake Malawi {*Pseudocrenilabrus philander* (Weber, 1897), *Astatotilapia calliptera* (Günther, 1894) and *Serranochromis robustus* (Günther, 1864)} are endemic to Lake Malawi, whereas for tilapiines only the five *Oreochromis* species are endemic to the lake (Weyl *et al.,* 2010), while the other two species are widespread in many African countries (IUCN, 2019). Most haplochromine fishes of Lake Malawi have specialised habitat types, for example rock, sand, macrophyte beds, open water, or the extreme depths (Ribbink *et al.,* 1983; Genner & Turner, 2012; 2015; Konings 2016).

One group of haplochromis cichlids of Lake Malawi that have specialized in the rocky habitats includes small darkly or brightly coloured species locally known as *mbuna* (Ribbink *et al.,* 1983). There are about 250 species within the *mbuna* group, belonging to 13 genera including *Cyathochromis*, *Cynotilapia*, *Genyochromis*, *Gephyrochromis*, *Iodotropheus*, *Labeotropheus*, *Labidochromis*, *Melanochromis*, *Petrotilapia*, *Pseudotropheus*, *Metriaclima*, *Chindongo* and *Tropheops* (Konings 2016). One special feature of the *mbuna* is that individual species are confined in localized rocky outcrops separated by sandy areas (Ribbink *et al.,* 1983; Konings 2016). Additionnally, most of the *mbuna* species are unsedscribed and are currently recognised by their temporary names. Though the term *mbuna* has been adopted and widely used in numerous publications about Lake Malawi cichlid fishes, it does not have any taxonomic meaning as several species and genera are involved.

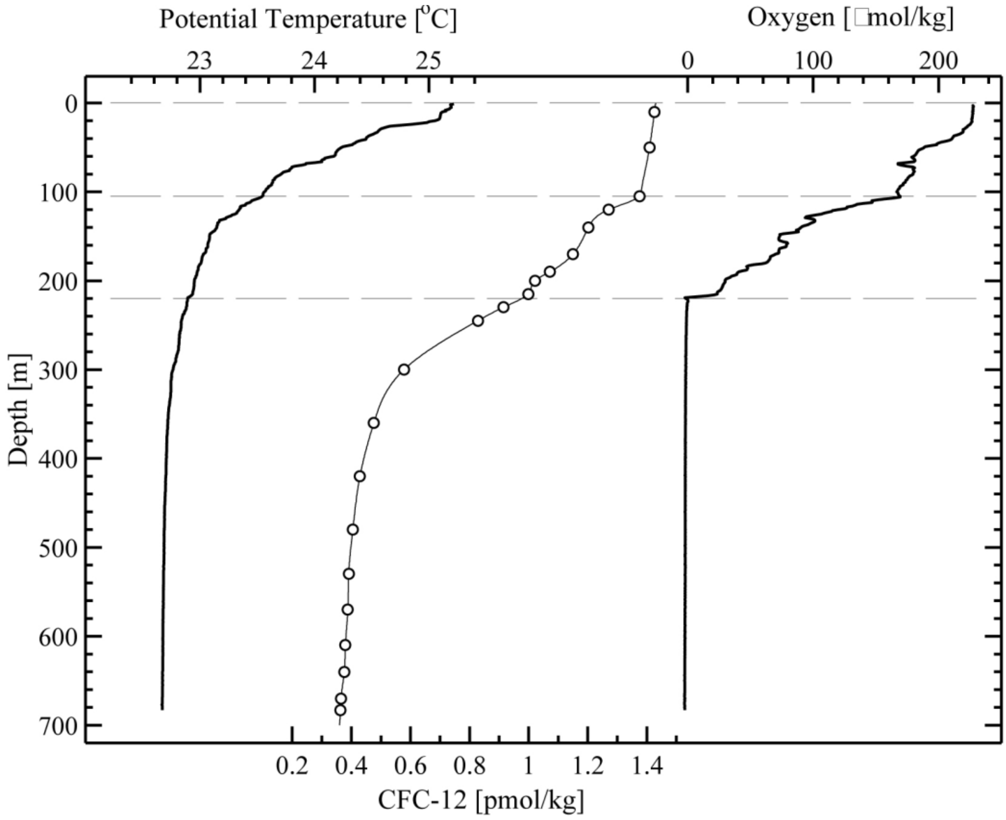

Figure 1-2. Profiles for potential temperature, CFC-12 and dissolved oxygen concentration at one deep station in Lake Malawi. Dashed lines denote the lake's surface and the boundaries between epilimnion and metalimnion at 105 m and between metalimnion and hypolimnion at 220 m (Source: Vollmer *et al.,* 1999).

Due to high fish species diversity, Lake Malawi is highly valued as a laboratory for testing theories of evolution (Ivory *et al.,* 2016). Almost all the ichthyofauna of Lake Malawi are believed to have evolved in the lake (Turner *et al*., 2001; Ivory *et al.,* 2016). The estimated age of Lake Malawi varies between 2 million years (Arnegard *et al.,* 1999 citing Banister & Clark, 1980) and 4 -5 million years (Sturmbauer *et al.,* 2001). Evolutionary biologists from all over the world have been challenged as to how so many species of fish arose within a relatively short geological time period. One hypothesized mechanism of radiation of ichthyofauna of Lake Malawi is intra-lacustrine allopatric speciation, which has been linked to past climatic variation that caused dramatic fluctuations of the lake levels (Smith & Cornfield, 2002; Genner & Turner, 2015; Lyons *et al.,* 2015). The other commonly stated mechanism of speciation of the fish is sexual selection by female choice. Colouration of male fish is hypothesized as a key trait upon which female choice operates (Ding *et al.,* 2014a; Knight *et al.,* 1998).

1.1.3 Fisheries of Lake Malawi

Lake Malawi supports one of the world's richest multispecies freshwater fisheries, which are characterised by numerous species and diverse fishing techniques and modes of utilisation (Weyl *et al.,* 2010, Irvine *et al.,* 2019). Fishing activities in Lake Malawi can be classified into artisanal fishing, industrial fishing and capture of live fish for ornamental fish export trade. Artisanal fishing includes many highly commercialised, small-scale fishers who use a variety of fishing gears including beach seines, open water seines, gill nets, traps and longlines. Artisanal fishers use plank boats with or without engines and dugout canoes. Industrial fishing which operates in the southern end of Lake Malawi, includes the use of pair trawl fishing, based on small, 38-HP engines, open-decked boats and stern trawlers for bottom and mid-water trawling (Weyl *et al.,* 2010) exploiting a multispecies community of inshore and offshore demersal and pelagic fish species (Irvine *et al*., 2019). The average annual fish landings from artisanal and industrial fishing in Malawi between 2000 and 2015 was 90000 metric tonnes (Malawi Government, 2016a). It was estimated that artisanal fisheries contributed an average of 80,000 metric tonnes per year (Weyl *et al.,* 2010; Malawi Government, 2016a; Irvine *et al.,* 2019) while the industrial fisheries contributed 10,000 metric tonnes (Malawi Government, 2016a). In the southern part of Lake Malawi, the artisanal fishery which previously equally targeted inshore and offshore stocks of both cichlid fishes and the cyprinid *Engraulicypris sardella,* is now largely based on *E. sardella* (Irvine *et al.,* 2019).

The ornamental fish export trade in Malawi is based on the *mbuna*, as the major target for exploitation (Ribbink *et al.,* 1983; Malawi Government 2016a). A majority of individual *mbuna* fish species are confined in localized rocky outcrops of the lake separated by sandy areas. This fishery subsector, which started operating in the 1970s, has been dominated by a few operators ranging from one to four (Malawi Government, 2016a).

Capture fisheries in Malawi (artisanal fishing, industrial fishing and capture of live ornamental fish export trade) play an important role in promotion of the economy of the country. The fisheries are considered a source of employment, food, rural income, exports, import substitution and biodiversity. The fisheries employ about 60,000 fishers and over 500,000 people are indirectly involved in fish processing, fish marketing, boat building and engine repair (Malawi Government, 2016a).

Besides capture fisheries, the fisheries sector in Malawi also includes fish farming, which started with development of small fish farming in ponds in the mid-1950s followed by commercialized fish farming in 2005 (Malawi Government, 2016a). Annual fish production from aquaculture is estimated at 3,600 tonnes (Malawi Government, 2016a).

1.1.4 Management of Fisheries in Malawi

To address various issues that affect the development of fisheries in Malawi and ensure sustainable management of fish resources, the Malawi Government revised the National Fisheries and Aquaculture Policy (NFAP) of 2001 (Malawi Government, 2016a). The main objective of the policy is “to sustainably increase fisheries and aquaculture productivity for accessible nutritious food and increased contribution to economic growth” (Malawi Government, 2016a). In addition, another policy document: The Implementation, Monitoring and Evaluation Strategy (IMES) was developed with details for operationalization of the revised policy (Malawi Government, 2016b). The revised fisheries policy is being implemented alongside many other development policies at both national and international levels. The revised NFAP and IMES focus on seven priority areas including: capture fisheries; aquaculture development; fish quality control and value addition; governance; social development and decent employment; research and information; and capacity development. Each of the policy priority areas has its stipulated policy statements as a means for achieving the priority area goals. Although the current Malawi National Fisheries Policy of 2016 recognises the existence of the aquarium fish trade, the IMES has very scanty detail about the aquarium fish trade but is comprehensive about capture fisheries for food and aquaculture. Promotion of the aquarium fish trade is captured in the IMES as one of the three outputs under the objective of promotion of public private partnerships and investment in capture fisheries within the first policy priority area (capture fisheries). Previous policy editions of fisheries management, including the Malawi National Fisheries Policy of 2001, did not also have any detail about management of ornamental fishes. This shows that capture of live fish for ornamental fish trade has not been a priority of fisheries management in Malawi, despite more than four decades of ornamental fish export from Malawi.

A management measure which is believed to offer some protection for some ornamental fish species of Lake Malawi is the Lake Malawi National Park (LMNP) (IUCN, 2019). LMNP was established in 1980 with an objective of protecting representatives of many fish species groups with conservation of mbuna as the highest priority. The national park covers terrestrial and aquatic areas in the southern end of Lake Malawi, including Nankumba Peninsula, Mwenya and Nkhuzi Hills and twelve islands (Figure 1-3). The aquatic area of the park includes a 100 m zone from the shoreline of the islands and the included terrestrial area to the water most of which are rocky habitats particularly for smaller islands. Within the shoreline of larger islands of LMNP such as Domwe, Thumbi West, Maleri and Mumbo Islands, some patches of sandy habitats are often found in between the predominant rocky habitats. Fishing is banned within the 100 m zone of the park and the Department of National Park and Wildlife in Malawi is responsible for management of the park including enforcement of all the regulations associated with the park. However, Reinthal (1993) argued that while many endemic species of rocky dwelling cichlids were protected in LMNP, there were still many endemic species outside the park that needed protection as well.

Though there is no documented information about the total area of the protected area of LMNP it is evident from Figure 1-3 that LMNP covers a very small portion of less than 5% of the entire shoreline of Lake Malawi.

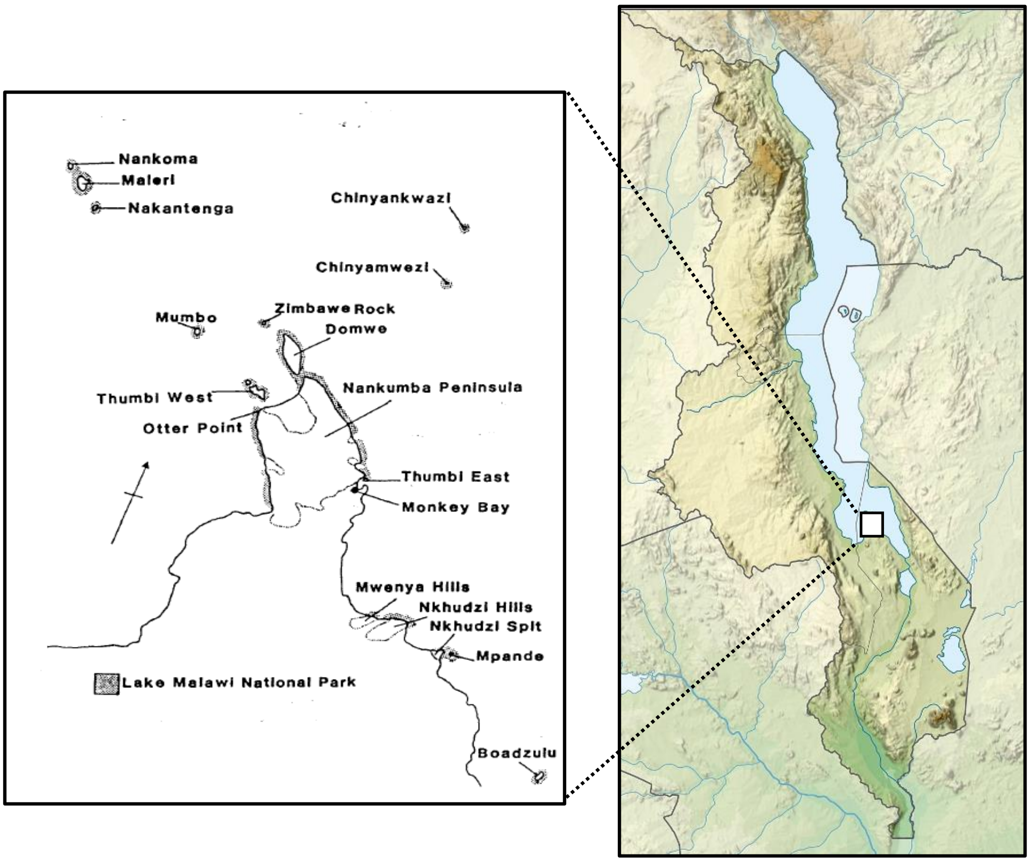

Figure 1-3. Location of Lake Malawi National Park in Malawi

1.1.5 Impacts of ornamental fish export trade

Globally it has been argued that sustainably managed trade in wild caught ornamental fishes can be a good income source for supporting rural community livelihoods (Tlusty, 2002; UNEP-WCMC, 2008; Ferse *et al.,* 2012; Raghavan *et al.,* 2013; Rhyne *et al.,* 2014; Albert *et al.,* 2015; Dey, 2016) and minimize activities that may destroy the environment (Watson, 2000). Exporting countries may also benefit from increased foreign exchange, which has a positive impact on the economy of the countries. However, concerns have been raised worldwide regarding the negative impacts of ornamental fish export trade.

The following are some examples of the documented negative impacts of ornamental fish export trades: The trade has been reported to cause reduction in the density and abundance of targeted fish populations and other fauna (Kolm & Berglund, 2003; Tissot & Hallacher, 2003; Tissot *et al.,* 2004; Shuman *et al*., 2005; Jones *et al.,* 2008). In some cases, concerns have been raised about the trade targeting rare and threatened fish species (Edwards & Shepherd, 1992; Watson, 2000; Dulvy *et al.,* 2004; Raghavan, 2013). Due to ornamental fish export trade, there has been translocation of some fish species from one part of the water bodies to other parts resulting in hybridization of different species and loss of genetic diversity (Smith *et al.,* 2003; Streelman *et al.*, 2004; Mertz 2008); competition for food and space with resident species (Watson 2000; Genner *et al.,* 2006; Mertz 2008); habitat alteration (Wood, 2001) and spread of diseases and parasites (Ellender & Weyl, 2014). There have been concerns about the effect of the trade on mortality of fish during post-capture holding and transportation (Edwards & Shepherd, 1992; Wood 2001; Livengood & Chapman, 2007; Townsend, 2011). Some fishers have used ornamental fish collection techniques that are destructive to habitats (Andrews, 1990; Edwards & Shepherd, 1992; Ekaratne, 2000; Welcomme, 2001; Wood, 2001; Livengood & Chapman, 2007; FAO, 2010; Townsend, 2011). Breeding of ornamental fish in developed countries has been considered damaging as it shifts economic base by removing a resource base from a developing area to developed countries with the infrastructure to support aquaculture operations (Watson, 2000; Tlusty, 2002). It is also recognized that there is unequitable distribution of benefits of the trade between fish collectors and players at the other end of the value chain in importing countries (Wood, 2001).

Currently there is very limited knowledge about the impacts of the ornamental fish export trade on the fish resources in Malawi. Translocation of fish within Lake Malawi due to the ornamental fish export trade has been reported as one of the causes of cichlid hybridization in Lake Malawi (Stauffer *et al.*, 1996; Stauffer & Hert cited by Smith *et al.,* 2003). Examples of reported incidents of fish hybridization in Lake Malawi include: hybridization between the cichlids, *Cynotilapia afra* (Günther, 1894) and *Metriaclima zebra* (Boulenger, 1899) at Thumbi West Island of LMNP (Stauffer *et al.,* 1996, Streelman *et al.,* 2004) and between the cichlids *Metriaclima pyrsonotos* Stauffer, Bowers, Kellogg & McKaye, 1997 and *Metriaclima* “sp zebra Chiofu” (Smith *et al.,* 2003).

1.2 Aims and objectives

The aim of this thesis was to determine the potential impacts of the ornamental fish export subsector on the targeted fish species of Lake Malawi with a view to recommending appropriate strategies for management of the ornamental fishery. The following specific objectives were pursued in this study.

- To investigate the trade in ornamental fish exported from Malawi by focusing on fish species exported, conservation status of the species, collection localities in Lake Malawi, export volumes and values and export destinations.
- To compare fish assemblages between protected and non-protected areas of Lake Malawi focusing on species composition and abundance.
- To investigate reproductive traits of the exploited ornamental fish species of Lake Malawi.
- To assess the relative risk of fish to exploitation based on the productivity sustainability analysis risk assessment criteria
- To recommend a management plan for the ornamental fishery of Lake Malawi.

1.3 Structure of the thesis

This thesis is presented according to the specific objectives which are covered in chapters 2 to 6. The following section is a summary of the thesis outline.

Chapter 2 investigates ornamental fish exported from Malawi by focusing on the following research questions: What is the volume and value of ornamental fish export from Malawi? What ornamental fish species are exported from Malawi and where in Lake Malawi are the fish collected from? Where are the fishes exported to? What is the IUCN conservation status of the exported species? What are the temporal patterns of fish collection localities, species exported and IUCN conservation status of the fish exported?

Chapter 3 compares fish assemblages between protected and non-protected areas of Lake Malawi focusing on species composition and abundance in order to determine whether exploitation of fish for the ornamental fish export trade has an impact on the fish assemblage structure.

Chapter 4 investigates reproductive traits (size at maturity, fecundity and egg sizes) of selected ornamental fish species of Lake Malawi in order to relate the traits to impact of fish exploitation for ornamental trade and use the information to assess the risk of overexploitation of the fish resources by applying the productivity sustainability analysis risk assessment criteria.

Chapter 5 uses the Productivity Susceptibility Analysis to assess the relative risk of overexploitation of targeted ornamental fish species by using productivity and susceptibility traits that the fish species possess. The outputs of this risk assessment are used for recommending appropriate management plans.

Chapter 6 discusses key issues regarding the impacts of ornamental fish export trade in Malawi which relate to conservation status, assemblage structure and reproductive traits of the exploited fish species and the risk from exploitation of ornamental fish species based on their productivity and susceptibility traits. Future research and a management plan for the ornamental fishery of Lake Malawi are proposed based on the key issues of the ornamental fishery.

Chapter 2 Ornamental fish export trade in Malawi

2.1 Introduction

The Global ornamental fish trade is more than a century old (Corfield *et al.*, 2008; Dey 2016), and started expanding gradually from the 1950s to the 1970s (Ekaratne, 2000; Bruckner, 2005; Corfield *et al.*, 2008). By the early 1970s most countries started exporting ornamental fishes, and some countries such as USA, Hong Kong, Singapore and Malaysia were exporting and re-exporting ornamental fishes (Wood, 2001). Ekaratne (2000) attributed the increase in the global ornamental fish trade to increase in numbers of ornamental fish hobbyists worldwide, popularity and affordability of air transport, expansion of domestic power supply, and development of cost-effective aquarium accessories, which facilitated the keeping of warm-water aquarium fish species in colder temperate countries. Aquarium fish keeping is a popular hobby with millions of enthusiasts worldwide (Livengood & Chapman, 2007; Whittington & Chong, 2007; FAO, 2010; Dey 2016). According to FAO (2010), only 28 countries were exporting aquarium fish in 1976 and the numbers of exporting countries started increasing significantly afterwards. Currently it is estimated that more than 125 countries are involved in the ornamental fish trade (Dey, 2016; Evers *et al*., 2019).

FAO (2010) reported that the major regional importers of ornamental fish worldwide based on import value were Europe (44.4%), Asia (23.2%) and North America (17.4%). When these ornamental fish imports were broken down by country, the largest importing countries were United States of America (13.2%), United Kingdom (10.4%), Germany (8.4%), France (6.4%), Netherlands (4.9%) and Italy (4.4%). In 2014 the top three countries on the list of importing countries were the same as those reported by FAO (2010) followed by Singapore, Japan, China/Hong Kong, France, Netherlands, Italy, Malaysia, Canada and Belgium (Dey, 2016). Furthermore, it was reported that these 12 countries shared over 74% of the global ornamental fish import value in 2014 (Dey, 2016). Countries such as Singapore, Germany, Hong Kong, Malaysia, and Netherlands re-export a major portion of their imports (Dey, 2016).

FAO (2010) estimated that more than 2 billion live ornamental fish were being traded annually worldwide but the current estimate is at over 1 billion individual fish (Teletchea, 2016; Evers *et al.,* 2019). However, it was acknowledged that the estimate of FAO (2010) was not accurate because the statistics was based on information from many countries and data varied with respect to reliability and completeness. Moreover, in the recent State of world fisheries and aquaculture report, FAO (2018) reports world fish production statistics in terms of weight (in tonnes) and monetary values of which ornamental fish trade statistics are grouped as non-food commodities alongside fishmeal and fish oil.

Estimates of the number of species of ornamental fish traded annually vary amongst different researchers and in different years, including: 2000 species (Livengood & Chapman, 2007), 4000 species (Whittington & Chong, 2007), 5300 freshwater species and 1802 marine species (Raghavan *et al.,* 2013; Evers *et al.,* 2019), 6000 species (Teletchea, 2016) and over 2500 species (Dey, 2016). However, the consensus is that freshwater fish species contribute 90% of global ornamental fish export volumes, of which all but 10% are captive bred (Livengood & Chapman, 2007; Raghavan *et al.,* 2013; Evers *et al.,* 2019).

The value of the global aquarium fish (freshwater and marine) trade inclusive of accessory products is estimated at US$ 15 – 30 billion per year (Raghavan *et al.,* 2013; Evers *et al.,* 2019). The value of the trade steadily increased from US$177.7 million in 2000 to a peak value of US$364.9 million in 2011 followed by a slight decrease to US338.59 million in 2013 and US$347.45 million in 2014 (Dey, 2016). In 2014, within the top ten regions that supplied more than 78.6% of aquarium fish to the export market, Asian countries accounted for about 57% of the trade value, followed in descending order by European countries at 26.7%, South America at 7.5%, North America at 3.98%, African countries at 2.2%, Oceania at 1.4% and the Middle East at 0.5% (Dey 2016). A comparison with corresponding estimates by FAO (2010), suggests an increase in the percentage contribution of Asia (51.4% to 57%) but a decrease for the other regions. Dey (2016) presented information that showed the following top 10 exporting countries of ornamental fish worldwide in 2014: Singapore accounting for 20% of the export value, followed by Japan (11.9%), Czech Republic (9.2%), Thailand (6.7%), Malaysia (6.5%), Indonesia (6.2%), Israel (5.5%), Brazil (5.3%) Sri Lanka (3.8%), Colombia (3.5%) and all the other remaining countries combined (21.4%).

Amongst the African Great Lakes region, Lake Malawi was reported to have contributed between 4% and 5% of the global ornamental fish export in 2010 (FAO, 2010). However, in 2014 the entire African continent was reported to have contributed only 2.2 % (Dey, 2016). Both FAO (2010) and Dey (2016) did not provide any details about the contribution of individual lakes within the African Great lakes to the global fish export market. Information about the Lake Malawi ornamental fish export trade is quite scarce.

There are two conflicting years as to when ornamental fish were first exported from Malawi - Ribbink *et al.* (1983) reported 1962 while Watson (2000) reported 1973. Also, Ribbink *et al.* (1983) quoted an estimated peak value of 400,000 fish being annually exported in the mid-1970s while Watson (2000) quotes a peak value of 250,000 around the same period. Additionally, Watson (2000) stated that up to 100 species of fish were being regularly exported from Malawi without specifying the exported species. Such conflicting information without any citation of its source and lack of detail in the reports, suggest that the information provided by the authors was probably based on guestmates other than any research data.

The ornamental fish sector in Malawi is a multispecies fishery that exploits mostly *mbuna* fish species (Ribbink *et al.* 1983, Watson, 2000), but there is no report of the species involved and export volumes by species. Knowledge about species being exported can help to identify species that are vulnerable to exploitation and deserve special management consideration.

Given the paucity and uncertainty in information highlighted above, this chapter investigates the trade in ornamental fish exported from Malawi by focusing on the following questions:

- What is the volume and value of ornamental fishes exported from Malawi?
- Where are the exported fishes collected from in Lake Malawi?
- Where are the fishes exported to?
- What ornamental fish species are exported from Malawi and what is the IUCN conservation status of the exported fish species?
- What are the temporal patterns of fish collection localities, species exported, and IUCN conservation status of the fish exported?

2.2 Methodology

2.2.1 Extraction of information from fish export returns

Before exportation, consignments of ornamental fish from Malawi are inspected and certified by the Department of Fisheries and copies of the certification documents (see Appendix 2.1) accompany the exported fish consignment to the importing countries. Furthermore, copies of all paperwork associated with the exportation of fish including hard copies of detailed information about exported fish (see Appendix 2.2) are filed with the Fisheries Department. Hard copies of existing records of fish exports between 1998 and 2017 were obtained and examined to extract information relevant for this study, including: date of fish exports, country where fish were exported to, name of exporter, trade names/scientific names of exported fish, number of fish exported by trade name/species, locality of fish collection in Lake Malawi, and export value of fish.

Identification of scientific names of fishes and determination of exported species conservation status: Fish exporters use either trade names or scientific names of species. Trade names used when exporting fish were substituted by valid names using various literature sources, including original descriptions of the species, FishBase (Froese & Pauly, 2019), textbook of Konings (2016) and IUCN (2019) Red List of Threatened Species. Formal names were substituted for temporary name of fish (used before the formal description of the fish) if there was enough information to support the substitution. Where no information was found about any formal species description being made from the temporally names used, the species under consideration was assumed to be undescribed and the temporary name was retained. In a few exceptional situations where some fish species had been described but were not updated in the Catalogue of Life, such names were assumed to be formal with authorities of the names noted. The conservation status of exported aquarium fish species was checked in the IUCN (2019) Red list, which identities the following categories: not evaluated (NE), data deficient (DD), least concern (LC), near threatened (NT), vulnerable (VU), endangered (EN), critically endangered (CR), extinct in the wild (EW) and extinct (EX). These compiled data were used for further analysis as explained in the following sections.

Locality of fish collection: Where locality of fish collection was specified, the information was extracted and the coordinates (latitude and longitude) were extracted from Google Maps (2017) and recorded. For localities whose names were not found in Google Map the information about their coordinates was extracted from web pages of ornamental fish traders/importers who provide information about individual fish species. Where information regarding fish locality was not provided but the species is known to occur only at one location in Lake Malawi, it was assumed that the specimens were collected from that locality. In some situations, general information which could not show any important detail about a specific location (e.g. "eastern coast", "eastern boarder") was used and therefore such fish were assumed to have unknown fish collection locality. All the information collected was entered into a Microsoft Excel database for later analysis.

Other species-specific information collected: Information on other fish species traits was reviewed from existing literature and entered into a separate database for further analysis of risk of exploitation to the fish stocks (see Chapter 5). Such information included: taxonomic/classification details (authority of formal name, synonyms, class, order, and family), ecological information (habitat type, depth range, distribution patterns, trophic category and diet), life history traits and reproductive strategy of the species.

2.2.2 Semi-structured interviews with fish exporters in Malawi

These interviews were conducted to collect a wide variety of information about the ornamental fish export trade supply chain. The information collected included: the most important species of fish exported, availability of the targeted species in the lake, trends of the catches of fish over years, months when fish were mostly caught, localities in the lake where fish were mostly caught, and major challenges of fish export trade. This information was triangulated with data extracted from fish export returns.

2.2.3 Analysis of data

Volume and value of exported fish: The total numbers of fish specimens exported between 1998 and 2017 and their export value were analysed. The value of all exported ornamental fish was calculated by converting various currencies to USD equivalent at the time of the export transactions using historical average annual currency rates (OFX, 2018) and the USD equivalent was adjusted to 2018 purchasing power using an inflation calculator (Anonymous, 2018). Total numbers and adjusted values of annual exports and monthly trends in exports were computed using Microsoft Excel Pivot table reports. Spearman Correlation Analysis between the number of exporters and the annual export volumes was conducted in R software (R core Team, 2018).

Ornamental fish collection localities: The numbers of fish exported by locality of collection within Lake Malawi was filtered from the compiled fish export data in Microsoft Excel using Pivot Table reports and the following analysis was performed on the filtered data of fish collection localities:

- For each locality of fish collection, geographic coordinates (latitude and longitude) were extracted from Google Maps (2017). The locality name, geographic coordinates and numbers of fish collected were entered into a Microsoft Excel spreadsheet file which was later uploaded in Arc GIS Software for plotting of the localities of fish exploitation. The maps were customised to provide information about the proportionate numbers of fish that were exported from every locality.
- From the compiled fish export data, a table of the numbers of fish exported by collection locality and year of exportation was filtered and imported into PRIMER v6 (Clarke & Gorley, 2006) and PERMANOVA + for PRIMER Software (Anderson *et al*., 2008). Cluster analysis and Similarity Profile (SIMPROF) using group average method of years based on Bray Curtis Resemblance of square root transformed data matrix were employed in PRIMER (Anderson *et al*., 2008). This cluster analysis was conducted to discriminate the years of fish exportation based on ornamental fish collection localities i.e. to test the hypothesis about existernce of temporal shifts of ornamental fish collection localities in Lake Malawi.

Ornamental fish export destinations: From the compiled data of fish exports that had been saved in Microsoft Excel, a matrix table of the total numbers of fish exported by export destination and years of exportation was filtered by using Pivot table reports.

Fish species exported: From the compiled fish export data in Microsoft Excel, the following information was filtered with respect to species exported using Pivot Table reports:

- The numbers of fish exported by family in order to compute the percentage representation of different fish families in the exported species.
- The number of species (grouped as either described or undescribed) exported by year.
- The counts of individual fish exported per taxon (in this context a taxon refers to both described species and undescribed species names) by years of fish exports in order visualize temporary trends in the species exported. These filtered data were imported into PRIMER v6 (Clarke & Gorley, 2006) and PERMANOVA + for PRIMER Software (Anderson *et al*., 2008). Cluster analysis was performed on the data using grouping average method and SIMPROF based on the Bray Curtis Resemblance matrix of square root transformed data (Anderson *et al*., 2008). This analysis was aimed at comparing the differences in number of fish of each taxon exported in each year in order to test the hypothesis of changes of species of fish exported with time.

Conservation status of exported species: From the compiled fish export data, the following information was filtered in relation to the IUCN conservation status (Red List category) of the exported fish by using Microsoft Excel Pivot Table reports.

- Number of taxa exported by IUCN conservation status based on the data across all years. This analysis was aimed at determining the extent to which threatened fish species of Lake Malawi are being exploited for the ornamental fish export trade.
- Number of taxa exported in different years by IUCN conservation status. These data were imported in PRIMER and PERMANOVA + for PRIMER Software. Cluster analysis of years of fish exportation was performed in PRIMER software based on the Bray Curtis resemblance matrix on square root transformed data using group average method and SIMPROF test (Anderson *et al*., 2008). In order to elucidate more details about the patterns of the cluster of years, the Bray Curtis similarity matrix of numbers of species exported by year and conservation status was further scrutinised using the Principal Coordinate Ordination (PCO) in PERMANOVA design (Anderson *et al*., 2008).
- Number of fish exported by conservation status and year based on combined data for all species of fish: These data were imported in PRIMER and PERMANOVA + for PRIMER Software and cluster analysis of years numbers of fish exported by IUCN conservation status was carried out based on the Bray Curtis resemblance matrix on square root transformed data using group average method and SIMPROF test. PCO analysis was further performed on the Bray Curtis similarity matrix on numbers of fish exported in

different years by IUCN conservation status using PERMANOVA design (Anderson *et al*., 2008).

2.3 Results

2.3.1 Volumes and values of export

A total of 499,918 fish specimens valued[2] at US$3,940,898 at 2018 prices were exported from Malawi between 1998 and 2017. The number of fish exported fluctuated annually around a mean of 24,996 fish (range 8553 - 37,544 fish) and average value of US$197,045 (range US$73,176 to US$292,787) (Figure 2-1). Between 1998 and 2011, the pattern of ornamental fish export value followed that of fish export volumes i.e. increasing value with the increase in volume of ornamental fish exports and vice versa. However, from 2011 to 2017, the value of the ornamental fish exports appeared to decrease as the volume of the fish exports increased. The latter trend is related to the fact that the unit prices of most ornamental fish species has been diluted with time due to competetion with farm bred ornamental fish in developed countries as discussed in section 2.4.2 of this chapter.

The ornamental fish export volumes were relatively low in 1998 because export data were available for only half of the year between July and December and between 2006 and 2009 the period dubbed by exporters of fish in Malawi as “bad years for ornamental fish export business”. The reasons for the low export volume during the latter period are discussed in detail in section 2.4.2, which include competition with farm bred fish in developed countries, global economic crisis and death of the owner of the major ornamental exporting fish exporting company in Malawi.

[2]. Packaging costs and air freight costs are not factored in this value because some fish exporters did not include the information.

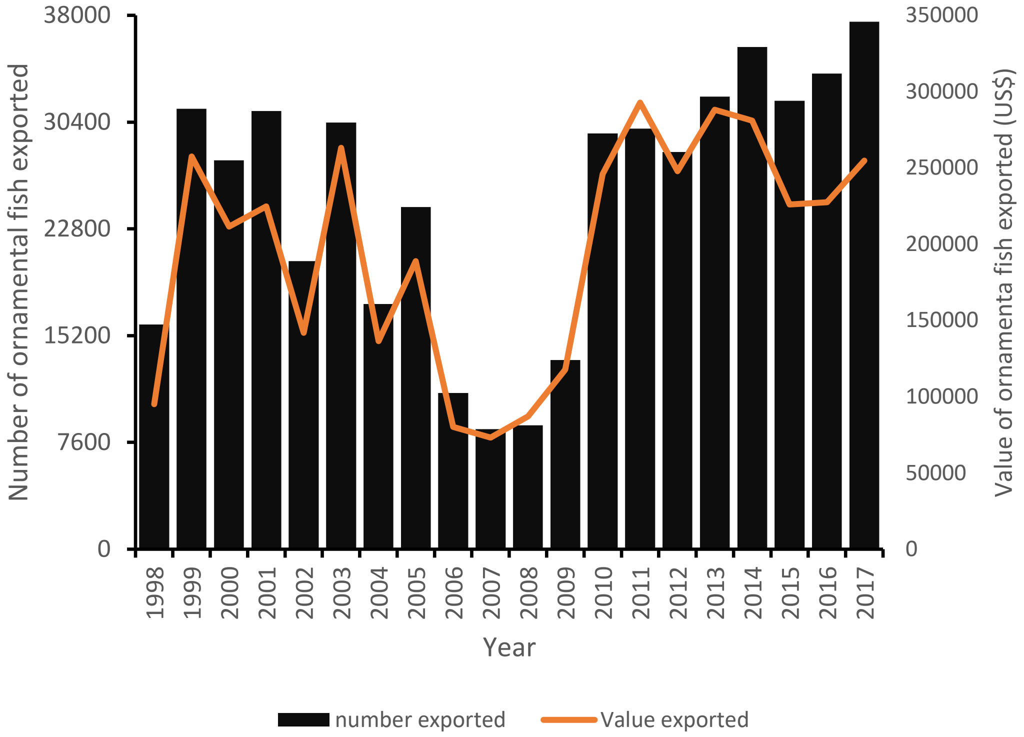

Figure 2-1. Number and value of ornamental fishes exported from Malawi between 1998 and 2017

The total volume of ornamental fish exported from Malawi varied between months with November and December associated with the highest numbers while July and August were the period of lowest numbers exported (Figure 2-2). According to interviews with the fish exporters, ornamental fish are difficult to catch during the cold months (June to August), which are also associated with rough lake conditions due to south-easterly winds (locally known as *mwera* winds). The exporters revealed that due to the risk to fishers' lives associated with rough lake conditions between the months of June and August, fishers stop operating during these months. The few fish exported during these months are those that were caught prior to this season and held for some period in their fish tank facilities.

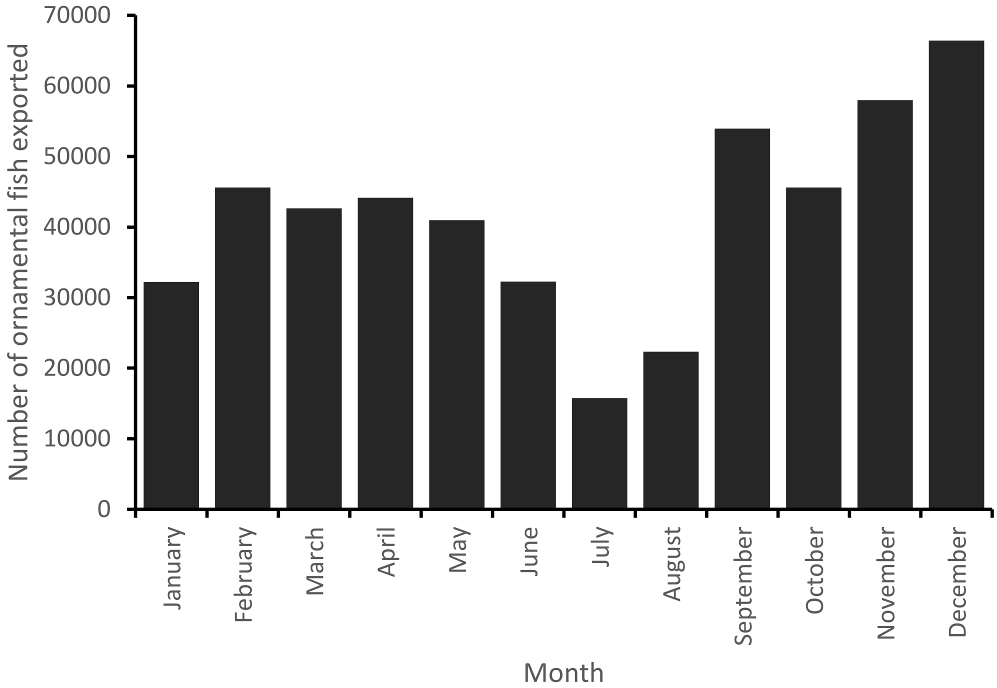

Figure 2-2. Total number of fish exported by month

There were four licenced exporters of ornamental fish from Lake Malawi between 1998 and 2017, each of whom started exporting fish in different years. The number of exporters operating in any single year varied between one and four, with 2014 and 2015 being the only years when all four exporters were operating (Figure 2-3). Some exporters did not renew their fishing licences for some years. Surprisingly, none of the exporters interviewed subscribed to the idea of existence of competition amongst exporters.

Spearman's rank correlation analysis indicated moderate but significant positive correlation between number of fish exporters and volume of exports (rho(18) = 0.539, $p < 0.05$).

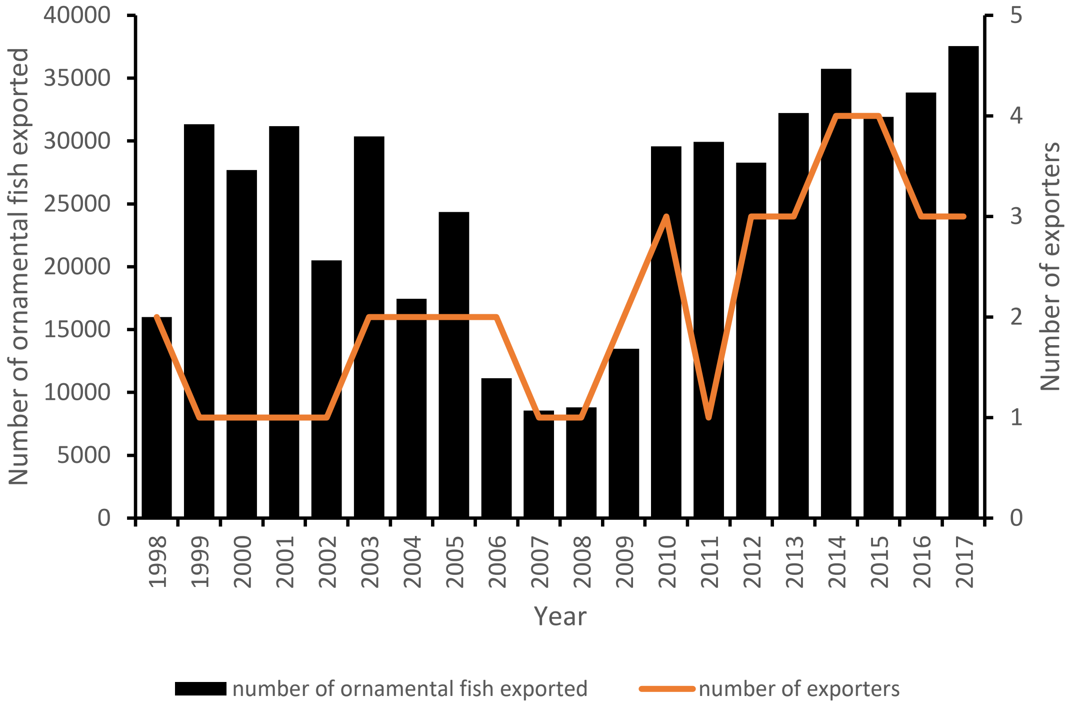

Figure 2-3. Association between number of exporters and number of ornamental fish exported from Malawi between 1998 and 2017

2.3.2 Localities where exported fish were caught from

Of the 499,918 live ornamental fish exported between 1998 and 2017, the locality of collection was specified for only 263,622 fish. Fish had been collected from a recorded 130 localities located between Ngara in the northern part of Lake Malawi to Makokola Reef in the southern part of the lake. Few fish were collected from areas inside LMNP (at Nankhoma, Nakanthenga, Nkhuzi and Boadzulu Island – See map of LMNP in Figure 1-3) and some fish were collected from three locations (streams/rivers) outside Lake Malawi, including: Mpatsanjoka in Salima District, Ntakataka in Dedza District and Domasi (Figure 2-4). Fish collection localities within Lake Malawi are confined to the rocky shoreline which covers 30% of the shoreline of the lake as stated in section 1.1.2 of this thesis. Areas of Figure 2-4 that do not have ornamental fish collecting are sandy shores.

Some localities had more fish collections than others as shown in Figure 2-4. The top 17 localities which together contributed 66.3% of the number of exported fish in descending order include: Mbenji Island, Likoma Island, Chilumba, Chizumulu Island, Nkhata Bay, Lion's Cove, Mdoka, Chipoka, Maisoni Reef, Usisya, Chewere, Gome, Chindunga Rocks, Kawanga, Garireya Reef and Mphanga Rocks. Each of these top localities individually contributed more than 2% of the exported fish.

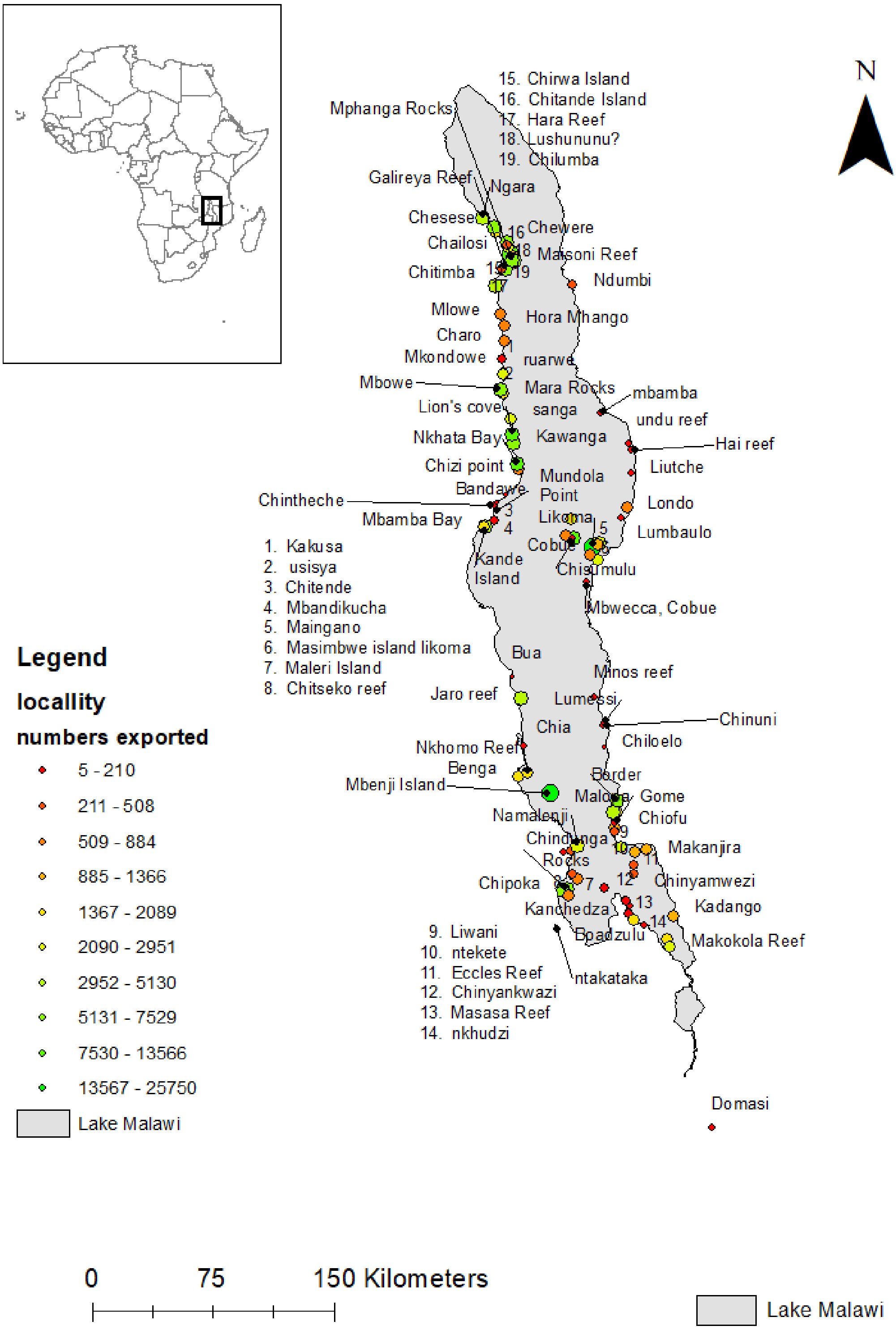

Figure 2-4. The locations of Lake Malawi where exported ornamental fish were collected and the numbers exported by location of collection between 1998 and 2017. Size of the dots on the map represents the proportionate numbers (to logarithm scale) which is also reflected by different colours as shown in the legend.

Temporary shifts in ornamental fish collection localities in Lake Malawi

Cluster analysis of years of ornamental exportation was performed on the number of fish exported by fish collection localities using SIMPROF test based on group average of the Bray Curtis Resemblance of square root transformed data for the years. Results of the cluster analysis are presented in Figure 2.5. Nine significant clusters of years were evident in the discrimination of change in localities fished (Figure 2-5), with between year similarity ranging from 49.9% (π = 5.21, p<=0.01) to 73.6% (π = 1.74, p< 0.01). Four of the clusters are single year clusters, while the other five clusters comprise two to four years. The output showed adjacent years forming single clusters, i.e. 1999-2001, 2002-2005, 2010-2012 and 2013-2016 were grouped, suggesting the fishers operated in specific locations for several years before moving to new locations.

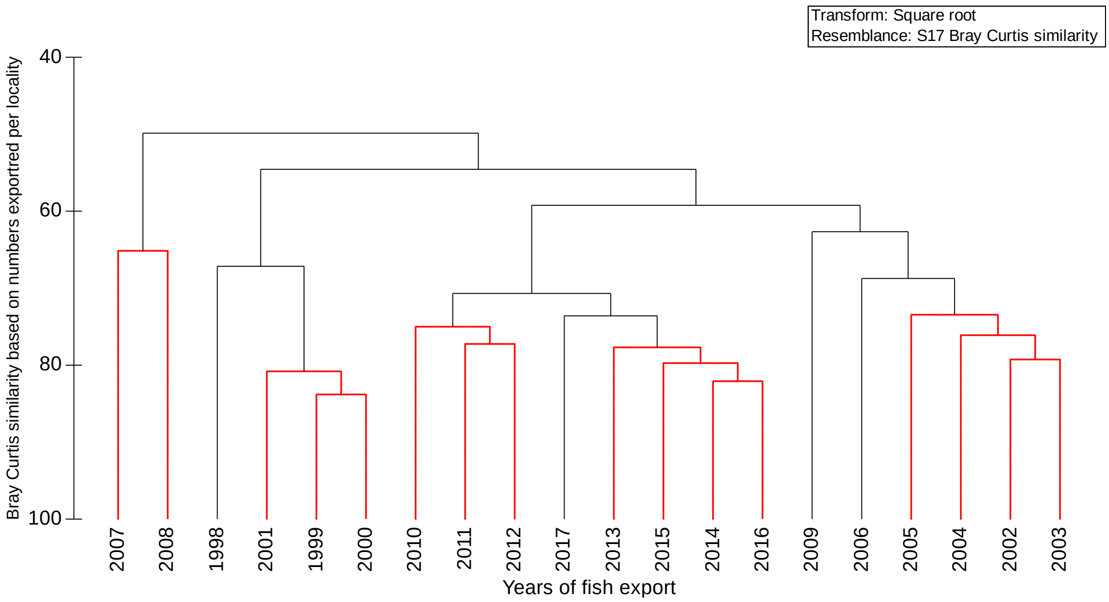

Figure 2-5. Clusters of years according to Bray Curtis similarity index based on numbers of fish exported by locality of fish collection. SIMPROF test detected nine significant clusters of years (P<0.01) which are in black colour. The clusters in red colour are not significantly different (P>0.05).

2.3.3 Export destinations

Ornamental fish from Malawi were exported to 23 countries between 1998 and 2017 (Figure 2-6). The top four major export destinations (Germany, France, Hong Kong and United States of America) accounted for 60.5% of export volumes, while the top ten countries accounted for 92.1% of the total export volumes.

Amongst the 23 fish importing countries; Germany, France, USA, Hong Kong, United Kingdom, Sweden, Denmark, Canada and South Africa were regular importers of ornamental fish from Malawi between 1998 and 2017, while the other countries were intermittent importers. Hong

Kong started importing ornamental fish from Malawi in 2008, but the numbers imported have steadily increased making Hong Kong the overall third largest importer of ornamental fish from Malawi (Figure 2-6).

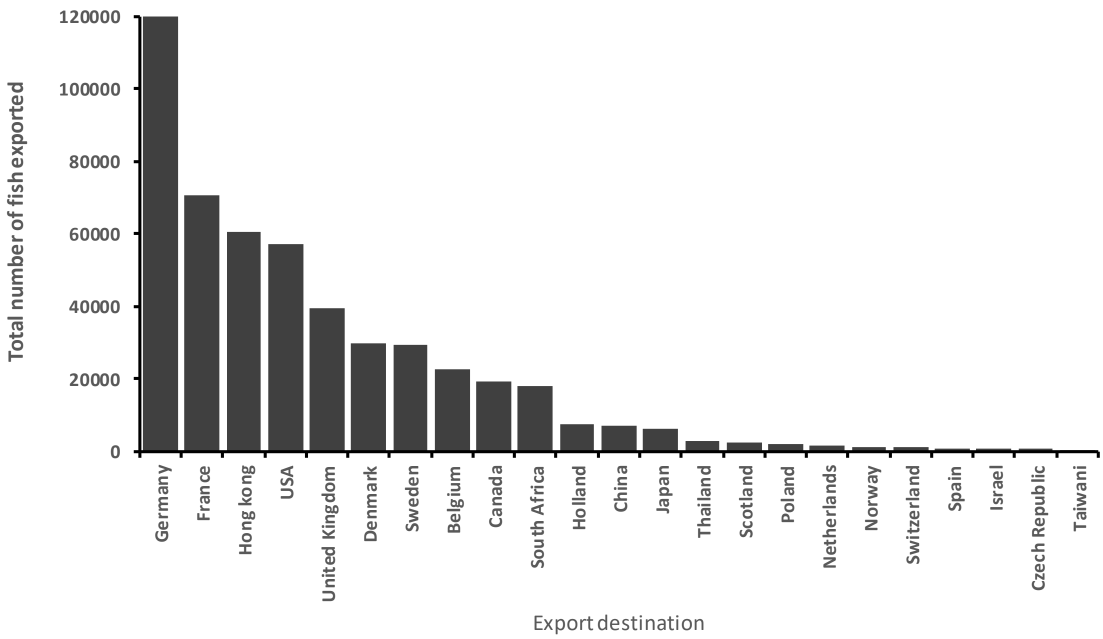

Figure 2-6. Total numbers of live ornamental fish exported from Malawi between 1998 and 2017 according to export destinations.

The number of countries that imported ornamental fish from Malawi between 1998 and 2017 ranged from four countries in 2007 to 13 countries in 2005, 2012 and 2016 (Figure 2-7). The four countries that imported fish during the worst years of trading were Denmark, France, South Africa and United Kingdom. Excluding the year 1998 (which had only 6 months of data analysed) and the years 2006 to 2008 (referred to as bad business years by fish exporters), suggests that 9 to 13 countries annually imported fish from Malawi with the numbers exported to individual countries varying annually (Figure 2-7).

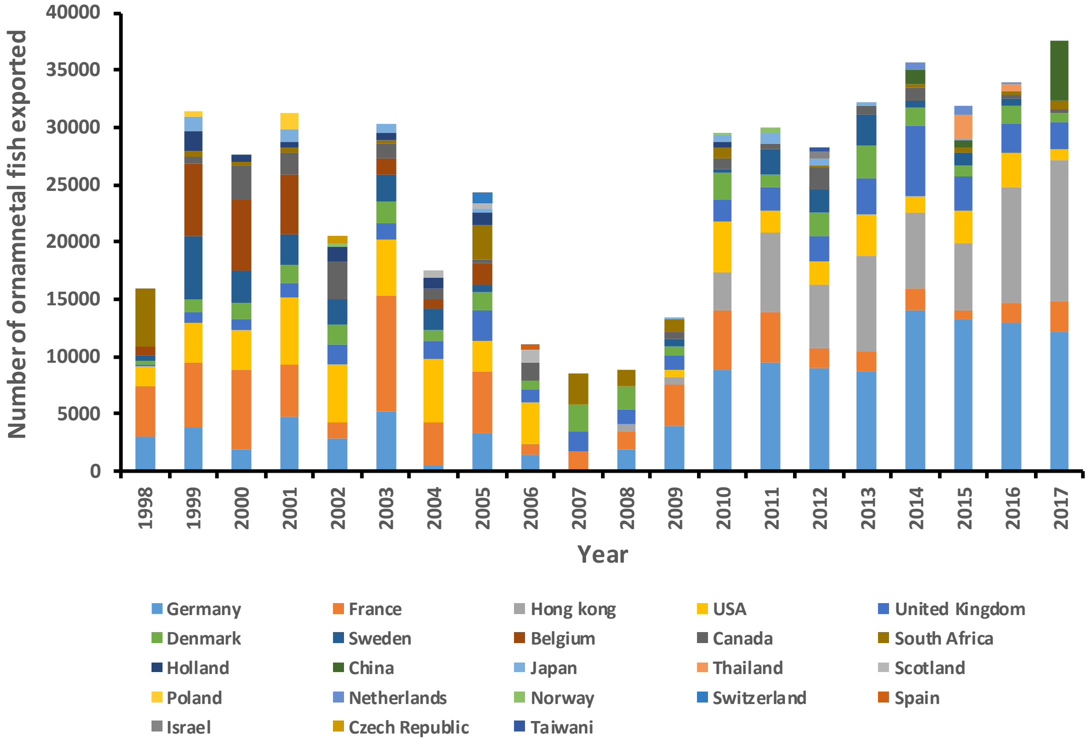

Figure 2-7. The number of ornamental fish exported from Malawi to different countries by year.

2.3.4 Species of fish exploited

The fish that were exported from Malawi between 1998 and 2017 belong to 257 described species (Appendix 2.4) and 279 "undescribed species " (Appendix 2.5), represented by a total of 64 genera (Appendix 2.3) plus two unspecified genera, one for cichlids and one for gastropods, and thirteen families assuming that the gastropods exported belonged to one family (Table 2-1). The exported species did not only include fish but also other animals, including shrimps (Atyidae), crabs (Potamonautidae), sponges (Malawispongiidae) and gastropods. Fifty percent of the fish export volumes were accounted for by the top 32 species comprising 27 described fish species and 5 undescribed fish species, while 90% of the export volumes were contributed by the top 145 species including 99 described species and 46 undescribed species.

Cichlidae dominated the exports accounting for 98.6% of the export volumes, while the other families represented a total of only 1.4% (Table 2-1).

Table 2-1. The total number and percentage of fish specimens exported according to the families they belonged to

Family	Total number exported	% of numbers exported
Cichlidae	492,917	98.600
Mochokidae	3131	0.626
Potamonautidae	2104	0.421
Mastacembelidae	1001	0.200
Cyprinidae	555	0.111
Atyidae	90	0.018
Bagridae	46	0.009
Poeciliidae	25	0.005
Clariidae	15	0.003
Malawispongiidae	16	0.003
Unspecified gastropods[3]	15	0.003
Protopteridae	3	0.001

The two most common genera (*Metriaclima* and *Aulonocara*) represented 42.6% of the numbers of fish exported while the four most common genera (*Metriaclima*, *Aulonocara*, *Pseudotropheus* and *Cynotilapia*) represented 58.6% of the ornamental fish exports from Malawi between 1998 and 2017 (Appendix 2.3). The ten most common genera (*Metriaclima*, *Aulonocara*, *Pseudotropheus*, *Cynotilapia*, *Copadichromis*, *Melanochromis*, *Protomelas*, *Labeotropheus*, *Tropheops* and *Chindongo*) represented 80.9% of the exported fish and the remaining 54 genera and two unidentified groups represented only 19.1% of the volume of exported fish. The proportion of the export volumes based on the taxonomic status were 72.8% for described species and 27.2% for undescribed species.

Whether the "undescribed species" should be considered as species or not is a question which may never be answered as there are no specimens of the undescribed fish that can be tied to the temporary names that had been used.

Temporal variation of the number of exported species: The number of species exported changed from 77 described species and 36 undescribed species in 1998 to 118 described species and 170 undescribed species in 2017 (Figure 2-8). The peak number of described species was 121 in 2016 while the peak number for undescribed species was 184 in 2014. It is also evident that the numbers of exported ornamental fish species are increasing with time.

[3] Indicated as snails (Class Gastropoda) but family not specified in the fish export returns

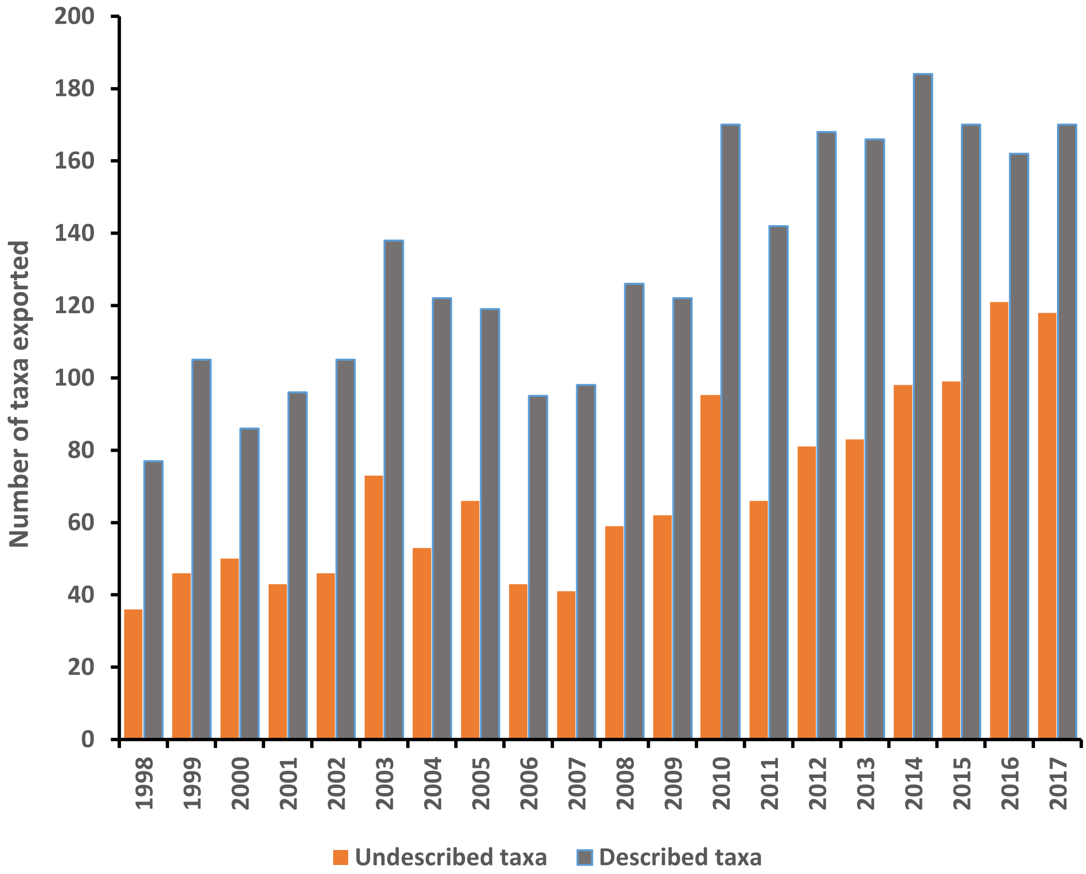

Figure 2-8. The number of currently described and undescribed species that were exported from Malawi between 1998 and 2017.

Clustering of years based on the numbers of individual fish exported per taxon

The Bray Curtis similarity on square root transformed number of exported fish per taxon ranged from 47.48% to 82.08%. Cluster analysis and SIMPROF test based on the Bray Curtis similarity showed 13 significant clusters of years with similarity ranging from 47.5% (π=5.69, p=0.001) to 75.5% (π=1.08, p = 0.005). Eight of the clusters comprised of single years (1998, 2002, 2006, 2009, 2010, 2013, 2016 and 2017) while the other clusters comprised two or three years per cluster (Figure 2-9). The relatively low Bray Curtis similarity and prevalence of many single year clusters suggests there were considerable differences in the number of individual species exported in different years. This can also be explained because most of the 279 undescribed species included within the 536 species analysed had few individual fish per taxon. The tendency for exporters and scientists to use provisional names every time an unidentified fish is encountered can also inflate the number of actual species.

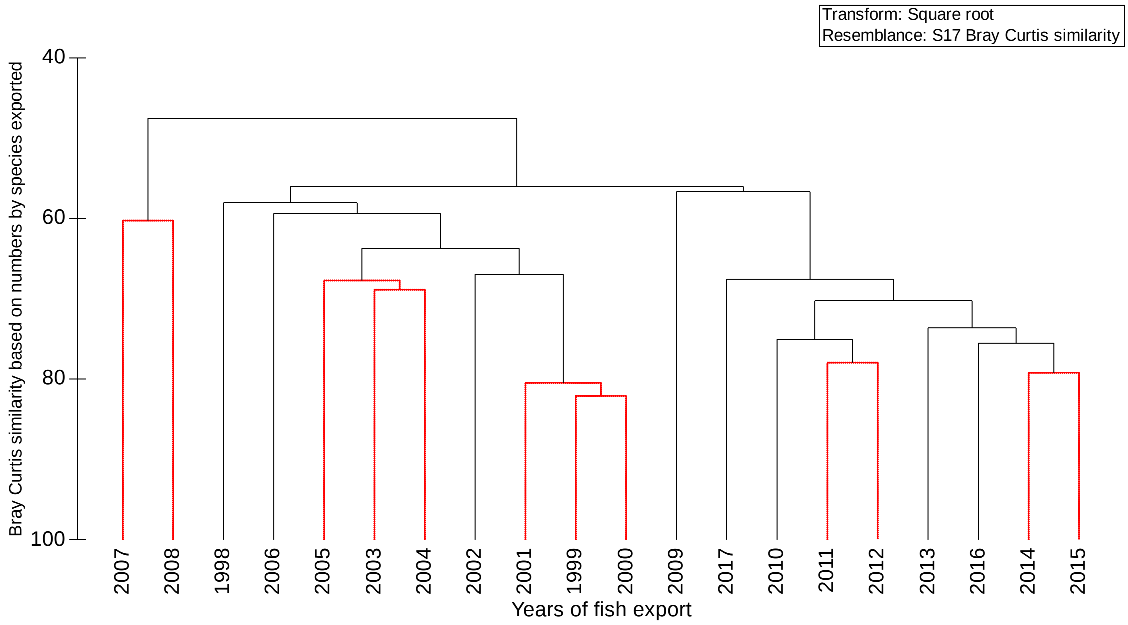

Figure 2-9. Clustering of years based on Bray Curtis similarity of the export volume of individual fish species All significantly different clusters ($p<0.05$) are shown in black while non-significant clusters ($P>0.05$) are in red colour.

2.3.5 IUCN conservation status of the exported fish

Results about the number of taxa exported by IUCN conservation status based on combined data across all years from 1998 to 2017 are presented in Figure 2-10. The conservation status of the exported species based on the IUCN (2019) Red List included 279 undescribed (or unidentified) species, 208 species of least concern, 21 near threatened species, 12 critically endangered species, 5 endangered species, 5 vulnerable species, 4 data deficient species, 1 species not evaluated and 1 species not applicable (Figure 2-10). Details of individual fish species falling under different IUCN (2019) conservation status categories are presented in Appendix 2.4. Of the 30 most exported described fish species, six (20%) are critically endangered and three (10%) are near threatened, while one (3.3%) is data deficient.

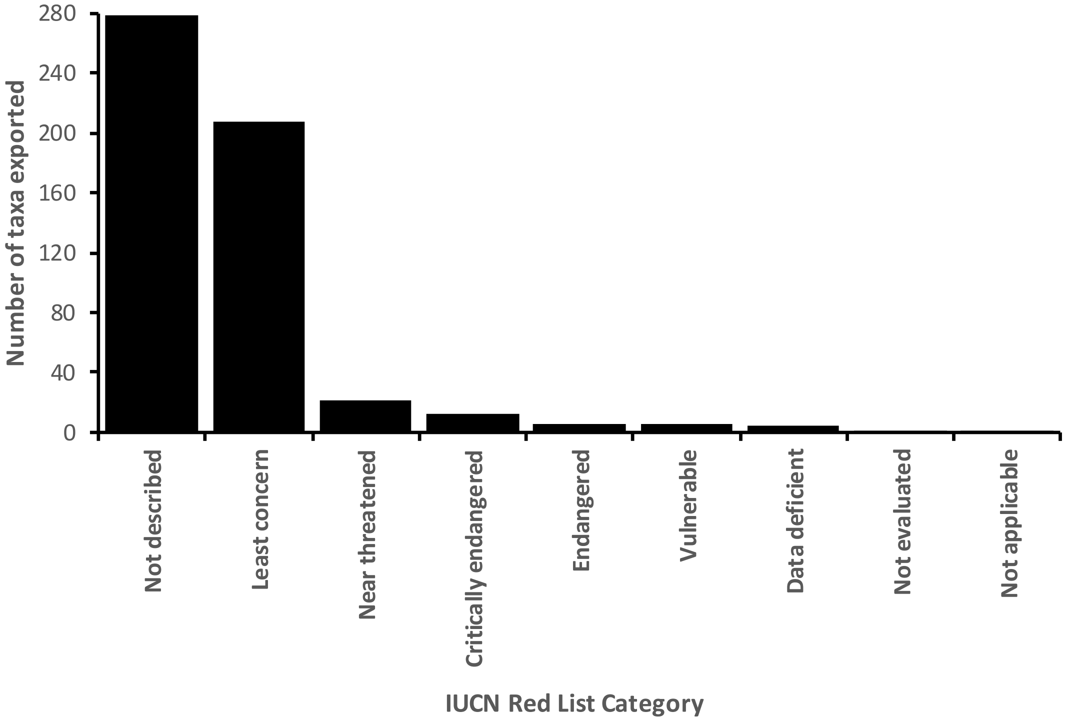

Figure 2-10. Total number of exported species according to conservation status of the species.

Clustering of years based on number of species exported by IUCN conservation status: The Bray Curtis Similarity of years based on log transformed number of species exported by conservation status ranged from 85.18% to 97.84%. Cluster analysis and SIMPROF test in PERMANOVA based on Bray Curtis similarity on number of species exported annually by conservation status showed three significant clusters of years at similarity level between 85.18% (π= 2.01, p = 0.001) and 90.58% (π= 0.86, p = 0.001) (Figure 2-11). The high percentage similarity and low number of clusters indicate that the number of species exported by conservation status was fairly uniform over the years.

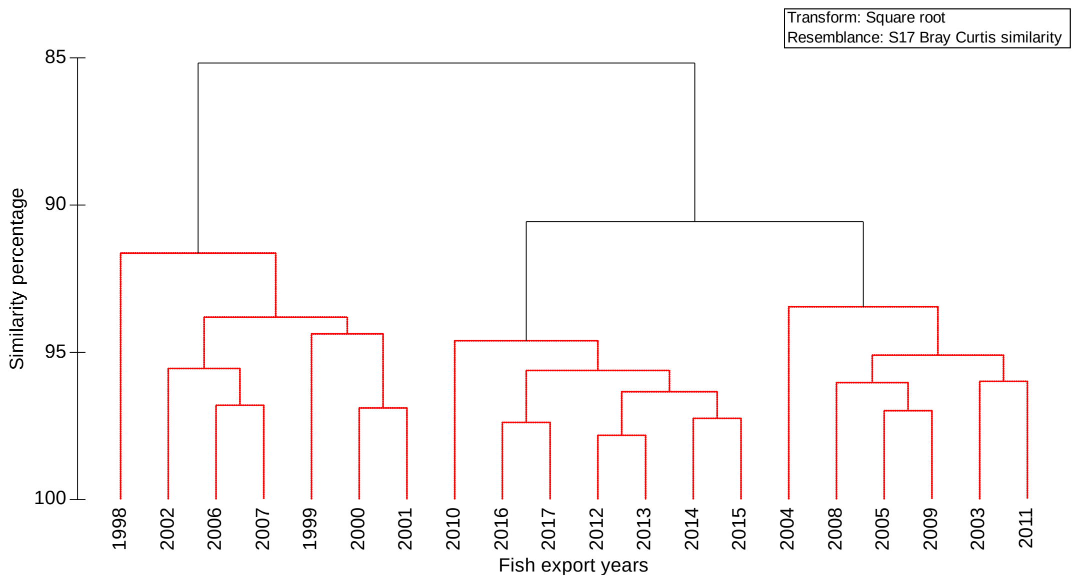

Figure 2-11. Cluster of years according to Bray Curtis similarity on square roots transformed numbers of species exported by conservation status. Three significant clusters (P<0.05) of the years are evident.

The Principal Coordinate Ordination of numbers exported by conservation status (Figure 2-12 found that PCO1 explained 86.3% of variation in the observed pattern and it was mainly influenced by a combination of undescribed, data deficient, near threatened, least concern and endangered species. PCO2 explained 6.6% of the total variation and was mainly influenced by a combination of not evaluated and critically endangered species in one direction and vulnerable species in an opposite direction.

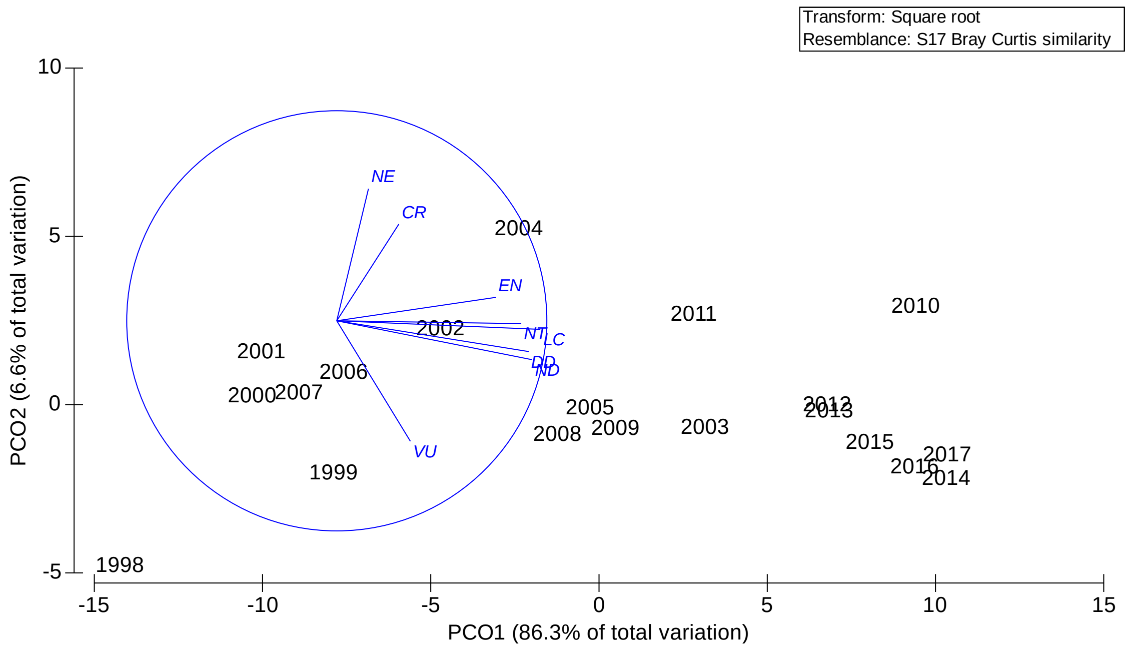

Figure 2-12. PCO plot based on Bray Curtis similarity of years and log transformed numbers of species exported with an overlay of vectors of number of species by conservation status.

Clustering of years based on quantities of ornamental fish exported per species and conservation status: Cluster analysis of the numbers of fish species exported in different years by IUCN conservations status categories showed four significant clusters at similarities ranging from 70.7% (π= 3.23, p = 0.001) to 89.2% (π= 0.83, p = 0.001) (Figure 2-13). With a few exceptions, the clusters showed a tendency for adjacent years to be grouped together suggesting that exporters probably export the same species for some years then gradually change after some time. However, the clustering was probably partly influenced by the number of ornamental fish exporters in Malawi fluctuating over the years between one and four operators, with the years between 2012 and 2017 having three or four operators. Moreover, during the interview with one exporter[4] it was revealed that the exporter had specialized in exporting more specific groups of species of fish than others unless special orders of other species of fish were received.

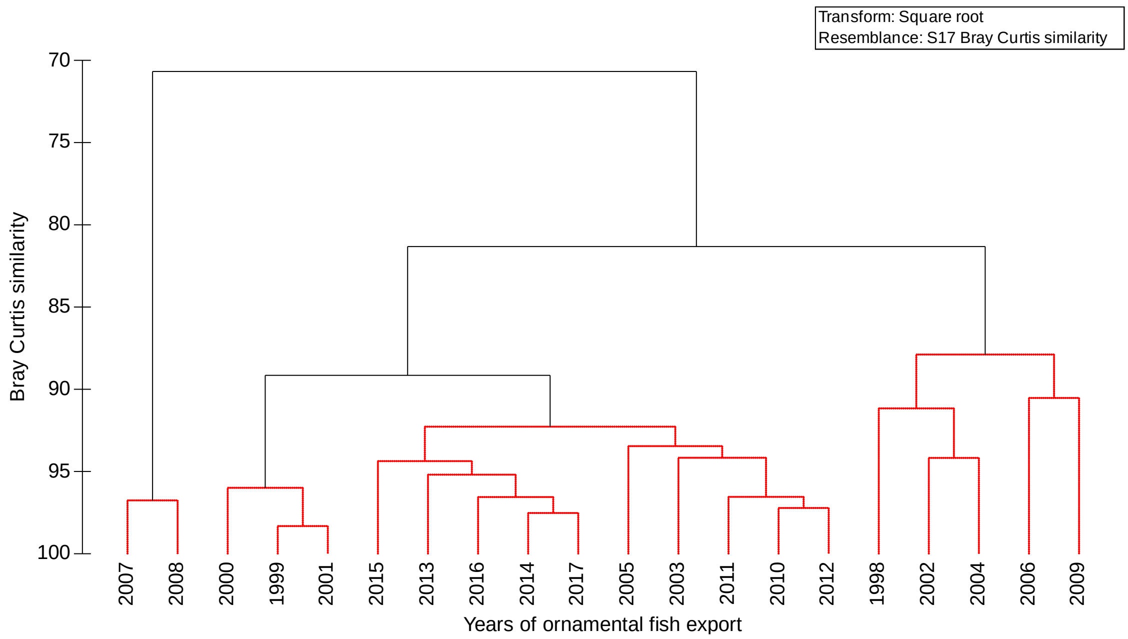

Figure 2-13. Clustering of the years of ornamental fish exportation from Malawi based on Bray Curtis similarity on numbers of fish exported according to the conservation status. Four significant clusters (P<0.05) were evident.

When the resemblance matrix was further examined in PERMANOVA using the Principal Coordinate Ordination (PCO), with an overlay of vectors of numbers of fish exported in different conservation status categories (Figure 2-14), PCO1 explained about 81% of the variation, which was mostly influenced by a combination of near threatened, least concern and data deficient

[4] On ethical grounds the name of the exporter and details of fish species the exporter specializes in exporting cannot be provided in this thesis.

species, while PCO2, which was mostly influenced by endangered and vulnerable species in one direction and critically endangered fish in another direction, explained about 15% of the variation. Thus, PCO1 and PCO2 combined account for 96% of the observed patterns.

One notable observation in the PCO is that the years 2006 to 2009 associated with low export volumes are separate from all the other years. This shows that the increase in number of exported fish was coupled with an increase in the numbers of near threatened, least concern and data deficient species.

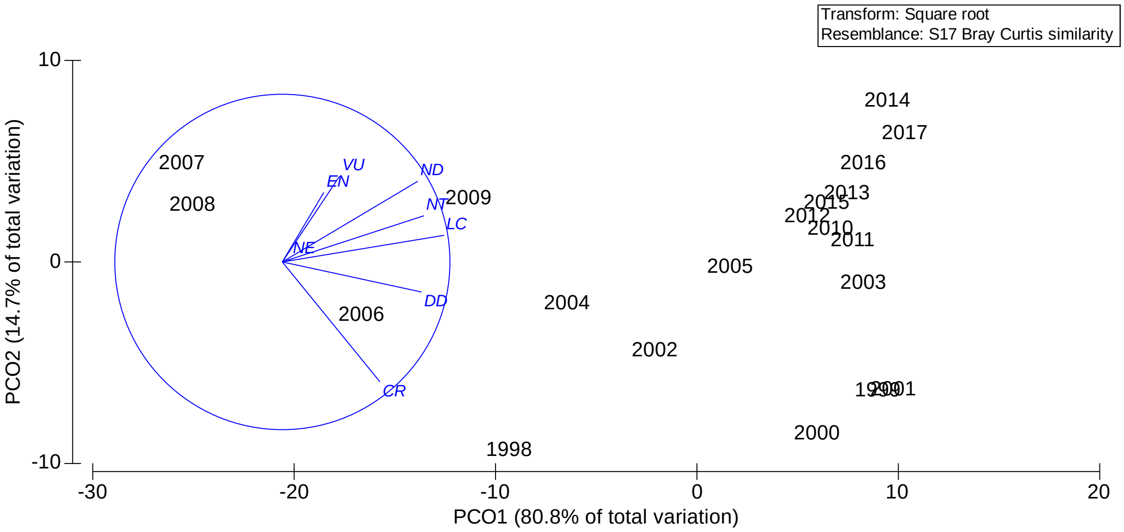

Figure 2-14. The PCO based on Bray Curtis similarity index of numbers of fish exported in different years with an overlay of vectors of numbers by conservation status of the species.

2.4 Discussion

2.4.1 Challenges and limitations of ornamental fish export data used

One of the assumptions of using the data of fish export returns maintained by the Department of Fisheries in Malawi was that names of fish recorded by exporters were based on accurate identification of fish species. However, there were a few potential sources of errors with respect to nomenclature of fish:

- In some cases, formal descriptions of species have been made and fish belonging to a single previously used temporary name have been split into more than one species when the species were formally described.
- Exporters have often used some temporary names of ornamental fish species which are of limited use because there is no information or preserved fish specimens to tie those

names to. Such names are different from those used by Ribbink *et al.* (1983) and Konings (2016) that are associated with morphometric or colour diagnostic information that could be used by other scientists.

- With time some fish species have been moved from one genus to another, which sometimes creates challenges when dealing with undescribed species. For example, according to Konings (2016 page 94) the species placed by Ribbink *et al.* (1983) in the *Pseudotropheus* sp *elongatus* group currently belong to four different groups including: *Metriaclima* sp *elongatus* group, *Tropheops* sp *elongatus* group, *Cynotilapia* sp *elongatus* group and *Pseudotropheus* sp *elongatus*. It is virtually impossible to reconcile these current groups with what was exported as *Pseudotropheus* sp *elongatus* a decade ago, especially if the locality of collection was not indicated. Besides, none of the fish exported under the name "*Pseudotropheus* sp *elongatus*" could be placed under the described species, *Chindongo elongatus* (Fryer, 1956), which was originally described under the genus *Pseudotropheus,* because this species is found only in Mbamba Bay, Tanzania (Seegers, 1996; Konings, 2016; IUCN 2019), which is a no-go zone for exporters of ornamental fish from Malawi.
- Some exporters used vague names or outdated generic names such as "*Haplochromis* spp", "*Haplochromis* cichlids", "Malawi Cichlid mixture", which did not make any taxonomic sense.

These challenges mean that the number of described species exported from Malawi is probably more reliable than that of undescribed species, which may not be distinct species. It appears that frequent creation of temporary names for unidentified fish inflates the number of species present. Moreover, cichlid fishes of Lake Malawi display a diversity of colour morphs within a single species (Ribbink *et al.,* 1983; Konings, 2016), which may lead to misidentification of fish species or inflation in number of species.

Despite all these challenges and limitations of the data used, they still provided useful insights about some aspects of the ornamental fish export trade in Malawi that were investigated, such as volumes and value of the trade, distribution of fish collection localities and temporal trends of the same aspects.

2.4.2 Current state of the ornamental fish export trade in Malawi

Ornamental fish export volumes were relatively low in 1998 and between 2006 and 2009. The low volume in 1998 was because fish export data were available for only six months, while low volumes between 2006 and 2009 can be attributed to three factors.

The first factor is increase in competition with farm bred Lake Malawi cichlid fishes. Cheap farmed fish from the Far East and Florida in USA is known to have reduced the demand of ornamental fish from Lake Malawi on export trade from the 1980s to late 1990s (Watson, 2000). The fall in export volumes between 2006 and 2009 was probably exacerbated by the reported increase in farming of freshwater ornamental fish in Czech Republic, Israel and Belgium to supply European Union countries during the mid-2000s (Dey 2016), which coincided with the period of sudden fall of the export of Lake Malawi ornamental fish. In addition, cichlid fishes from Lake Malawi are easy to breed, which has enabled cichlid fish keepers in importing countries to breed them at home and supply ornamental fish hobbyists and retailers (Watson, 2000). Watson (2000) projected that the decrease of ornamental fish demand due to competition from breeders would be followed by recovery of demand due to the need to renew the breeding stock at some stage, a view which exporters of ornamental fish in Malawi appeared to agree with. This may be one of the reasons for the increase in export volumes from 2009 onwards.

The second factor is that the period between 2006 and 2009 coincided with the global economic crisis, which resulted in losses of employment and Gross Domestic Product in many developed countries as many industries collapsed (Fratesi & Perucca, 2018; Osabuohien *et al.,* 2018). Since the ornamental fish trade is linked to the state of the national economies, and since import volumes are higher for countries with better economies (FAO, 2010; Dey 2016), it is likely that the global economic crisis resulted in reduced demand for some ornamental fish species from Malawi. Similar observations were made by Rhyne *et al.* (2012) who noted a decline in the number of coral reef species that were imported by the USA during the same time period. Furthermore, FAO (2010) reported that the economic crisis made the major importing countries reduce importation of ornamental fish species of high absolute value, particularly those captured in the wild.

The third factor is the death of the owner of the major exporting company in 2007 which resulted in the exporting company halting the business for two years in 2007 and 2008 during which time only one exporting company was operational.

The moderate correlation between the number of ornamental fish exporters and export volumes suggests that demand for ornamental fish is probably not high enough for the increase in number of exporters to lead to substantial changes of the export volumes. With exclusion of export data for 1998 and between 2006 and 2009, the results suggest that the volumes and values of ornamental fish exported from Malawi have not significantly changed between 1998 and 2017 despite the fluctuations in numbers of fish exporters during the same years, a view that the three exporters interviewed subscribed to.

Compared with the global annual ornamental fish export volume of over 1 billion fish (Teletchea, 2016; Evers *et al.,* 2019), the export volumes of ornamental fish from Malawi may appear unsubstantial. For instance, assuming every year about 1 billion individual ornamental fish are exported globally (Teletchea, 2016; Evers *et al.,* 2019), the average annual export volume of 25,000 fish from Malawi translate into a negligible proportion of 0.0025% of the global export volume. However, in terms of species composition Malawi may contribute a substantial proportion of the species to the estimated total number of 5300 freshwater species being exported globally (Raghavan *et al.,* 2013; Evers *et al.,* 2019). Indeed the 257 described species exported from Malawi translate into 4.85% of the freshwater species exported globally and if undescribed species are added the percentage contribution of Malawi to global trade biodiversity could be as high as 10.11% if each of the undescribed species is to be considered as a valid species.

Ornamental fish export volumes reported in the current study are quite contrary to some of the information reported by Ribbink *et al.* (1983) and Watson (2000). Ribbink *et al.* (1983) quoted a peak of 400,000 fish being annually exported from Malawi in the mid-1970s while Watson (2000) quoted a peak of 250,000 fish being exported from Malawi around the same period. Unfortunately, no report (published or unpublished) exists about the numbers of ornamental fish that have been previously exported from Malawi. The peak volumes previously quoted were probably based on guestimates or some narratives at that time. Comparisons of the previously cited peak export volumes of 250,000 and 400,000 fish with the current average annual export volume of 24,996 fish found in this study for the twenty-year period suggests that the current fish export volumes are between 10 and 16 times less than the peak export value of the 1970s. In other words, the total export volumes for the 20-year period of 1998 to 2017 are between 1.25 and 2 times the annual peak value of the 1970s. Interviews with the exporters did not corroborate with this finding. When asked about the trends of export volumes, exporters talked about poor export between 2006 and 2009 compared with other years without mentioning anything about the sharp decline of export volumes between the 1970s and 1990s. Unfortunately, fish export records currently maintained at Fisheries Department only date back to July 1998 making it difficult to ascertain the trend of ornamental fish export volumes from Malawi between 1970s and 1998.

The average annual value of ornamental fish exports from Malawi between 1998 and 2017 was estimated in this study to be US$197,045 at 2018 prices. Russell *et al.* (2008 citing FAO) quoted a value of ornamental fish exports from Malawi of US$60,548 in 1999, yet the current study established a value of US$257,538 at 2018 price which is equivalent to US$170,555 at 1999 price. Unfortunately, there is no detail about how the value cited by Russell *et al.* (2008) was arrived at. It is possible that the prices on which the value cited by Russell *et al.* (2008) was based, are different from the ones used in the current study.

2.4.3 Fish collection patterns

Ornamental fish exported from Malawi were collected from various rocky areas on the Malawian side of Lake Malawi and a few places from the Mozambican side, with the numbers collected varying widely between localities. The fish collection pattern observed is consistent with Watson (2000) who reported that besides fishing the Malawi side of Lake Malawi, one exporter had established a special relationship with people in the Mozambican side and was allowed to collect ornamental fish for trade.

The tendency for adjacent years to form single clusters based on fish collection localities suggests that exporters probably focus on collecting fish from certain localities for a few years before shifting to other localities. This means they collect fish of distinct species in specific locations before moving on to new locations and new species, which is in line with Ribbink *et al*. (1983), and Konings (2016) who reported of segregation of different rock dwelling species of Lake Malawi around distinct rocky areas. Generally, fishers are flexible and able to shift between localities for a number of reasons including: changes of resource location and abundance, knowledge and experience of fishers, regulatory regimes, shoreline infrastructure, costs incurred, and environmental pressures (Monroy *et al.,* 2010; Young *et al.,* 2019). Collection of ornamental fish from Lake Malawi probably follows similar fishing behaviour. One possible reason that influenced the clustering of years with respect to fish collection localities in this study is that fish exporters try to look for new fish species that fetch higher prices. During interviews with some fish exporters it was revealed that new and rare species are always in higher demand by importers, which encourages some exporters to offer special bonus rewards to their fishers (divers) for catching new or rare fish species. The second reason for shifting to other localities could be associated with reduction of numbers of target species of fish in the already exploited localities. Two of the three interviewed exporters revealed that one of the challenges they faced was to get enough numbers of the species they targeted, which forced their divers to cover wider areas of rocky reefs in search of the fish.

The pattern of some localities being associated with more fish collection than others could pose a risk of overexploitation to target species in small but heavily fished rocky reefs. For instance, amongst the top 17 fish collection localities listed (see section 2.3.2), the following rocky reefs appear to be too small to sustain heavy collection pressure (personal observation): Chindunga Rocks, Galireya Reef, Lions Cove and Mphanga Rocks. Moreover, populations of some small rocky reef fish species in Lake Malawi are less than 1000 individuals (Konings, 2016, IUCN, 2019).

Dulvy *et al.* (2004) and Raghavan *et al.* (2013) stated that species of fish with small geographic ranges and high catchability are more likely to be negatively impacted by ornamental fish trade than other species of fish.

2.4.4 Export destinations

This study revealed that ornamental fish from Malawi are exported to 23 countries with top ten countries accounting for 92.1% of the export volumes. These findings are supported by available statistics of ornamental fish trade on the global market (FAO, 2010; Dey, 2016). The top three global ornamental fish importing countries; USA, Germany and UK in the years 2010 (FAO, 2010) and 2014 (Dey, 2016), were amongst the top five importers of ornamental fish from Malawi. Furthermore, the list of importers of Lake Malawi ornamental fish was dominated by European countries, which was the largest trade bloc of ornamental fish trade (Leal *et al.,* 2016; Evers *et al.,* 2019). USA has been the world largest market followed by UK which has been the largest European market of ornamental fish for many years (Dey, 2016; Evers *et al.,* 2019).

Some observations made during interviews with fish exporters were that individual exporters of ornamental fish from Malawi were linked to specific importers in one or more of the importing countries. Furthermore, some exporters revealed that they had been approached if they could supply fish to importers in other countries, such as Czech Republic, Poland, Russia, Brazil and Mexico, but they had turned the offers down because of the problem of flight connections to such countries. It was alleged that long hours of flight increase the risk of fish mortality as well as the flight costs. These limitations to exportation of ornamental fish were also highlighted by Watson (2000).

2.4.5 Species preferred and their conservation status

Many described and undescribed species of ornamental fish belonging to the Family Cichlidae have been exported from Malawi between 1998 and 2017. Although species exported are represented by 64 genera, only a few genera dominate export volumes of ornamental fish from Malawi. The number of exported species has been increasing with time probably because more species were being described with time enabling exporters to identify and export more species. New species of fish from Lake Malawi are frequently being described with frequent splitting of some species / fish species complexes (Konings, 2016).

Exporting of many undescribed fish using temporary names with insufficient information for identification of the fish being tied to such names, is of management concern. It is not possible to assess the status of fish that are unknown. Secondly, exported fish were represented by 22 threatened species (critically endangered, endangered or vulnerable) and 21 near threatened species based on the IUCN (2019) Red List. Additionally, 30% of the 30 most exported described species between 1998 and 2017 are either threatened or near threatened. These species belonged to 18 genera including: *Aulonocara*, *Chindongo*, *Melanochromis*, *Pseudotropheus*, *Cyrtocara*, *Placidochromis*, *Metriaclima*, *Nyassachromis*, *Rhamphochromis*, *Nimbochromis*, *Serranochromis*, *Labidochromis*, *Bagrus*, *Mchenga*, *Copadichromis*, *Trematocranus*, *Iodotropheus* and *Tropheops*.

According to the IUCN (2019) Red List, in addition to extraction of fish for the ornamental fish export trade, the various fish species are also exposed to other threats, including: fishing (commercial and subsistence food fishery), sedimentation, localized water pollution, habitat destruction and fish being of limited population size (Figure 2-15). Most of the fish species classified as threatened or near threatened have restricted distribution range, which makes them vulnerable to exploitation. The majority of the threatened fish species have a combination of more than two threats.

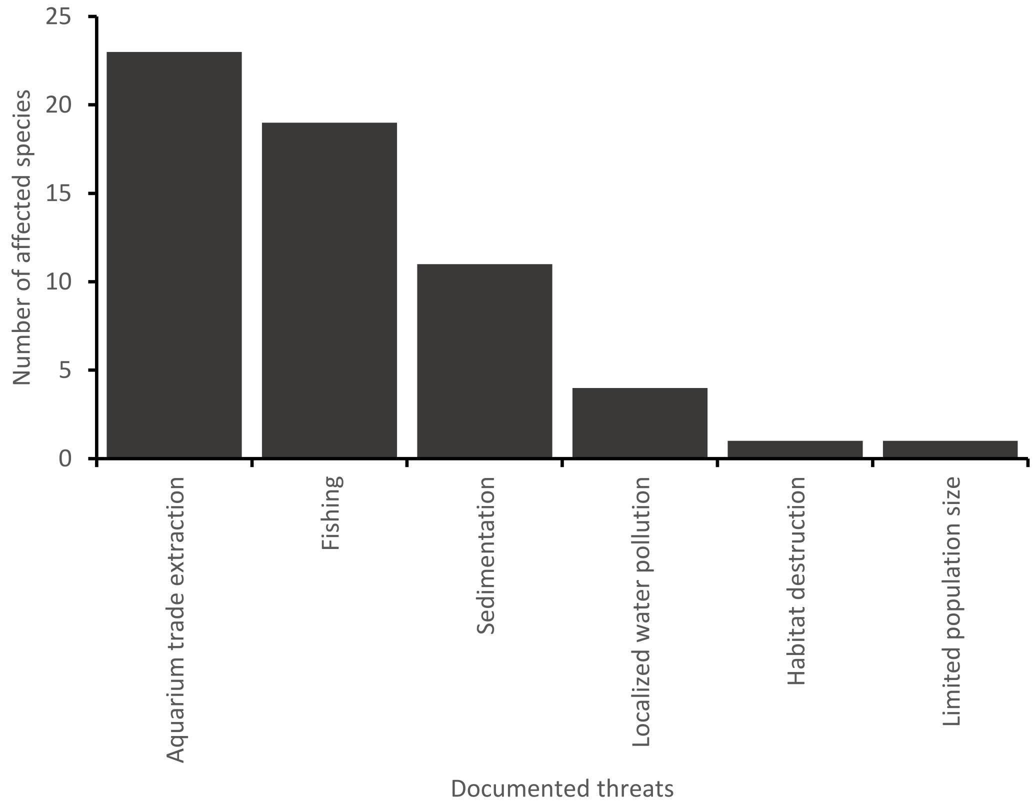

Figure 2-15. Distribution of threatened[5] species affected by various threats based on IUCN (2019) Red List.

[5] Threatened in this context refers to fish that were classified in the IUCN Red List as one of the following: near threatened, critically endangered, endangered and vulnerable. Together these added to 43 species, some of which were affected by multiple threats.

IUCN (2019) split the threat of fishing for food fish into two categories: commercial fishing and subsistence fishing. Based on field observations during the current study, a third fishing category can be added to this list - catching of *mbuna* as bait for the hook and line fishery that targets bigger-sized fish species such as *Rhamphochromis* spp., *Bathyclarias* spp., *Bagrus meridionalis* (Gunther, 1894) and *Dimidiochromis kiwinge* (Ahl, 1926). *Mbuna* bait fishing was observed around Mbenji Island and Nkhata Bay area where some fishers have specialized in this type of fishing to supply bait to all other hook and line fishers. Bait *mbuna* fishers use food items such as roasted catfish and hard porridge (locally known as *nsima*), which they break into small pieces and spread in a specific part of a rocky area to attract *mbuna* at a single point. Once the fish congregate around the bait, free-diving fishers encircle the fish with a net and take their catch into a boat anchored nearby. Using this method, the fishers were observed to catch hundreds of fish specimens at depths between extreme shallows and 8 metres in less than 30 minutes.

Field observations during this study suggested that fishing of *mbuna* for food and bait is a more serious threat than currently perceived, despite contravening existing fishery regulation which ban catching of *mbuna* by fishers in Lake Malawi. The ban was made due to the vulnerability of localized *mbuna* populations to artisanal food fisheries which use gears such as seine nets and gillnets. The threat of fishing *mbuna* for food was observed at all sampling localities outside LMNP during this study including: Chindunga Rocks, Mbenji Island and Nkhata Bay. Fishers used various gears to catch the *mbuna* including hand lines (around Chindunga and Nkhata Bay), small seine nets and gillnets (around Mbenji Island). During the two days of field sampling at Mbenji Island it was noted that about 40% of the small cichlids caught and sun-dried on the fish drying racks were *mbuna* fishes (Figure 2-16)

Figure 2-16. Sun drying of *mbuna* fish at Mbenji Island

2.4.6 Management of the ornamental fishery in Malawi

Raghavan *et al.* (2013) warned against the danger of unmanaged exploitation of endemic ornamental species to freshwater biodiversity, particularly where threatened species are being exploited, and this situation appears to be prevalent in Lake Malawi.

IUCN (2019) reported two existing conservation measures for some of the exploited ornamental fish species of Malawi namely, protection afforded by LMNP to some species and restocking of some of the threatened species of fish. However, existence of the LMNP does not benefit most of the exploited species, which have limited and localized distribution. On the other hand, restocking of threatened ornamental fish species is an initiative of the Stuart Grant Cichlid Conservation Fund (Cichlidpress.com, undated; Konings, 2017), which the Department of Fisheries in Malawi is not aware of. According to the current Director of Fisheries (Dr Friday Njaya) and other senior staff members of Fisheries Department in Malawi, the Department of Fisheries has never been involved in the conservation activities of the fund yet the fund has been operational since 2007 (Konings, 2017). It is reported that the trust collects donations to fund projects aimed at conserving cichlids of Lake Malawi and Tanganyika. Previously projects purported to have been funded include placing anti-netting devices in the LMNP, supporting restoration of populations of threatened cichlid species due to aquarium trade through restocking, and propaganda warnings to aquarists to refrain from buying the wild threatened species of fish particularly *Chindongo saulosi* (Konings, 1990). The implementation of a restocking programme without involving the Department of Fisheries and research institutions is a cause for concern. It has been demonstrated that if not properly conducted, restocking of fish populations with captively bred fish may result in negative effects such as loss of genetic diversity, inbreeding, reduction in fitness of the fish (Benhaïm *et al*., 2012; 2013; Coimbra *et al*., 2017; Cushman *et al*., 2019), disease introductions (Cushman *et al*., 2019) and poor adaptation with respect to evasion of natural predators (Tang *et al*., 2017). Furthermore, loss of genetic diversity of a fish population may negatively affect long term sustainability of the fish population since it affects the ability of the population to adapt to a changing environment (Cushman *et al*., 2019). The inability of the restocking programme to register success for the ornamental fish of Lake Malawi (Konings 2017, IUCN, 2019) could partly be attributed to such negative effects of restocking.

It should also be noted that the initiative of ornamental fish restocking programme by the Stuart Grant Cichlid Conservation Fund suggests that exporters and fish hobbyists have information about the status of the populations of specific species of exploited ornamental fish in Malawi, which Fisheries Department in Malawi is not aware of.

There is no formal report about the disappearance of any fish species from Lake Malawi due to exploitation for ornamental fish trade. However, some information exists on one Malawi cichlids forum website about the disappearance of *Chindongo saulosi; Aulonocara baenschi* Meyer & Riel, 1985; *Aulonocara* sp mamelela; *Melanochromis chipokae* Johnson, 1975; and *Pseudotropheus cyaneorhabdos* (Bowers & Stauffer, 1997) in the natural environment due to fishing for the aquarium trade and *Aulonocara kandeense* Tawil & Allgayer, 1987; *Copadichromis* sp virginalis gold; and *Copadichromis pleurostigma* (Trewavas, 1935) due to the food fishery (Malawicichlides.fr., 2018).

2.4.7 Conclusions and recommendation for management

The following conclusions are made from this study:

- A high diversity of ornamental fish species was exported from Malawi between 1998 and 2017, including 257 described species and 279 undescribed (or perhaps described but unidentified) species.
- The number of species exported has increased over time.
- Excluding the years between 2006 and 2009, export volumes of ornamental fish from Malawi were quite stable.
- Ornamental fish are collected from various localities of Malawian side of Lake Malawi with some localities experiencing more fish collection than others.
- A majority (208) of exported ornamental fish species are classified as of least concern, but the exports also included 23 threatened species and 21 near threatened species based on IUCN (2019) red list.
- There was high similarity of the numbers of species exported in different years according to their conservation status.

Some of the findings of this chapter are further discussed in Chapter 3 which compares fish assemblage between protected and non-protected areas of Lake Malawi in order to determine if protection is positively affecting the fish assemblage structure; chapter 4 which investigates reproductive traits of selected ornamental fish species in Lake Malawi; and Chapter 5 which incorporates findings of different chapters of this thesis to assess the risk of the exported ornamental fish species to exploitation by the ornamental fishery.

The following recommendations are made based on findings of this chapter:

- There is need for the Department of Fisheries to develop an electronic data base of fish exports returns submitted by exporters and regularly analyse the fish export data to track changes of species exported.

- There is need for investments in taxonomy and systematics of cichlid fishes of Lake Malawi to enhance formal description of the undescribed fish species.
- There is need to compile all currently used names of ornamental fish species of Lake Malawi (scientific names, common names and trade names) which can be used for the purposes of monitoring the exported species and enforcing fishery management regulations that will be developed.
- There is need to assess the impacts of restocking overexploited ornamental fish species in Lake Malawi.
- There is need for introducing management measures for conservation of threatened ornamental fish species of Lake Malawi.
- Rotational harvesting of ornamental fish should be promoted in small rocky areas which cannot sustain continuous exploitation of the fish.
- Monitoring populations of ornamental fish should be conducted in heavily fished rocky reefs such as: Chilumba Area, Nkhata Bay, Likoma and Chizumulu Islands, Mbenji Island, Chindunga Rocks and Mozambique Border.
- There is need to strengthen the collaboration between the Department of Fisheries and all other fishery stakeholders including the Stuart Grant Cichlid Conservation Fund in management of the ornamental fishing industry.

These recommendations have been integrated in the proposed framework for the Lake Malawi ornamental fisheries conservation plan presented in section 6.5 of Chapter 6 of this thesis.

Chapter 3 Status of populations of the exploited ornamental fish species of Lake Malawi

3.1 Introduction

Knowledge about the status of fish stocks and how they respond to exploitation is a prerequisite for development of policies for management of fisheries resources. Wood (2001) advocated the need to collect data about the biology, population dynamics, recruitment and conservation importance of the species involved in the ornamental fishery as a basis for understanding the impacts of the fishery on the exploited ornamental fish stocks and developing appropriate management strategies.

It has been suggested that collection of ornamental fish for the export trade could result in overexploitation of target fish species (Tlusty, 2002; Townsend, 2011; Raghavan *et al.,* 2013), particularly for fish with no pelagic dispersal of fertilized eggs (Dulvy *et al.*, 2004; Townsend, 2011) and endemic species either listed as threatened in the IUCN or with relatively small geographic ranges and high catchability (Dulvy *et al.*, 2004; Raghavan *et al.*, 2013). Such impacts have been demonstrated using underwater visual census of a few fish species including: anemone fishes in reefs of Cebu in the Central Visayas Region of the Phillipines (Shuman *et al*., 2005) and in reefs of two regions of the Great Barrier Reef Marine Park (Jones *et al.,* 2008); cardinalfish (*Pterapogon kauderni* Koumans, 1933) of the Banggai Archipelago (Kolm & Berglund, 2003); and coral reef aquarium fish species in Hawaii (Tissot & Hallacher, 2003; Tissot *et al.,* 2004).

Ornamental fish have been exported from Lake Malawi since the 1960s (Ribbink *et al.,* 1983), but there is limited knowledge about how the populations of targeted ornamental fishes have changed as a result of the trade. Ribbink *et al.* (1983) provided baseline information about the populations of the rock-dwelling cichlid fishes of Lake Malawi, locally known as *mbuna*. The information included distribution, colouration, preferred habitat characteristics, territoriality and feeding behaviour of 196 undescribed pecies of fish. Since most of the *mbuna* were not described, temporary names were assigned to "species". After Ribbink *et al.* (1983), numerous studies have been conducted on various aspects of *mbuna* such as evolution, systematics and taxonomy, genetics and ecology. Reinthal (1993) reasoned that the ornamental fish trade was likely to have insignificant effect on exploited *mbuna* of Lake Malawi. However, based on underwater observations of *mbuna* fish in various places around Lake Malawi, Konings (2016) reported decreasing population trends of some species targeted by the ornamental fish trade, such as *Chindongo saulosi* and *Aulonocara kandeense* (Tawil & Allgayer, 1987). IUCN (2019) has classified the conservation status of many *mbuna* fishes of Lake Malawi based in part on information provided by Konings (2016) and perhaps unpublished information about population trends of some fish species provided by Konings, who was responsible for the IUCN assessment of the status of *mbuna*. Unfortunately, it appears that the Department of Fisheries in Malawi does not obtain information about the status of exploited ornamental fishes, which seems to be only shared amongst ornamental fish hobbyists.

One option for assessing the possible impacts of the ornamental fish trade is to compare populations of fish in the protected area of the LMNP and open access, exploited areas by mostly focusing on the *mbuna* which includes 250 species of fish belonging to 13 genera listed in section 1.1.2 of Chapter 1 and are the most targeted for ornamental fish export trade. The objective of this chapter is to compare fish assemblages between protected and non-protected areas of Lake Malawi focusing on species composition and abundance in order to test the hypothesis that protected areas of LMNP have higher fish species composition and abundance than non-protected areas where the ornamental fishes are collected for export trade. Besides comparison of fish inside and outside protected areas, the other objective was to compare findings of the current study with the baseline study of Ribbink *et al*. (1983) in order to gain some insights about the changes of the fish population structure that had occurred over time. However, the latter objective was dropped because the current study used a different methodology from that of Ribbink *et al*. (1983) in order to abide to the health and safety regulations of the University of Hull as explained in section 3.2.2.

3.2 Methodology

3.2.1 Description of the study sites

The study was conducted on the Malawian side of Lake Malawi, which is in the southern part of Africa (see Figure 1-1 in Chapter 1). Initially eight rocky areas of which four (Thumbi West, Maleri, Chinyankhwazi and Chinyamwezi Islands) are inside LMNP while another four areas (Nkhata Bay, Mbenji Island, Chindunga Rocks and Chizumulu Island) are outside LMNP, were to be targeted for this study.

These areas had been sampled from the list of areas studied by Ribbink *et al*. (1983) which is summarized in Appendix 3.1 with an addition of Chindunga Rocks[6] to the sampling frame. Sampling of study areas was undertaken by sorting the sampling frame according to the protection status of the area and size of the rocky islands/reefs[7] and then randomly selecting two small rocky islands/reefs and two larger rocky islands/reefs within both the protected and unprotected areas of the sampling frame.

All the eight areas comprised of rocky shorelines with rocky habitats from the shallow waters up to 25 metres depth. However, as the depth increased there was an increase in patches of sandy areas between rock habitats.

Due to challenges faced in the field, only five of the targeted eight rocky areas were sampled to investigate the relative abundance and community structure of fish. The sampled areas included two rocky areas (Nkhata Bay and Mbenji Island) outside the protected area of LMNP and three rocky areas (Thumbi West, Chinyankhwazi and Chinyamwezi Islands) inside LMNP. Sampling was not conducted at Maleri Island inside LMNP because during two sampling attempts there were heavy winds and rough lake conditions which made sampling dangerous and impossible. At Chindunga Rocks the water was too turbid due to sediment plumes from the nearby Linthipe River which militated against the use of the underwater fish visual census technique described in section 3.2.2. At Chizumulu Island it was too risky to take a small fibre glass boat across a 50 km distance from Malawian side of Lake Malawi to this Island.

For each of the five rocky areas sampled, the number of sites sampled varied between one and three depending on the size and /or patchiness of the rocky areas. Nkhata Bay had three sampling sites i.e. small rocky reefs (Chindozwa, Chirundu and Mwafufu), the larger rocky islands Mbenji and Thumbi West had two sampling sites each while the small Chinyankhwazi and Chinyamwezi islands had one sampling site each – making a total of nine sampling sites (Figure 3-1).

Based on personal observation, these nine sites appeared to vary with respect to human disturbances, which have the potential to contribute to variation in the observed patterns of the ichthyofauna of these sites (Britton *et al*., 2017). Amongst the three sites in Nkhata Bay,

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[6] The area around Chindunga Rocks was added to the sampling frame because it was observed to be popular for artisanal fishers using handlines and open water seine nets as well as for collection of fish for ornamental export trade.

[7] These have been grouped into two categories including small rocky islands/ reefs of less than 40 m in longest dimension and large rocky islands/reefs of more than 500 metres in the longest dimesion.

Chirundu site is about 700 metres from the dockyard with potentially higher degree of human disturbance due to pollution at the dockyard than Mwafufu and Chindozwa which are about 5 km and 1.0 km respectively away from the same dockyard. Furthermore, all the three sites at Nkhata Bay are associated with some human settlement in the terrestrial catchment areas and some subsistence fishing using handlines and gillnets. The two sites at Mbenji Island are associated with seasonal human settlements at the island during the traditional fishing season[8] (between April and November) and there is high deforestation in the terrestrial area and high potential for local pollution of water along the shoreline and subsistence overploitatioin of shallow water fish species. The sites at Thumbi West Island have well conserved terrestrial area of the island within the LMNP (and it is close to LMNP offices), with some tourism activities taking place along its rocky shores and sandy beaches, which are controlled and monitored by the LMNP management. Chinyankwazi and Chinyamwezi are small rocky islands of LMNP which are frequently used by artisanal fishers as temporary refugee areas during rough lake conditions or for resting, with the high potential for local pollution of the shallow water areas around these sites. In addition, Chinyankwazi and Chinyamwezi islands are far from the LMNP offices and are rarely patrolled (less than once in three months) by the Law enforcement team of the LMNP (Mr Chinguwo, Research Officer at LMNP, Personal communication).

One common feature of the nine study sites is that none of them had agricultural activities taking place in their terrestrial catchment areas with chemical inputs that could affect the quality of the water in such such sites.

[8] The Mbenji Island Fishery is the only fishery in Malawi which has been managed by traditional leaders since 1950s. The fishery is closed for fishing between December and March to allow the stocks to recover, during which period no fisher is allowed to stay at the island.

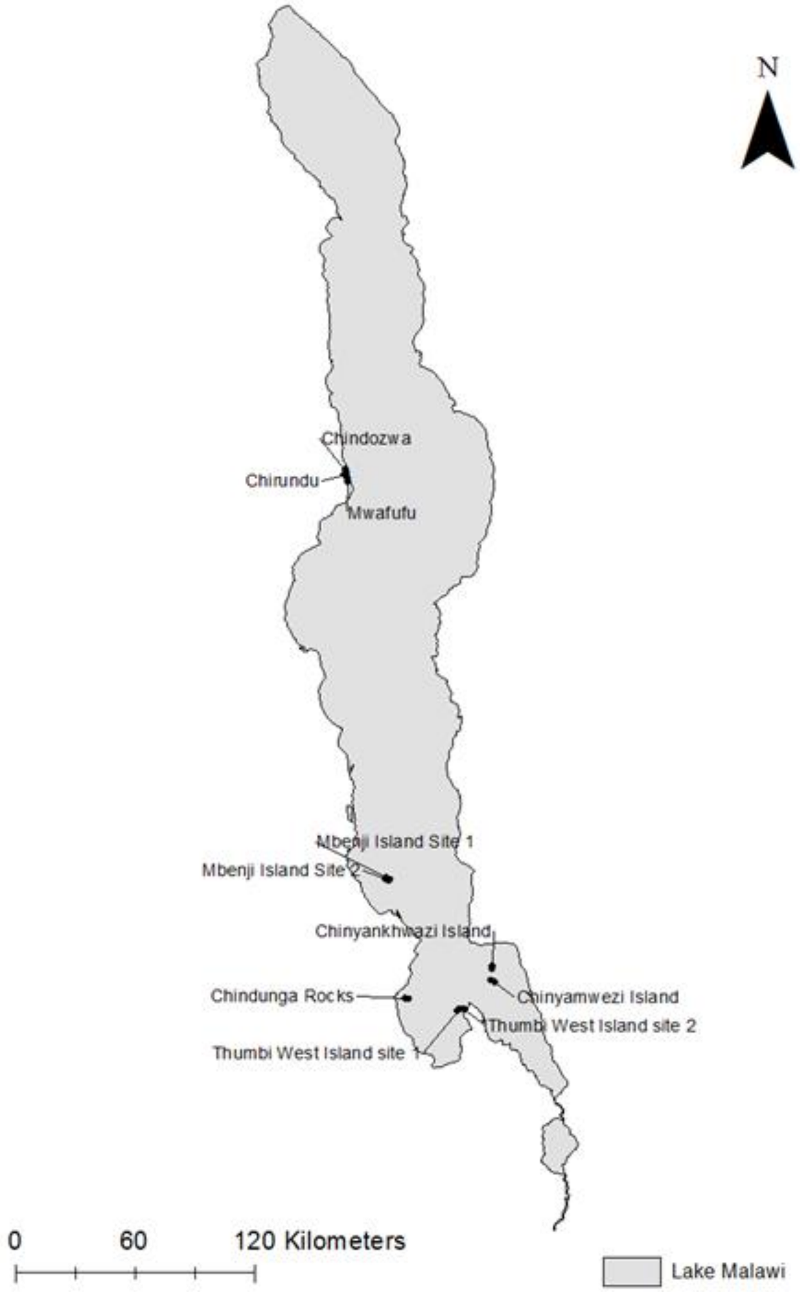

Figure 3-1. Sites sampled for the study of impacts of the ornamental fish export trade on exploited populations of ornamental fish in Lake Malawi

3.2.2 Underwater visual census of fish

Underwater visual census of fish population was undertaken at the study sites described in section 3.2.1 during a three months period between September and November 2017. The initial plan was to employ SCUBA diver based line transect method which has been commonly used for estimating the relative abundance of both Lake Malawi mbuna (Ribbink *et al.,* 1983; Genner *et al.,* 2004; 2006) and coral reef fishes (Tissot *et al.,* 2004). However, this method could not be employed in this study because it was against the health and safety regulations of the University of Hull which required the dive research team to be accompanied by a SCUBA dive master, a qualification which the research team did not have (only had open water diving qualifications). Use of towed drop-down camera technique described by Hitchin *et al*. (2015), as an alternative for SCUBA diver based line transect did not work because of the rocky terrain which made it impossible for a camera to uniformly focus on fish along the entire transect. The other transect type which has been used for estimating Lake Malawi *mbuna* relative abundance is the point transect method (Ribbink *et al.,* 1983; Trendall, 1988). This method involves a stationery diver observing fish within a given radius depending on the visibility of the water, which was adapted from the study of birds (MacArthur, 1964 cited by Ribbink *et al.,* 1983). Both the line transects, and point transects methods provide estimates of fish relative abundance as the number of fish per unit area or per transect of known area.

The current study adopted the point transect method using the underwater camera to capture video footages of the fish instead of the SCUBA diver observations. The camera based fish population census method have been commonly used and have the following advantages over the SCUBA diver based observations: removal of the influence of the diver/observer on the observed fish population, the underwater video footages can be kept and subsequently analysed, the raw data can be kept and evaluated facilitating repeatbility and reproducibility of the results (Cruz *et al*., 2008; Widmer *et al*., 2019). Camera based data collection is also considered more efficient, accurate and appropriate for long term monitoring programmes when compared with SCUBA diver-based surveys of fish populations. However, the effectiveness of camera based underwater fish surveys is dependent on water visibility (Hitchin *et al*., 2015; Widmer *et al*., 2019).

At each site, a drop-down video camera - Sea Viewer underwater video systems (Figure 3-2), was used to capture point transect video footages of fish at five targeted depth categories (5 m, 10 m, 15 m, 20 m and 25 m). This is within the depth range that Ribbink *et al.* (1983) reported most *mbuna* to occur. At each depth, video footages were replicated at three random points within a strip of 4 m by 25 m. This was a modification of the widely used SCUBA diver based transect census method (Ribbink *et al.,* 1983; Tissot *et al.,* 2004; Genner *et al.,* 2004; 2006), which would not work in this study as already explained in the last paragraph.

Figure 3-2. Drop-down video camera used for capturing point transect video footages

Fish sampling operations were undertaken from a fibre glass boat powered by a 50 hp outboard engine (Figure 3-3). A hand-held depth finder was used for locating the target depth at each sampling point. The drop-down video camera was connected to a laptop (Panasonic Toughbook), which enabled the video footage being captured to be viewed on a laptop screen. The camera and laptop were powered by a 12-volt car battery with a camera directly connected to the battery power while the laptop was connected via an inverter.

Figure 3-3. A fibre glass boat that was used for conducting research in Malawi

Using a cable that connected the camera to the rest of the Sea Viewer underwater video systems, the camera was slowly lowered until fish at the target depth were clearly visible. Before recording the video, a period of one minute was allowed to enable fish to settle from disturbance by the camera. These fish were observed to settle quickly within 1 mninute after lowering the camera to a target depth perhaps because the camera did not significantly disturb the water due to its small size. Normally the same fish would take between 3 minutes (Ribbink *et al*., 1983) and 5 minutes (Genner *et al*., 2004) to settle after being disturbed by SCUBA divers when setting underwater pole and rope transects. To ensure that the fish were continuously within the camera focus range, the position of the camera was periodically adjusted by slightly pulling or slackening the cable whenever the camera position shifted upwards or downwards due to wave action. Movement of the cable also made it possible to change direction of the camera to ensure the entire circumference of the point transect was captured in the video footage. This entire circumference of the area covered by the video footage was considered as the point transect in the current study. The average duration of the video footage for each point transect was 1.5 min with a range of 1.25 to 2.1 min. This was longer than the planned duration of one minute because of extra time associated with adjustments of the camera position. Video footages of longer than 2 min duration were avoided to minimize drifting of the boat away from the point transect position due to wave/wind action. Ideally 135 point transects were aimed to be captured from the 9 sampling sites (9 sampling sites x 5 depths per site x 3 point transect points at depth) but only a total of 119 point transect video footages was captured from the sampled sites (Table 3-1). The video footages could not be undertaken at some points for two reasons: The first reason was the problem of high wave action for some points particularly in the exposed shallow water (which was experienced at Thumbi West Island Site 1 at 5 m depth and Thumbi West Island Site 2 at 5 m and 10 m depths). The second reason was the danger of the camera getting stuck between rocks, which was possible at: Chinyankhwazi Island at 20 and 25 m depths, Thumbi West Island Site 1 at 25 m depth and Thumbi West Island Site 2 at 20 m depths. Each captured video was saved as a separate file while ensuring that sampled site name and depth were correctly recorded.

Table 3-1. Number of underwater video point transects taken by depth and site. Sites in grey shading are inside the LMNP while the rest are outside the LMNP

Name of Transect site	Number of Point transects captured by depth (m)					Site Totals
	5 m	10 m	15 m	20 m	25 m	
Chinyamwezi	3	3	3	3	3	15
Chinyankhwazi	3	3	3	1	0	10
Mbenji site 1	3	3	3	3	3	15
Mbenji site 2	3	3	3	3	3	15
Thumbi West 1	2	3	3	3	2	13
Thumbi West 2	0	3	3	2	3	11
Chindozwa	3	3	2	3	3	14
Chirundu	3	3	3	3	2	14
Mwafufu	2	3	3	2	2	12
Totals	22	27	26	23	21	119

3.2.3 Initial processing of video footage data

The video footages were viewed on a computer screen using VCL media player at 10% to 40% of the normal speed to decode the information on fish abundance. The VCL media player speed was adjusted according to the density of the fish in the footage, decreasing the speed as the fish density increased. The videos were alternately paused and played and often rewound and replayed to ensure that all the fish within the visibility radius of 3 metres from the center of the point transect video footage (see snapshot of part of the video footage in Figure 3-4) were observed, identified and counted. In order to avoid double counting of the same fish individuals, the maximum number of indivuals of each fish species per video frame was counted and recorded. Where there was enough evidence (such as size and male nuptial colour difference) that more individuals of the same fish species were being observed, the numbers of such individuals were included in the point transect counts of the species.

Figure 3-4. Snapshot of good images of fish with visible colour markings for species identification

Fish were identified to either species or genus level mainly by using colour pictures of Konings (2016) and Ribbink *et al.* (1983). Temporary names of undescribed fish species used by Konings (2016) were adopted. Other traits that were used for differentiating species with similar colour patterns included conspicuous morphological features, e.g. slope of the vomer (Konings, 2016), feeding behaviour with respect to the angle at which the fish fed from the substrate (Ribbink *et al.,* 1983; Konings, 2016), and whether the fish was elongated or not. For a few situations fish could not be identified to both genus and species level due to poor visibility of the water column and/or the video footage capturing insufficient detail for identification of the fish (see Figure 3-5). Nonetheless some outstanding fish background colour patterns (vertical and horizontal bars) and shape unique for groups of fishes were still visible and used for grouping the unidentified fish as either *mbuna* or *non-mbuna.* Such grouping could potentially result in underreporting species richness as these groups do not make taxonomic sense and embraced many fish species.

Figure 3-5. Snapshot of bad image of fish which could not be identified to species and genus level

The information collected was entered into a Microsoft Excel spreadsheet with the following details: name of rocky area, sampling site, point transect identification number, counts of fish by species, the sampling design factors (protection status, depth and size of the rocky area) and observable environmental factors, including bottom substrate characteristics and visibility of the water column. The following categories of environmental factors were recorded based on the point transect video footage analysis:

- Five levels of substrate type:
    - Mostly sandy (MS) - more than 75% was sandy patches and the rest were either rocks, stones or snail shells,
    - Mostly rocky (MR) - more than 75% was rocky substratum and the rest comprised isolated patches of sand,
    - Equal portions of sandy and rocky substrate (SR),
    - Only sandy substrate (S),
    - Only rocky substrate (R).
- Three levels of water visibility:
    - Good – fish clearly seen and identifiable to species level from a distance more than 3 m radius,

- Fair visibility – Fish could be seen from a distance of up to 3 m but some colour markings were not clear enough for species identification,
- Poor – fish seen up to 2 m but most colour markings for species identification not conspicuous.

3.2.4 Analysis of data

Comparisons of numerical abundance of fish: Total counts of individual fish species within 3 metre radius of the replicate point transect at a given depth category for each sampling site, were computed from the dataset using Pivot Table reports in Microsoft Excel. The computed data were saved as a separate spreadsheet with details of factors of interest - sampling depth, site of transect, protection status of the site, size of the rocky reef/island, bottom substrate type and observed visibility of the water. Further univariate analysis of fish transect counts data was undertaken in R software (R Core Team, 2018). A generalized linear mixed effect model (GLMM) of the family Poisson from the lme4 R package (Bates *et al.,* 2015) was fitted to fish transect count data to compare the overall relative abundance of fish in protected and non-protected areas. The factors included in the GLMM were "fish transect counts" as dependent variable and "protection status", "depth" and "size" of rocky area as main factors with "depth" nested within "site" as random factors scripted in R software as:

*glmer0 <- glmer (Fish count ~ protection * depth + size + (1 | site/depth), family='poisson', data=dataframe).*

Quality of GLMM fit to the data was examined by looking at normal Q-Q plot, histogram of residuals and a plot of residuals against fitted values. Subsequent analyses and/or adjustments of the GLMM included estimation of overdispersion factor, stepwise reduction and quasi likelihood analysis of the GLMM following the procedure suggested by Bolker *et al.* (2018) as presented in Appendix 3.2b. It was not possible to test a GLMM with more factors using the data collected in this study because the data were unbalanced for the observed factors and the model required more data points to converge or avoid singular model fit. However, all factors were included during initial visualization of the patterns of fish transect counts.

Comparisons of species diversity:

Using data summarized in Excel spreadsheet described under the previous subheading "Comparisons of numerical abundance of fish", counts of fish taxa per sampling site were computed using Excel pivot table reports (after aggregating all point transects per site) based on protection status of the site and fish identification level. This analysis was aimed at comparing the number of fish taxa occurring in protected and unprotected sites. Counts of fish taxa were also computed based on the number of sampling sites in which the taxa occurred by fish taxonomic level of identification in order to gain insights about the general distribution of the taxa within the sites sampled inside and outside the protected areas.

The spreadsheet of fish transects counts described under the previous subheading "Comparisons of numerical abundance of fish" was also exported to PRIMER v6 (Clarke & Gorley, 2006) and PERMANOVA + for PRIMER Software (Anderson *et al*., 2008). A summary of fish diversity information was computed using the Analyse, DIVERSE option in PRIMER and the outputs were exported to a Microsoft Excel worksheet and saved. The following formula were used in PRIMER software (Clarke & Gorley, 2006) to compute the species diversity indices:

Species richness: S = number of species observed per point transect

Species richness (Margalef): d = (S-1)/Ln(N)

Where: *d* =Margalef Index, *S* = number of species, *N* = number of individual fish in the sample.

Shannon Index: H' = ∑(Pi * Ln(Pi));

Where *H'* = the Shannon-Weiner index, *Pi* = the proportion of individuals belonging to species *i*

Simpsons Index: 1 - λ = 1 – ∑(Ni(Ni-1)/N*(N-1))*;

Where λ is a measure of dominance that takes the value between 0 and 1, *Ni* = number of individuals belonging to species *i, N* = total number of all fish in the sample.

Indices relating to species richness (first two) and a combination of species richness and evenness (Shannon and Simpsons Indices) were selected as they are complementary (Arzamani *et al*., 2018). Using more than one diversity index was necessary since different species diversity indices can lead to different conclusions (Heino *et al*., 2007; Saether *et al*., 2013).

These computed species diversity indices were further compared between sampling design factors using statistical packages associated with R Software (R Core Team, 2018). The analysis excluded unidentified fish classified as either *mbuna* or *non-mbuna* because the number of distinct species could not be determined for these fish groups due to either poor visibility or the video footage capturing insufficient features for identification of fish to species and genus level. The following species diversity indices were calculated:

Shapiro test of normality showed that the distribution of Margalef Species richness index was not significantly different from normal ($p>0.05$) and Bartlett Test showed insignificant difference of homogeneity of variance of Margalef index for both “Protection Status” ($p>0.05$) and “Depth” ($p>0.05$) factors’ levels. Two-way ANOVA was therefore employed for comparisons of Margalef Species diversity index between the factors of “protection status” and “depth”. Type 1 sum squares was used as the design was not balanced.

On the other hand, Shapiro test of normality was significantly different from normal in relation to Species richness, *S,* ($p<0.05$), Shannon Index ($p<0.001$) and Simpsons index ($p<0.001$). Tests of homogeneity of variance using Bartlett Test showed insignificant differences of variance of both species richness and Shannon Indices with respect to levels of both factors “Protection Status” and “Depth” ($p>0.05$), but significant difference of variance of Simpsons index in relation to both “Protection status” ($p<0.01$) and “Depth” ($p<0.001$). Mann-Whitney U test was therefore used to compare the values of Species richness (S), Shannon Index and Simpsons Index between Protected and unprotected sites while Kruskal Wallis test was used for comparing the same indices between different depth categories. It should be noted that species richness, *S*, was compared for all transect points while Shannon and Simpsons indices were compared only for point transects that had more than one species. Mann-Whitney U test and Kruskal Wallis test were used to analyse the significance of the effects of protected areas and depth, respectively. These statistical tests were chosen because the non-parametric equivalent of two-way ANOVA (Friedman test, which is applicable to repeated measures designs or matched subjects designs) requires balanced data (Helsel & Hirsch, 2002), and this was not the case for the data collected in the current study. This kind of approach has the shortfall of not being able to determine the effect of interaction between two factors.

Comparison of similarity based on species composition and abundance: To compare fish species composition and abundance based on the hypothesised factors, the video footage data were summarized in Microsoft Excel in relation to two scenarios. The first scenario involved computation of total number of fish observed per species per point transect at a given depth category for each sampling site. The second scenario involved computation of total number of fish per species per sampling site after aggregating together all point transects for different depths at the sampling site. The study design factors were summarized alongside the information for each scenario. Summary data for each scenario were saved as separate worksheets which were imported into PRIMER for further analysis.

In PRIMER software, the data were square root transformed followed by computation of the Bray Curtis Resemblance Matrix and clustering of samples using group average as the linkage method and similarity profile (SIMPROF) permutation test to determine statistically significant clusters (Clarke & Gorley, 2006).

PERMANOVA designs were used for testing the hypothesis of differences in the resemblance patterns of fish assemblage based on the study design factors “Protection Status” and “Size” of the rocky reef/island. PERMDIST tests were also conducted to clarify nature of multivariate effects for the observed resemblance patterns and account for wide dispersions of the resemblance patterns as suggested by Anderson *et al.* (2008). PERMANOVA main tests were run using Type 111 (Partial) sums of squares by fitting the factor “Protection status” first, permutation of residuals under a reduced model, fixed effects sum to zero (i.e. restricted model), with 999 permutations. Type 111 sums of squares were used because the design was unbalanced. According to Anderson *et al.* (2008) type 111 sum squares are more conservative than the other two options (Type 1 and Type 11 sums squares) available in the PERMANOVA dialogue box.

3.3 Results

3.3.1 Fish numerical abundance

Initial inspection of the data showed various patterns of ornamental fish relative abundance (expressed as fish counts per transect) with respect to sampling design factors (Figure 3-6). Amongst the sampled sites, the median values of relative fish abundance ranged from 10 fish per transect for Chirundu, which is outside protected area, to 109.5 fish per transect for Thumbi West 1, which is inside protected area of LMNP, and closest to the administration office of the protected areas of LMNP amongst all the sampled sites. Protected areas had higher median fish abundance (80 fish per transect) than non-protected areas (56.5 fish per transect). Smaller rocky reefs had lower median values of fish abundance (46 fish per transect) than larger sized rocky reefs (93 fish per transect). Fish relative abundance increased with depth from 5 m with median fish relative abundance of 43.5 fish per transect to 15 m with median fish relative abundance of 94 fish per transect, after which the fish abundance decreased with further increase in depth to a value of 43 fish per transect at 25 m depth. Fish transect counts increased as water visibility increased, with median values of 37.5 fish per transect in water with poor visibility, 80 fish per transect in water of medium visibility and 109 fish per transect in water with good visibility. Fish abundance increased with an increase of the rocky substrate area with median fish counts ranging from 11.5 fish per transect in sandy areas to 87 fish per transect in rocky areas. Intermediate substrate types also showed intermediate fish abundance.

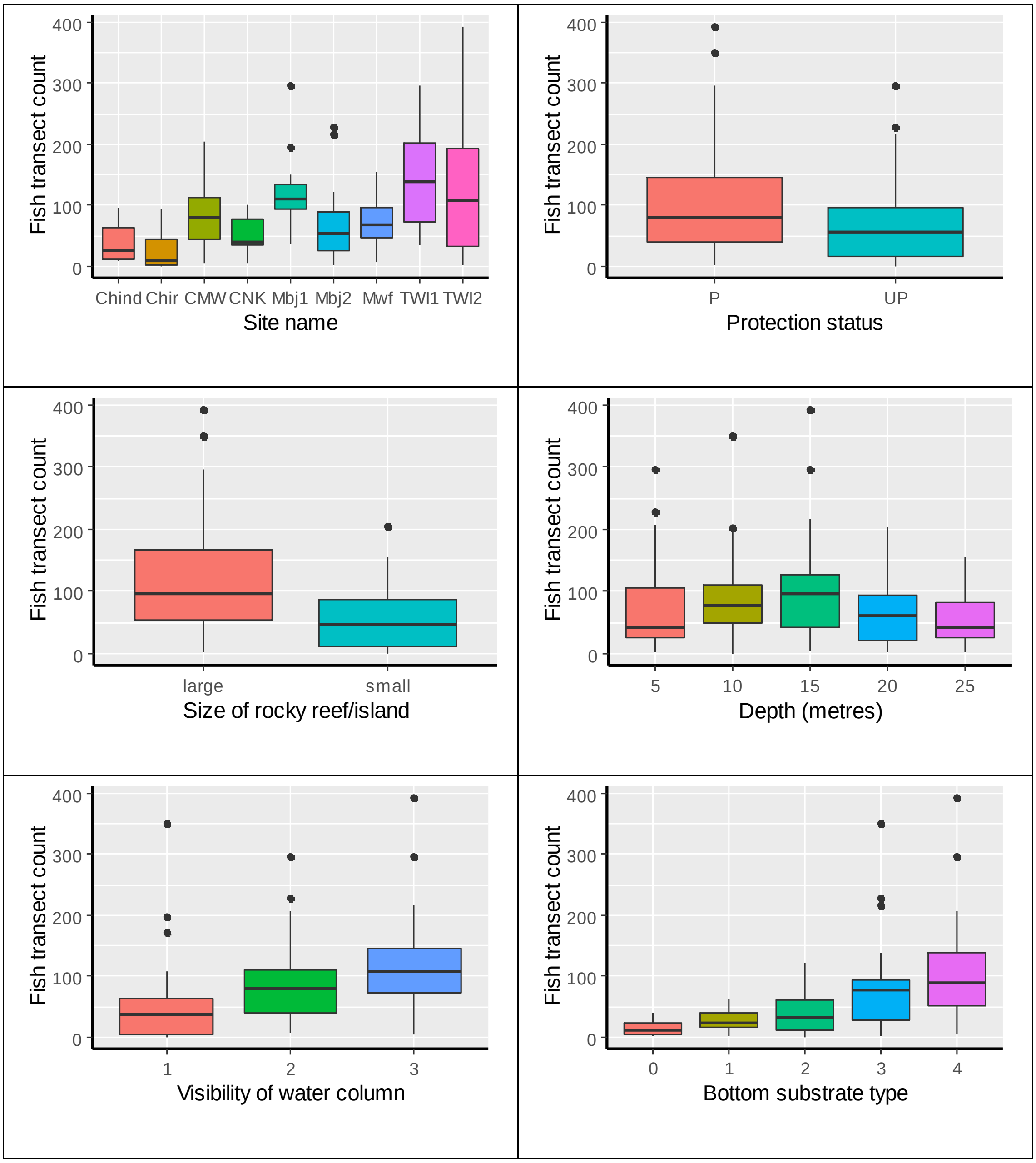

Figure 3-6. Box and whisker plots of fish counts relating to: Sampling sites (Chind=Chindozwa, CMW=Chinyamwezi, CNK=Chinyankhwazi, Chir = Chirundu, Mwf=Mwafufu, Mbj1 = Mbenji1, Mbj2 = Mbenji2, TWI1 = Thumbi West 1, TWI2 = Thumbi West 2) and levels of the factors: Protection status (the protected sites include CMW, CNK, TWI1 and TWI2 while unprotected sites include Chind, Chir, Mwf, Mbj1 and Mbj2), Depth, Rocky reef/island size, Visibility of water column (1 =poor, 2= fair, 3 = good), and Bottom substrate type (0 = sandy, 1 = mostly sandy, 2 =sandy/rocky, 3 = mostly rocky, 4 = rocky).

No significant effect of interaction between "protection status" and "depth" on fish transect counts ($p>0.05$) was found by the GLMM. There was no significant effect of "Protection status" on fish transect counts ($p>0.05$) although protected areas had higher fish transect counts than unprotected areas (Figure 3-7). Smaller sized rocky sites had significantly lower fish transect counts ($p<0.05$) than larger sized rocky areas (Figure 3-8). The estimated standard deviation of fish counts due to the nested random factor "depth:site" was 0.6577, which was close to the magnitude of the highest fixed factor effect of -0.7157 for rocky area size suggesting the wide variation of fish transect counts by both depth and site.

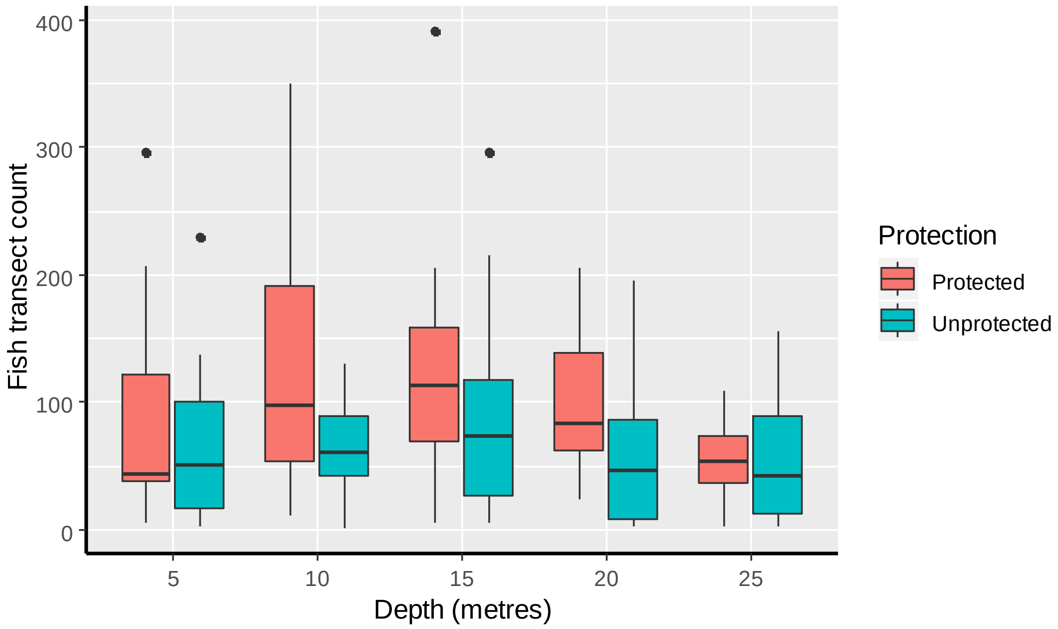

Figure 3-7. Box and whisker plot of fish point transect counts at five different depths of protected and non-protected areas sampled in Lake Malawi

Stepwise simplification of the GLMM by first dropping, the non-significant interaction between “Protection status” and “depth” (minimum p=0.5475), followed by dropping, non-significant depth effect (minimum p=0.2229) and protection effect (p=0.0667) resulted in only “rocky reef/island size” being the significant factor (p<0.05) affecting fish transect counts (Figure 3-8). Surprisingly, for the minimum adequate model, the random effect “Depth:Size” had a standard deviation value of 0.7198, which was of higher magnitude than that of the “rocky reef/island size” effect of -0.6827 suggesting the wide variation of fish transect counts by depths and rocky area sizes.

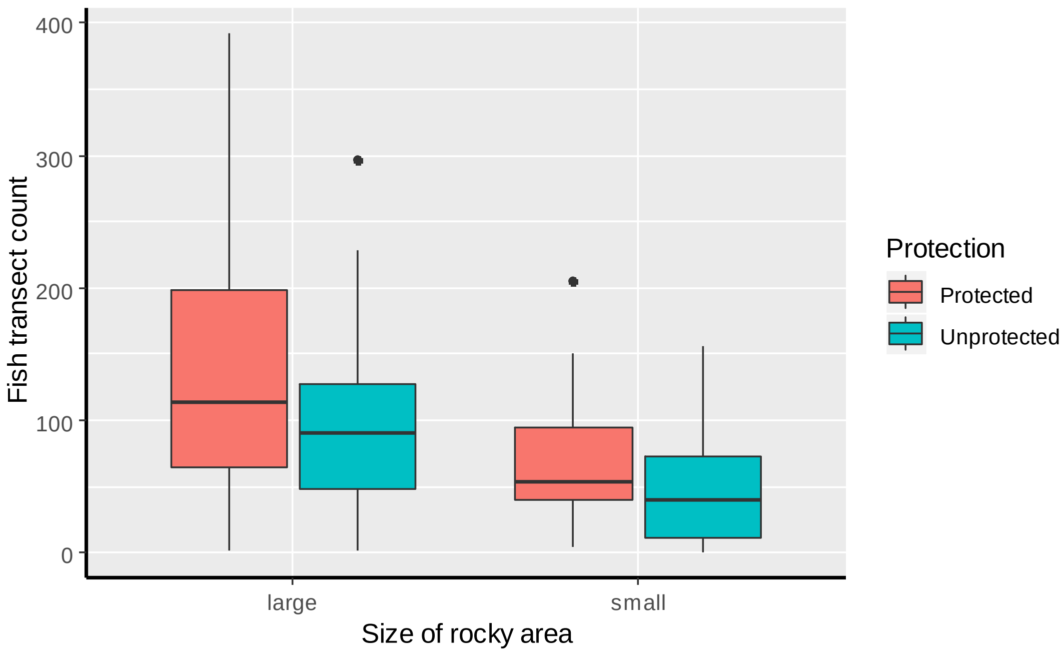

Figure 3-8. Box and whisker plot of fish point transect counts by size of the rocky area and protection status of the sampling locality.

Normal Q-Q plots and histograms of residuals of GLMM suggested a good fit of the GLMM to the data while a plot of residuals against fitted values showed evidence of heteroscedasticity. This prompted an estimation of an overdispersion factor from the sum of squared Pearson residuals and residuals degrees of freedom by using the overdispersion function suggested by Bolker *et al.* (2018) (see Appendix 3.2a). The GLMM had a highly significant ($P<0.0001$) overdispersion factor of 21.8. Quasi likelihood analysis option for the GLMM fit was explored by adjusting the GLMM coefficient table by multiplying the standard error by the square root of the dispersion factor and recomputing Z- and p- values using the function suggested by Bolker *et al.* (2018) (see Appendix 3.2b). The final (minimal) GLMM, after stepwise reduction and adjustment for overdispersion, was the null model scripted in R software as:

Glmer <- glmer(abundance ~ (1 | site/depth), family='poisson', data=dataframe)

This null minimal model only provides a picture about the overall mean of fish abundance for the randomly selected sites without any information about the effects of the design factors.

3.3.2 Species diversity

Fish captured by video point transects belonged to 88 taxa (Appendix 3.3). Some fish could not be identified to either species or genus level due to insufficient detail being captured in the video footage and because of poor water visibility. Of the 88 fish taxa captured in the point transects, 20 occurred only in protected sites, 28 occurred only in unprotected sites, and 40 occurred in both protected and unproteted sites (Figure 3-9). Amongst the taxa that occurred only in protected sites, 16 were described species, 2 were undescribed species and two were identified to genus level. For the taxa occurring only in the unprotected sites, 14 were described species, 8 were underscribed species and 6 were identified to genus level. Fish taxa that occurred in both protected and unprotected sites comprised of 23 described species, 3 undescribed species and 14 identified to genus level (Figure 3-9).

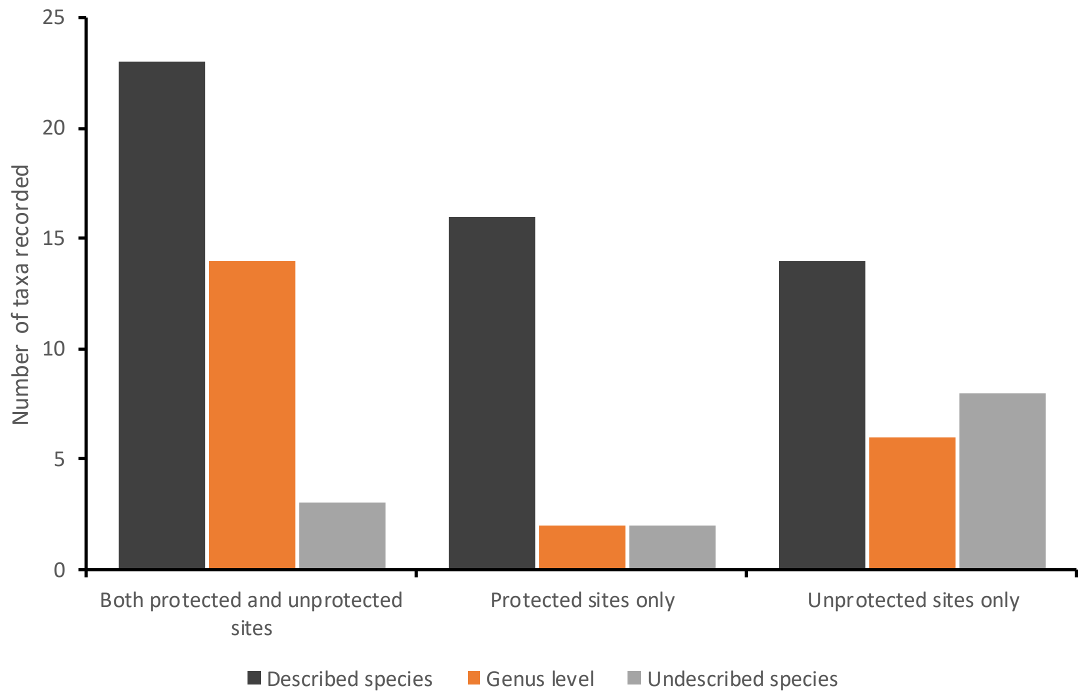

Figure 3-9. The counts of fish taxa recorded by protection status of the sampled sites and taxa taxonomic status/level

Further analysis of the data of fish species that occurred per site after aggregating point transect data for each of the 9 sampling sites (shown in Table 3-1), revealed that a majority of fish taxa occurred at 1 to 4 sampling. The taxa occurring at only one site were the most common (33) followed by the taxa occurring at two sampling sites (15) and the taxa occurring at four sampling sites (10). Only 22 of the 88 taxa captured in the video point transects occurred in five to nine sites and these species were either those identified to genus level or described *non-mbuna* species (Figure 3-10, Appendix 3.3). Although 40 taxa occurred in both protected and unproteted sites, the number of protected and unprotected sites in which these taxa occurred were relatively few.

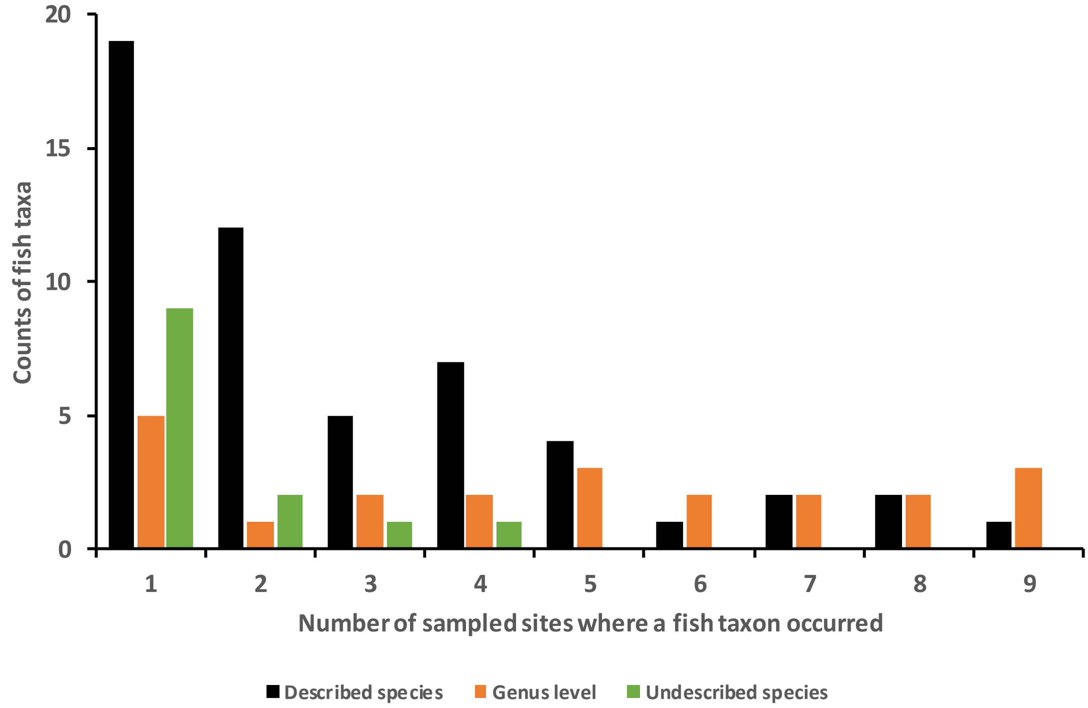

Figure 3-10. Counts of fish taxa versus number of sites in which the taxa occurred by taxa identification level.

Species counts per transect appeared to vary according to sampling sites, rocky area size, water visibility and substrate type (Figure 3-11) in a similar pattern to total fish transect count (Figure 3-6).

The median of species counts per transect was lowest for Chirundu and highest for Thumbi West 1 (Figure 3-11 top left). Sites in the protected area had higher median species count per transect than those in non-protected areas (Figure 3-11 top right). Large rocky reefs/islands had higher median species count per transect than small rocky areas (Figure 3-11 middle left). The median of species count per transect increased from 5 m to 15 m depth after which it declined with depth to 25 m (Figure 3-11 middle right). As water visibility increased the median of species counts per transect also increased (Figure 3-11 bottom left). Species counts increased with an increase in the proportion of rocky areas in a transect. Transect sites in sandy areas had the lowest median number of fish species per transect while sites in rocky areas had the highest number of fish species per transect (Figure 3-11 bottom right).

Unfortunately, data on species count were unbalanced for different factor levels (with wide variation of data points amongst factors levels) making it difficult to use reliable statistical models to establish the effects of interactions and differences between factors on the observed species counts.

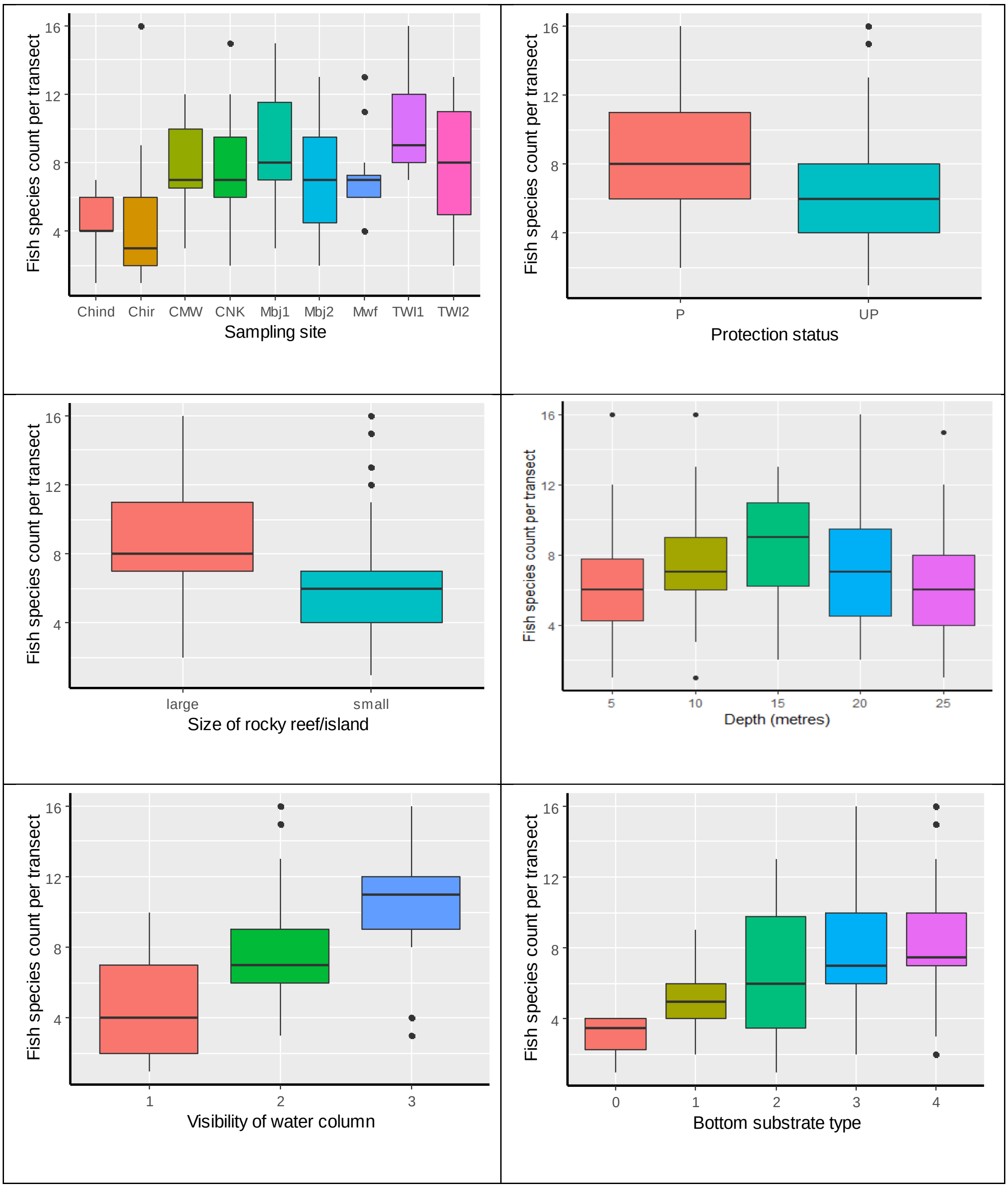

Figure 3-11. Box and whisker plots of species counts per transect in relation to: sampling Sites (Chind=Chindozwa, CMW=Chinyamwezi, CNK=Chinyankhwazi, Chir = Chirundu, Mwf=Mwafufu, Mbj1 = Mbenji1, Mbj2 = Mbenji2, TWI1 = Thumbi West 1, TWI2 = Thumbi West 2) and levels of the factors: Protection status {P=Protected which include (CMW, CNK, TWI1 and TWI2) and UP = Unprotected which include Chind, Chir, Mwf, Mbj1 and Mbj2)}, Depth (metres), Rocky area size, Visibility of water column (1 =poor, 2= fair, 3 = good), and Bottom substrate (0 = sandy, 1 = mostly sandy, 2 =sandy/rocky, 3 = mostly rocky, 4 = rocky). Note that each of the box and whisker plots shows fish transect counts with information for all other factor levels aggregated together.

Box and whisker plots of species diversity indices based on the factors “Protection status” and “depth” (the only two factors with sufficient data points for their levels) are presented in Figure 3-12. Species richness *S*, Margalef Index and Shannon Index showed similar patterns with protected areas showing higher values than unprotected areas at 20 m depth. Simpson's Index appeared to be relatively uniform with respect to both factors "Depth" and "Protection status".

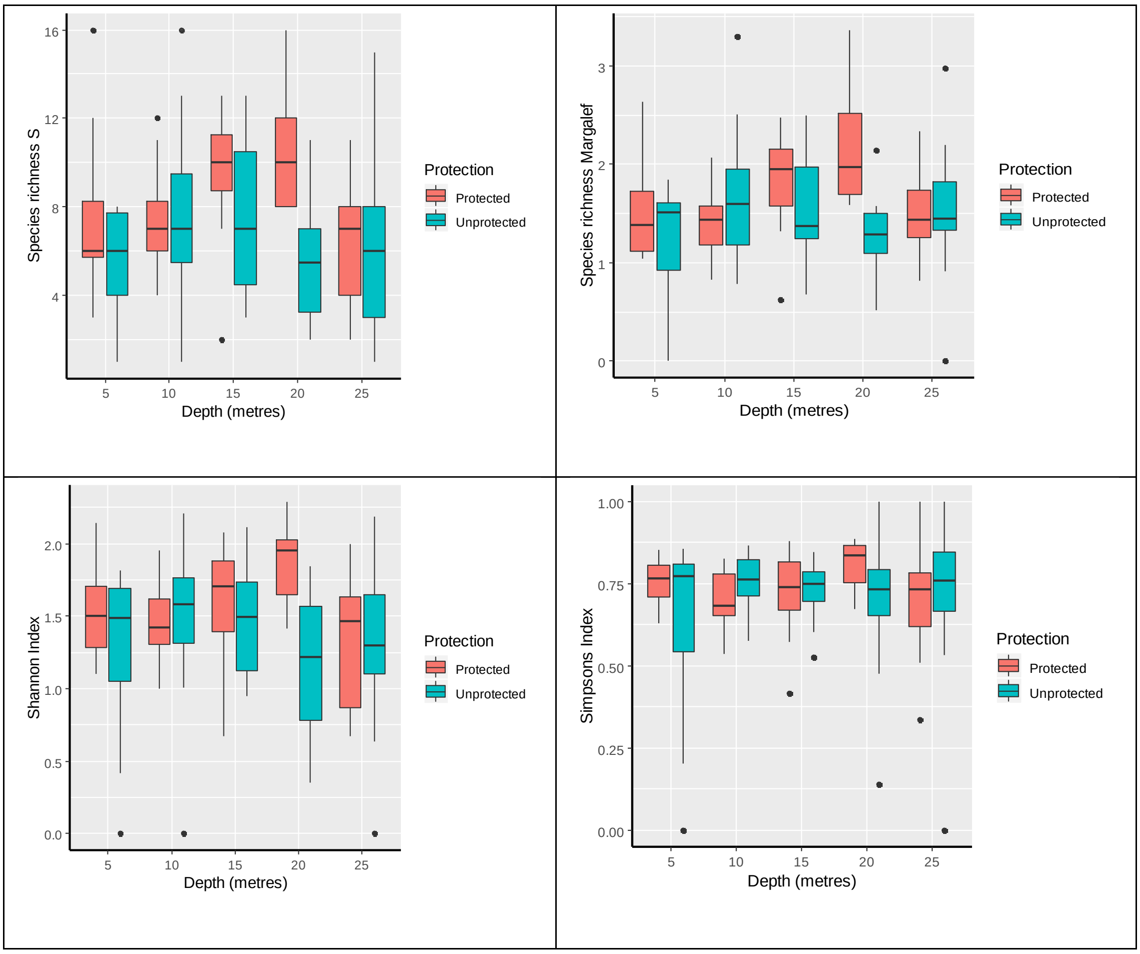

Figure 3-12. Box and whisker plots of rock dwelling fish species diversity indices (Species richness *S*, Margalef Index, Shannon Index, *H'* and Simpsons Index) based on point transects video footages taken at five depth categories inside and outside protected areas of Lake Malawi.

Two Way Analysis of Variance for Margalef Species Richness Index showed that the interaction between "Protection status" and "Depth" (Figure 3-12 top right) was significant (DF=4, F=3.185, p<0.05). There were significant differences in Margalef species richness between protected and unprotected sites (DF=1, F=5.67, p<0.05) with mean values of 1.73±0.550 in protected sites and 1.53±0.545 in unprotected sites. Depth had no significant effect on Margalef species richness Index (DF=4, F=1.013, p>0.05).

Mann-Whitney U test (Wilcox Sum rank test with continuity correction) showed significant differences in Species richness index, *S* (W = 2127.5, p<0.01), but non-significant differences in Shannon Index, *H'* (W = 1929.5, p>0.05) and Simpson's Diversity Index ($1- \lambda$) (W = 1664, p>0.05) between protected and unprotected areas. Kruskal Wallis tests showed that there was no significant effect of depth on Species richness (X^2 = 5.8767, DF=4, p>0.05), Shannon Index (X^2 = 1.9311, DF=4, p>0.05) and Simpson's Index (X^2 = 0.8596, DF=4, p>0.05).

3.3.3 Resemblance based on species composition and abundance

Scenario 1 – analysis based on point transect: Similarities of transect points based on Bray Curtis resemblance matrices of square root transformed species composition and abundance ranged from 0.99% to 82.84%. Cluster analysis and SIMPROF test in PRIMER based on Bray Curtis Resemblance Matrix of square root transformed data showed eight statistically significant clusters between the similarity levels of 0.99% (π=2.63, p = 0.001) and 20.73% (π=1.14, p = 0.002). The largest cluster (C) comprised 88 point transects, followed by cluster B with 15 point transects and cluster A with 9 points transects. One cluster had three transects while the other four clusters were single point transect clusters (Figure 3-13).

PERMANOVA test of the hypothesis for differences of the patterns of fish assemblage based on "Protection status" and "rocky reef/island size" showed significant effect of both factors "Size of rocky reefs/island" (p< 0.01) and "Protection Status" (p< 0.01) and the interaction between them (p<0.01).

Anderson *et al.* (2008) suggested that PERMDIST tests conducted alongside PERMANOVA tests can help to clarify the nature of multivariate effects for a particular resemblance measure, especially when wide dispersions of the resemblance measure are apparent. In the current study, testing of homogeneity using PERMDIST showed significant dispersion from the centroid for the factor "Protection status" (F=6.13, p<0.05) and non-significant dispersion with respect to the factor "Size of rocky reef/island" (F=0.05, p>0.05). According to Anderson *et al.* (2008, page 104 in Table 2.1), since both the outputs of PERMANOVA and PERMDIST are significant for the "Protection Status" factor, it can be inferred that dispersion effect influenced PERMANOVA multivariate results for the "Protection status". By contrast, the output of PERMANOVA was significant in relation to "Size of rocky reef/island", while the output of PERMDIST was not significant, indicating that "Size of rocky reef/island" significantly influenced the PERMANOVA results. Thus, the observed patterns of fish assemblage are related to "size of rocky reef/island" but not to "Protection status" of the site.

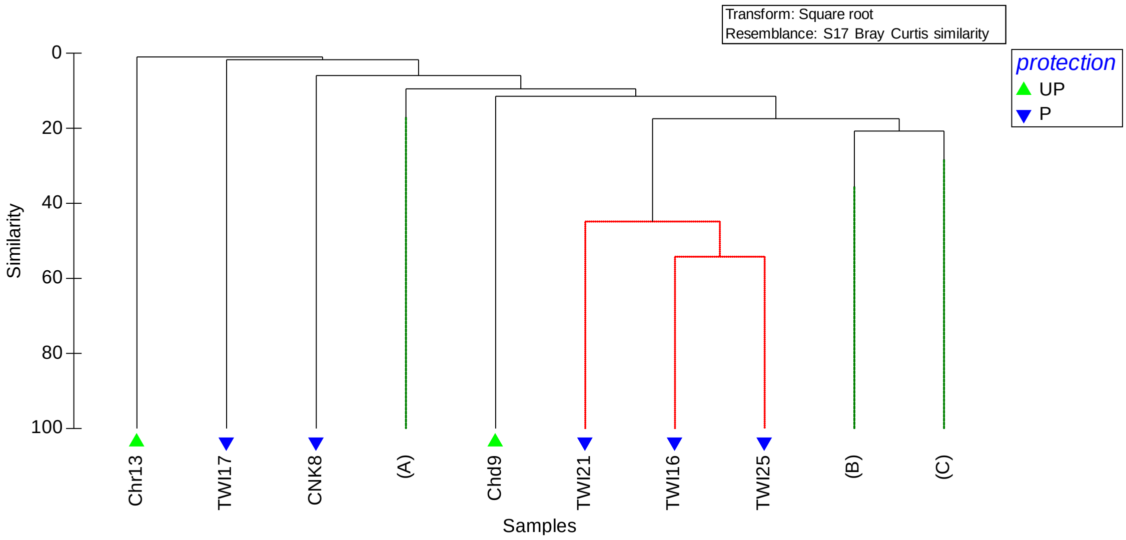

Figure 3-13. Dendrogram showing statistically significant clusters of point transects based on the Bray Curtis similarity of square root transformed number of fish per species per transect point. Sampling sites are classified according to their "Protection status" (Up = unprotected area, P = protected area). Cluster A comprises 9 point transects (Chd3, Mwf12, TWI18, TWI19, Mbj25, Mbj26, Mbj29, Mbj27 and Mbj28). Cluster B has 15 point transects (Chd8, Mwf1, Chd14, CMW3, CNK6, Chr10, Chr9, Chr3, Chr4, Chr14, Chr8, Chd5, Chd7, Chd4 and Chr1). Cluster C includes 88 point transects (Mwf8, Mwf9, TWI10, TWI13, TWI32, TWI33, CMW12, CMW13, CNK4, CNK5, Chd6, CMW6, Mwf11. Mwf5, CMW14, Mwf10, CMW4, Mwf3, Mwf4, CMW9, TWI23, Mbj22, Mbj8, Mbj14, Mbj20, Mbj21, Mbj23, Mbj24, Mbj30, TWI22, Mbj10, Mbj15, CMW7, TWI24, CMW10, CMW11, Mbj12, Mbj11, Mbj9, Mbj13, TWI12, TWI8, TWI11, TWI15, TWI9, TWI29, TWI30, Mwf13, TWI31, Chd15, Chd10, Chd12, Chr5, Chr11, Chr6, CNK10, CNK7, Mbj1, Mbj18, Mbj4, CMW5, Mbj2, CNK1, CNK9, Chd1, Chr12, CNK2, Mbj16, CMW8, Chr2, Chr7, Mbj19, Chd2, CMW1, Mbj3, Mwf7, CMW15, Mwf6, TWI27, TWI29b, Mbj17, Mbj6, TWI26, Mbj7, CMW2, Mbj5, Chd13, CNK3).

Scenario 2 – analysis based on data for all transects for a sampling site pooled together:

Similarity of species assemblage based on Bray Curtis resemblance after aggregating together the point transects for the sites ranged from 46.2% to 67.55%. Cluster analysis and SIMPROF test based on Bray Curtis resemblance matrix of square root transformed data indicated non-significant clusters even at the lowest similarity level of 46.2% (π=1.34, p > 0.05) (Figure 3-14).

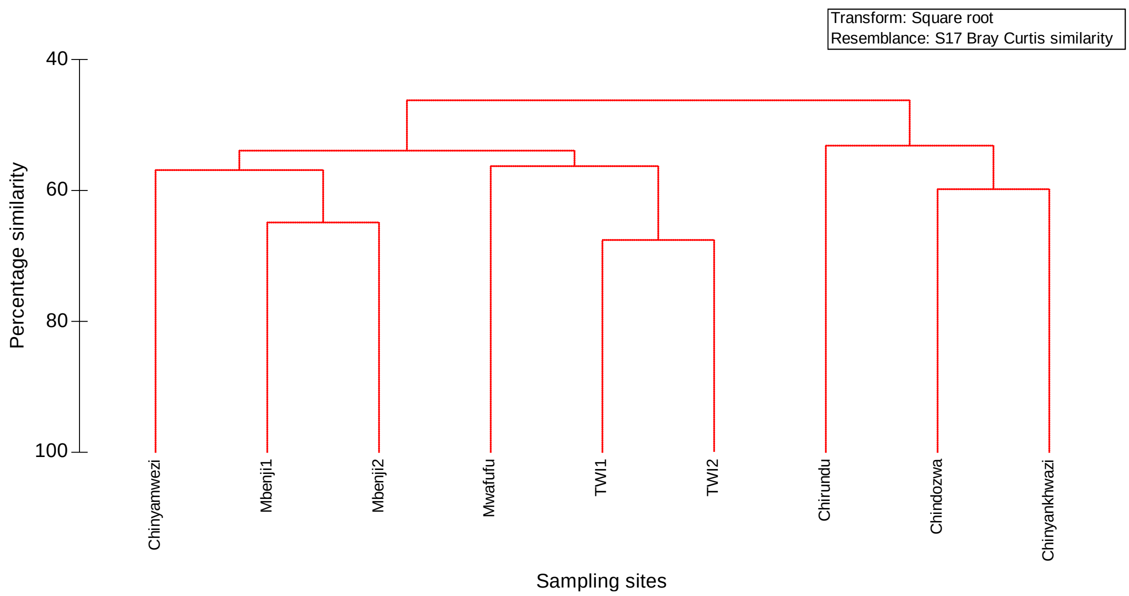

Figure 3-14. Dendrogram showing non-significant clusters of sampling sites based on Bray Curtis resemblance of square root transformed species composition and abundance data.

PERMANOVA tests for differences in the patterns of fish assemblage based on “Protection status” and “rocky reef/island size” of the sampling sites showed non-significant effects of the interaction between “protection status” and “rocky reef/island size” ($p>0.05$), non-significant “protection status” effect ($p>0.1$), but significant “rocky reef/island size” effect ($p<0.05$). Tests of homogeneity using PERMDIST showed non-significant dispersion in relation to both factors “Protection Status” ($F=2.96$, $p>0.1$) and “Size of rock reef/island ($F=4.04$, $p>0.05$). Since both PERMANOVA and PERMDIST outputs are not significant for the Protection factor it is inferred that there is no effect of “Protection status” on fish assemblage structure. On the contrary, since PERMANOVA results were significant while PERMDIST not significant for the “rocky reef/island size” effect it was concluded that fish assemblage structure is affected by Size of rocky reef/islands.

3.4 Discussions and conclusions

The present study has shown some interesting patterns of the ornamental fish species assemblage inside and outside the protected areas of Lake Malawi which are discussed under the following four subheadings of this section.

3.4.1 Abundance of ornamental fish inside and outside protected areas of Lake Malawi

Analysis of data using GLMM of family Poisson and adjustment of GLMM using quasi likelihood analysis of the data resulted in two different results with the former showing significant effect of “size of rocky reef/island” while the latter resulted in a minimum model being a null model. The GLMM had significant overdispersion which invalidated the apparently significant effect of size of rocky reef/island on fish abundance. According to Crawley (2007), one of the causes of overdispersion when modelling count data is inability to account for one or more factors that affect the dependent variable of the model. Since this study was exploratory in nature, it is likely that some important factor(s) that determine fish abundance in Lake Malawi were not accounted for in the fish sampling design (i.e. the factors were missed by the randomization process). It is very difficult to control for multiple explanatory variables in an exploratory field survey (Warton *et al.,* 2016).

Besides the factors hypothesized in this study, in Lake Malawi the distribution and abundance of rock-dwelling cichlid fishes has been reported to be influenced by sampling time of the day (Duponchelle *et al.,* 2000c), availability of resources for survival, and features of microhabitat (Ribbink *et al.,* 1983; Genner *et al.,* 2004; Ding *et al.,* 2014b; Konings, 2016) such as size of the rocks, amount of sediment, exposure to wave action, slope of the substrate and predation pressure. In addition to these, Duponchelle *et al.* (2000c) observed at Maleri Island in Lake Malawi that an increase in turbidity changed behaviour of most rock dwelling cichlid fishes by making them immobile and staying close to the entrance to their hideaways amongst the rocks. With such behaviour most fish can easily be missed when estimating their abundance using either SCUBA diving or underwater video footage. Moreover, almost all the fish species studied are small sized with a maximum standard length between 5.4 cm and 15 cm (see section 5.2.2, Figure 5-2), which can make it difficult to capture them all accurately using underwater video footages when visibility of water is reduced.

It was difficult to control for the effect of sampling time of day because of changing weather conditions on the lake, which forced sampling to be made at different times of the day depending on when the lake was calm and safe for sampling. It is therefore conceivable to assume that all these unaccounted factors in this study resulted in the observed GLMM overdispersion.

It has been demonstrated in other water bodies that fish abundance increases with an increase in complexity of habitats (Gratwicke & Speight, 2005; Giakoumi & Kokkoris, 2013). In the current study, bottom substrate type and visibility of the water column appeared to have significant effects on fish abundance. Unfortunately, the two factors were not included in the GLMM because both factors were unbalanced with limited data points for some of the factor levels. In addition, Britton *et al*. (2017) provided evidence that suggested that human disturbance contributed to heterogeinity of the rocky shore cichlid fish communities in Lake Tanganyika by affecting both abundance and diversity of the fish. Though the human disturbance was not ranked in the current study, the results of this study appear to support those of Britton *et al*.

(2017) based on the qualitative description of human activies presented in section 3.2.1 and fish counts data (see Figure 3-6 top left). For instance Chirundu Point which is outside the protected area and is potentially associated with different types of human disturbance (pollution from the dockyard which is about 700 mertres away, human activity in the Nkhata Bay Town and subsistence fishing activites), had the lowest median of 10 fish per point transect. In the contrary, Thumbi West Island 1 inside LMNP, which appeared to have the lowest human disturbance amongst all the sampled sites (controlled and monitored tourism activites), had a median of 109.5 fish per point transect. Other sampled sites of the current study which appeared to have intermediate human disturbance between that of Chirundu Point and Thumbi West Island 1 (see description in section 3.2.1) also had intermediate median fish transect counts (Figure 3-6 top left).

An alternative way of interpretation of the minimum adequate GLMM being a null model is that all the factors included in the model were not important determinants of observed fish abundance. This implies that protection status of sampled sites had no significant effect on fish abundance, a result that is further discussed in section 3.4.4, after collaborating this finding with multivariate analysis taking into account PERMANOVA comparisons of resemblance matrices of species composition and abundance data (Section 3.4.3).

3.4.2 Diversity of exploited ornamental fishes

In this study, a cumulative total of 88 fish taxa were identified from point transect video footages, which is probably an underreporting of the actual number of species that could be found in the sampled localities if comparisons were to be made with the information presented by Konings (2016). Unfortunately, such information is scattered throughout his book of 432 pages without any summary of species by location, which makes it impractical to extract the information.

The other challenge is that the current study findings about the number of taxa in the sampled localities cannot be compared directly with earlier reports (e.g. Ribbink *et al.,* 1983; Reinthal, 1993) because of the changes in names that have occurred, with the frequent splitting of some previous species names. Konings (2016) has also included some fish names that are not found in the report of Ribbink *et al.* (1983).

Some of the possible reasons for observing fewer fish species than expected may include:

- Point transects covered a small area (radius of about 3 m) resulting in limited number of observable fish.
- For some transects, visibility of water was poor, which negatively affected the ability to identify all fish to species level.

- It is likely that the video camera did not capture cryptic fish species. Many fish species of Lake Malawi are known to spend some time in the caves or hiding in rocks when they are either spawning {e.g. *Aulonocara ethelwynnae* Meyer & Riehl & Zetzsche, 1987; *Labeotropheus fuelleborni* Ahl 1926; *Labeotropheus trewavasae* Fryer, 1956; *Melanochromis auratus* (Boulenger, 1897); *Metriaclima callainos* (Stauffer & Hert, 1992); *Metriaclima barlowi* (McKaye & Stauffer, 1986); *Metriaclima flavifemina* Konings & Stauffer, 2006; *Metriaclima mbenjii Stauffer, Bowers, Kellogg & McKaye, 1997}*; or mouth brooding {e.g. *Metriaclima zebra* (Boulenger, 1899); *L. trewavasae*, *M. callainos* and *Protomelas taeniolatus* (Trewavas, 1935)} (IUCN, 2019). Additionally, individuals of one fish species *Metriaclima lanisticola* (Burgess, 1976) are known to hide in shells of the snail, *Lanistes nyassanus* Dohrn, 1865 when frightened (personal observation). All the mentioned examples of fish species have been reported to have distribution ranges covering the sampling sites of this study (Konings 2016, IUCN, 2019) yet not all these species were observed in the current study, thus it can be assumed that some of them were present in the sampling sites but not captured in the point transect video footages.
- It is possible that some fish species could not be differentiated based on colour and morphological features alone because of the similarities of these two traits amongst some fish species of Lake Malawi (which may require knowledge about other features such as meristic traits which cannot be captured in video footages).

Despite these limitations for the data collected, some insights about the differences in species diversity between the study design factor levels can still be gained based on the data collected.

This study demonstrated that amongst the 88 fish taxa captured in the point transects, a majority of 40 taxa were shared between at least one site in protected and unprotedted area (Figure 3 9). However, the observation of a majority of the fish taxa being shared between protected and unprotected sites at only two to four of the nine sampled sites while 20 taxa occurred only in protected sites and 28 fish taxa only in unprotected sites (Figure 3 10), reflect that most of the fish are confined to limited localities of the Lake. This is a typical trait of Lake Malawi *mbuna* (Ribbink *et al*., 1983; Konings, 2016).

This study found that protected areas had significantly higher values of species richness *S*, and Margalef species index than unprotected areas (Figure 3-12), which concurs with findings of other researchers (McClanahan *et al.,* 2006; Penha *et al.,* 2014, Muallil *et al.,* 2015; Appolloni *et al.,* 2017; Chu *et al.,* 2017; Turnbull *et al.,* 2018). These findings support the notion that marine reserves are important for biodiversity conservation (Pendleton *et al.,* 2018; MacKeracher *et al.,* 2019), and presumably the same interpretation would be true for freshwater protected areas.

However, there was no significant difference in Simpson's Index and Shannon Index between protected and non-protected areas. Since both Simpsons and Shannon indices are dependent on species richness and evenness, the results suggest that species evenness was higher in unprotected areas than protected areas, which probably offset the effect of higher species richness observed in protected areas than unprotected areas.

There was no evidence about the effect of depth on Species richness, Margalef Index, Shannon Index and Simpson's Index. This is contrary to findings of other studies, in different marine water bodies, which reported significant variation in fish diversity indices with depth (Mesa *et al.,* 2006; Merigot *et al.,* 2007; Yemane *et al.,* 2010; Zintzen *et al.,* 2012; Feiner *et al.,* 2016; Pereira *et al.,* 2018). The similarity of species diversity indices between depths observed in the current study reflects an overlap of the occurrence of most of the observed species amongst sampled depths between 5 and 25 m, while most of the studies that reported significant differences in fish diversity indices with depth were based on depth ranges of hundreds of metres.

The fact that species richness and Margalef Index differed between protected and unprotected areas while the overall abundance was not significantly different, suggests that exploitation of rock-dwelling fish species was probably affecting species composition without affecting the overall abundance of fish. However, these results were probably confounded by the other characetristics of sampled sites contributing to differences in median fish species counts per transect. The most likely site charasteristics that probably contributed to the observed patterns of fish species diversity indices include rocky area size (Figure 3.11 middle left), visibility (turbidity) of water at different sites (Figure 3.11 bottom left) and variations in sampled sites bottom substrate types (Figure 3.11 bottom right). Based on study of Lake Tanganyika cichlids, Britton *et al*. (2017) speculated that an increase in water turbidity due to sedimentation from the watershed and eutrophication from towship domestic waste may affect algae feeding fish diversity by lowering the biomass of epilithic and filamentous algae. This is also applicable for sites of Lake Malawi with higher water turbidity than others. It was not possible to model the effects of all these factors on species richness using a generalised linear model because of the unbalanced nature of the data collected which had missing data for many factor levels.

It was not possible to differentiate the effect of fishing for ornamental fish trade and that of artisanal fishing for food. Field observations indicated that colourful, rock-dwelling cichlid fishes were being commonly targeted by artisanal fishers using gillnets, hand lines and small seine nets in all locations visited in Lake Malawi, which is against fisheries regulations in Malawi (see section 2.4.5 in Chapter 2). The number of artisanal fishers targeting colourful, rock-dwelling fish species appears to have increased with the decline in stocks of the popular food fish species as the human population increases. Two days of observations of catches of artisanal fishers around Mbenji Island indicated that approximately 40% of the catches of small cichlids that were being sun dried around the island were colourful rock dwelling cichlids. It was noted that the quantities of fish being caught by artisanal fishers far exceeded the amount exporters were collecting.

3.4.3 Resemblance based on fish species composition and abundance

This study showed that the multivariate similarity range for point transects based on the Bray Curtis Resemblance matrices of square root transformed data of individual fish species abundance (0.99% to 82.84%) was wider than the range between sampling sites (46.2% to 67.55%). Cluster analysis revealed eight significant clusters at point transect level (Figure 3-13) but non-significant clusters at sampling site level (Figure 3-14). In addition, PERMANOVA and PERMDIST at both point transect and sampling site levels showed that the effect of "protection status" on the patterns of fish species abundance was not significant, but there were significant effects of multivariate dispersion and "size of rock reefs/island" on fish species relative abundance. The reasons for significant multivariate dispersions are similar to those discussed under Section 3.4.1, i.e. the inability to account for all possible factors that possibly determined fish transect counts in sampled sites. These results are further discussed in section 3.4.4, which summarises the findings of comparisons of fish assemblages according to factors investigated.

3.4.4 Comparisons of fish assemblage between protected and unprotected sites

Comparison of overall fish abundance inside and outside protected areas based on GLMM lead to similar conclusions as those based on the PERMANOVA comparisons of resemblance matrices of species composition and abundance data. Both analyses suggested that there was no significant difference in the measured parameters between protected and unprotected sites. The only difference in the two analyses related to the significance of the effect of "size of rocky reefs/island". When the GLMM was adjusted for overdispersion using quasi likelihood analysis the apparent significant effect of "size of rocky reefs/islands" was nullified while the PERMANOVA and PERMDIST tests lead to the conclusion that "size of rocky reef/island" significantly influenced the observed patterns of fish assemblage.

The non-significant effect of protection status on overall abundance / fish assemblage is contrary to other studies that reported higher abundance of ornamental fish in protected areas than in exploited areas (e.g. Kolm & Berglund, 2003; Tissot & Hallacher, 2003; Tissot *et al.*, 2004, Shuman *et al.,* 2005; Muallil *et al.,* 2015). The anomaly between the findings of this study and previous studies can be attributed to the ornamental fish trade targeting specific fish species, with the likelihood that the impact of exploitation is probably noticeable at species level without affecting the overall fish abundance in a particular area. This view is further supported by there being significant differences in species richness and Margalef Index between protected and unprotected areas. In this case, reduction of the population of the target species may be compensated by replacement with non-target species without significantly changing the overall fish abundance. Unfortunately, it was not possible in this study to compare individual fish species populations between protected and unprotected places since very few species were common in sites inside and outside the protected area of LMNP. Rock-dwelling fish species of Lake Malawi have very limited and localized distribution ranges with individual species occupying specific rocky reefs, some of which are very small in size (Ribbink *et al.,* 1983), and the fish also have very limited dispersal ability (Genner *et al.,* 2004). This makes species-based comparisons of the populations between protected and unprotected areas difficult.

3.4.5 Conclusions and recommendations for management of the ornamental fishery of Lake Malawi

The following conclusions are made based on the findings of this chapter:

- Based on the generalised linear mixed effect model, there was no significant difference ($p>0.05$) in the overall fish abundance between protected and non-protected sites (Figure 3-7).
- Protected sites had significantly higher values ($p<0.05$) of species richness (S) and Margalef Index than non-protected sites (Figure 3-12, top left and right respectively). However, there was no significant difference in Simpson's Index and Shannon Index between protected and non-protected sites (Figure 3-12 bottom right and left respectively).
- There was no significant difference in fish assemblage structure between protected and unprotected sites as defined by both overall fish abundance comparisons (Figure 3-7) and multivariate analysis of the Bray Curtis resemblance matrices of fish species composition and abundance using PERMANOVA designs (Figure 3-13 and Figure 3-14).
- Analysis of the multivariate data using PERMANOVA designs showed that size of the rocky reef/islands had significant effect on fish assemblage structure.

Based on findings of this Chapter, the following recommendations are made:

- It is recommended that future research into fish population be undertaken using more rigorous sampling to account for possible causes of overdispersion of the data at the microhabitat level. The sampling should combine the use of video footages and SCUBA divers using strip transects to estimate populations of fish and exploratory surveys to search for rare and /or cryptic fish species.

- The lack of differentiation of overall fish abundance and fish species assemblage between protected and unprotected areas when species richness was significantly different between protected and unprotected sites suggests the need for conservation and management of the ornamental fishery to focus on rare and threatened fish species which could easily be overexploited.
- To determine the impacts of fish exploitation on individual fish species, long-term monitoring of populations of the key export species at their known localities is recommended. At each known distribution locality for commonly exported fish species, permanent quadrants (strip transects) should be established where fish population could be periodically (e.g. annually) assessed through SCUBA diving techniques to determine relative population density changes.

Further discussions and recommendations of some of the the issues raised in this chapter are made in section 6.2 of Chapter 6 which discusses issues from all chapters of this thesis.

Chapter 4 Reproductive traits of selected exploited ornamental fish species of Lake Malawi

4.1 Introduction

An understanding of fish life history traits provides useful information about how various fish species adapt to their environments and exploitation pressures, and how fishes may respond to changes in their environment (Serrat *et al.,* 2018; Rius *et al.,* 2019). Fish life history traits are used as response variables in a number of models, e.g. models that assess how environmental productivity and competition for resources affect fish populations (Ward *et al.,* 2017); models that assess the effect of fish harvesting on populations of fish and the risk of population collapse (Hobday *et al.,* 2011, Fujita *et al.,* 2013; Micheli *et al.,* 2014; Okemwa *et al.,* 2016). In the Productivity Susceptibility Analysis group of risk assessment models for effect of fishing, fish life history traits are factored in as a component of productivity (Hobday *et al.,* 2011). The ultimate goal of applying fish life history traits in various models is development of management systems for sustainability of the fisheries (Bakke *et al.,* 2018; Carreón-Zapiain *et al.,* 2018; De Queiroz *et al.,* 2018; Dey *et al.,* 2018; Serrat *et al.,* 2018; Ashfaq *et al.,* 2019; Zhao *et al.,* 2019).

There is a paucity of information regarding life history traits of cichlid fishes of Lake Malawi, despite the importance of the information for sustainable management of fish resources. The only comprehensive studies of Lake Malawi fish life history traits were based on demersal (Duponchelle *et al.,* 2000a) and semi pelagic (Thompson *et al.,* 1996) fish species caught by trawling. Very limited studies have been conducted in relation to life history traits of the *mbuna* of Lake Malawi (Marsh *et al.,* 1986; Munthali & Ribbink, 1998). Marsh *et al*. (1986) studied the breeding biology of the following ten *mbuna* fish species of Lake Malawi: *Metriaclima zebra*, *Tropheops* sp orange chest, *Pseudotropheus* sp elongatus aggressive, *Petrotilapia genalutea*, *Petrotilapia nigra*, *Petrotilapia tridentiger*, *Labeotropheus fuelleborni*, *Protomelas taeniolatus*, *Melanochromis auratus* and *Melanochromis joanjohnsonae*. On the other hand, Munthali & Ribbink (1998) investigated the fecundity of the following three *mbuna* fish species of Lake Malawi: *Cynotilapia afra*, *Metriaclima callainos*, and *Tropheops* sp red cheek. These two studies covered only few species and limited suit of life history traits yet there are about 250 species of the *mbuna* cichlid fish species in Lake Malawi (Konings, 2016; see also section 1.1.2 of Chapter 1 of this thesis for more details about *mbuna* fish) indicating the need for more studies of the other *mbuna* life history traits.

The objective of this chapter is to investigate reproductive traits consisting of length at maturity, absolute fecundities, fish fecundity length relationships and egg sizes for a sample of the exploited ornamental fish species of Lake Malawi as a contribution to the knowledge base that is important for informed management of the fish species. The information generated from this chapter may be incorporated in development of various models for management of the exploited ornamental fish species. The secondary objective is to use the findings, alongside the other information reviewed from scientific literature, to assess overexploitation risk of ornamental fish species in Lake Malawi using a Productivity Sustainability Analysis model. The latter is covered in Chapter 5.

4.2 Methodology

4.2.1 Fish sampling

Of the 64 genera of fish that were represented by the ornamental fish exports from Malawi (See section 2.3.4 in Chapter 2), the top 10 genera that accounted for 80.9% of the ornamental fish exports from Malawi, were targeted in this study. However, only 7 genera: (*Copadichromis*, *Labeotropheus*, *Melanochromis*, *Metriaclima*, *Protomelas*, *Pseudotropheus and Tropheops*), which together contributed 55.2% of the exports, were mainly sampled for the study of selected life history parameters. Three of the 10 targeted genera (*Aulonocara*, *Cynotilapia* and *Chindongo*) were not common in the localities where sampling was conducted. Additionally, specimens of fish belonging to some other genera (e.g. *Labidochromis, Petrotilapia* and *Genyochromis*) were also occasionally encountered and represented in the samples.

During the time periods from September 2017 to November 2017 and August 2018 to September 2018, fish specimens were sampled from Chindunga Rocks, Mbenji Islands and three sites at Nkhata Bay (Chirundu, Chindozwa and Mwafufu) (Figure 3-1). Sampling was selected away from locations where video point transects of fish abundance (described in Chapter 3 Section 3.2.2) were recorded. All fish specimens {except for one species, *Metriaclima barlowi* (McKaye & Stauffer, 1986), which was sampled from two gillnet catches probably in a slightly different depth range}, were sampled at depths of 2 to 8 m by snorkelers using a 1-inch mesh sized net of 5 m length and 1.5 m width. Two snorkelers caught the target fish species by chasing them into a net and encircling them.

After being caught, the fish were kept in holding buckets covered with nets and submerged in water until a required sample was obtained. The fish specimens were taken into the boat alive where they were sorted by species and held in plastic buckets with fresh water. Fish were identified to species based on their colour patterns and general body shape using pictures of Ribbink *et al.* (1983) and Konings (2016). Where Konings (2016) and Ribbink *et al.* (1983) used different temporally names of undescribed fish species[9], the names from Konings (2016) were adopted.

Water in the bucket was frequently changed to minimize stress on the fish while they were being sorted into species. After sorting, fish were euthanized by using clove oil at a concentration of 400 mg per litre of water as recommended by RSPCA (undated) and preserved in 5% formalin solution for further analysis. Names of the sampled fish species and the localities where they were sampled are summarised in Table 4-1.

After collection, the preserved fish specimens were transferred to Aquaculture and Fisheries Science dry laboratory of Lilongwe University of Agriculture and Natural Resources (LUANAR) in Malawi for further processing.

[9] Konings (2016) split many of the undescribed fish species names of Ribbink *et al* (1983) into more than one.

Table 4-1. Species of fish sampled for the study of reproductive traits

Species name	Locality of sampling	Number of specimens examined
Copadichromis atripinnis Stauffer & Sato, 2002	Chindunga Rocks	101
Copadichromis borleyi (Iles, 1960)	Chindunga Rocks	32
Copadichromis mbenjii Konings, 1990	Mbenji Island	39
Copadichromis pleurostigmoides (Iles, 1960)	Nkhata Bay	27
Cynotilapia aurifrons (Tawil, 2011)	Nkhata Bay	31
Genyochromis mento Trewavas, 1935	Chindunga Rocks, Mbenji Island, Nkhata Bay	19
Labeotropheus fuelleborni Ahl, 1926	Chindunga Rocks, Mbenji Island, Nkhata Bay	284
Labeotropheus fuelleborni OB	Mbenji Island	22
Labeotropheus trewavasae Fryer, 1956	Chindunga Rocks	28
Labidochromis ianthinus Lewis, 1982	Mbenji Island	43
Labidochromis mbenjii Lewis, 1982	Mbenji Island	88
Melanochromis auratus (Boulenger, 1897)	Chindunga Rocks	115
Melanochromis heterochromis Bowers & Stauffer, 1993	Mbenji Island	22
Metriaclima barlowi (McKaye & Stauffer, 1986)	Mbenji Island	217
Metriaclima callainos (Stauffer & Hert, 1992)	Chindunga Rocks and Nkhata Bay	246
Metriaclima mbenjii Stauffer, Bowers, Kellogg & McKaye, 1997)	Mbenji Island	35
Metriaclima sp patricki	Chindunga Rocks	156
Metriaclima zebra (Boulenger, 1899)	Chindunga Rocks	53
Petrotilapia genalutea Marsh, 1983	Chindunga and Mbenji	66
Petrotilapia microgalana Ruffing, Lambert & Stauffer, 2006	Nkhata Bay	33
Petrotilapia sp fuscous	Mbenji Island	28
Protomelas spilonotus (Trewavas, 1935)	Mbenji Island	42
Protomelas taeniolatus (Trewavas, 1935)	Chindunga, Mbenji, Nkhata Bay	209
Pseudotropheus sp williamsi mbenji	Mbenji Island	67
Pseudotropheus sp williamsi north	Nkhata Bay	85
Tropheops gracilior (Trewavas, 1935)	Nkhata Bay	110
Tropheops sp lilac	Chindunga Rocks	126
Tropheops sp mauve yellow	Nkhata Bay	28
Tropheops sp mbenji yellow	Mbenji Island	293
Tropheops sp olive	Nkhata Bay	29

4.2.2 Processing of the fish samples

In the Aquaculture and Fisheries Science laboratory at LUANAR fish samples were transferred into trays and thoroughly rinsed of formalin solution under a tap of running water for 24 hours. The specimens were examined for size at maturity, fecundity and egg sizes as described in the following subsections. Age-based life history traits were not studied due to the difficulty of ageing these fishes. Traditional length-based methods used in tropical waters was not possible because it requires multiple samples from the site over many months.

Gonad maturity staging: Each fish specimen was measured for the standard length (mm), dissected and the gonads were macroscopically examined to determine sex and the development stage. Fish gonad maturity stages were macroscopically scored using the criteria of Núñez & Duponchelle (2008), which specify six female and four male fish maturation stages (Table 4-2). The criteria of Núñez & Duponchelle (2008) was slightly extended in female fish to reflect ovaries that showed evidence of having previously spawned and were either maturing (5.2) or in advanced maturation stage (5.3), i.e. these were post-spawning females that were in another cycle of vitellogenesis. Evidence of previous spawning included remnants of eggs (atretic eggs) and large sized ovaries with relatively large empty space. Ideally, length at maturity is determined at the peak of the breeding season for each species to increase accuracy of estimated length at maturity (Duponchelle *et al.,* 2000a; 2000c, Weyl *et al.,* 2005). The peak breeding season for the fish species examined was unknown and fish sampling was limited to only a few months. However, the current study was conducted during the months of August to November, which coincide with the previously reported peak breeding season of some rock-dwelling cichlids fishes of Lake Malawi (Marsh *et al.,* 1986; Munthali & Ribbink, 1998), as discussed in section 4.4.2. Moreover, the ability to differentiate fish ovaries of spent fish in stages 2 and 5.2, a major potential source of error when categorizing the individual fish as either mature or immature outside the peak breeding season(Flores *et al*., 2015), minimized errors of estimating length at maturity.

The other methods that are used for determining fish maturity such as histology and use of gonadosomatic index (Flores *et al*., 2015) could not be employed in this study because of the field limitations. The major challenge was limited availability of electricity during field research period (ranging from only three hours of electricity per day to continuous power blackouts for more than two days) which was required for powering the microscopes for histological investigations and sensitive digital scales for weighing individual fish samples and fish gonads. The other challenge was that the period to conduct field research was limited to a maximum of 6 months as per the Scholarship sponsors requirements. Using samples of fish collected for less than 12 months period made application of the gonadosomatic indices difficult as this index requires data collected during the complete year (Flores *et al*., 2015).

The data collected from these fish specimens were entered into a Microsoft Excel spreadsheet for further analysis.

Table 4-2. Macroscopic gonadal maturation stages for fish (Adapted from Núñez & Duponchelle, 2008).

Female fish		
Gonadal maturation stage	Description of characteristics	
	Annual spawners	Multiple spawners
1. Immature	Ovaries of circular section, small thin, partly translucent and opaque or sometimes pinkish. Oocytes invisible to the naked eye	Immature: Same as for annual spawners
2. Maturing	Ovaries much larger, occupying a significant part of abdominal cavity. Filled with white or yellowish oocytes of different sizes	Maturing: Same as for annual spawners
3. Advanced maturation	Ovaries are larger and fuller. The oocytes, orange or greenish depending on the species, are now larger and more homogenous in size.	Similar to that of annual spawners but vitellogenic oocytes of different sizes can be seen in between the larger oocytes to be released at the next spawn.
4. Ripe	Aspect almost identical to stage 3 but the oocytes are partially ovulated (free in the ovarian cavity) and can be expelled with a gentle pressure on the fish flanks. The ovary reaches its maximum development. This is the ephemeral stage just before the actual spawning event.	Similar to that of annual spawners but vitellogenic oocytes of different sizes can be seen in between the oocytes undergoing maturation and ovules are partially filling the ovarian cavity
5. Spent	The ovaries are still large but almost empty, flaccid, often bloody. Some remaining ripe oocytes can still be visible along with atretic follicles.	Spawned and recovering: Similar to stages 5 and 2. Ovaries still relatively large and flaccid with remaining empty spaces, and sometimes atretic follicles. As time after spawning increases, it may be difficult to distinguish from stage 2. This stage characterizes the beginning of one or more new spawning cycles until the end of the breeding season.
5.1 Resting	Ovaries like stage 1 but usually larger, wider and pink to dark red in colour. Ovarian wall is also thicker. It distinguishes between a mature and resting female and an immature 1.	Resting. Same as for annual spawners.
Males		
1. Immature	Testes are like two silvery or translucent threads, thinner and longer than stage 1 ovaries	Same as for annual spawners
2. Maturing	Testes are longer, wider, often of triangular or circular section and whitish to pinkish color.	Same as for annual spawners
3. Ripe	Testes are larger, fuller and completely white. Sperm emitted with a gentle pressure on the abdomen	Same as for annual spawners
4. Spent	Testes still large as a stage 3, but flaccid, empty-like	Same as for annual spawners

Fecundity determination: After scoring and recording gonad maturity stage, ovaries in stage 4 were extracted and used for determination of absolute fecundity (number of eggs produced by a female for a given spawning event or period) and egg sizes.

Each stage 4 ovary was placed in a petri dish and the eggs were removed from the ovary by carefully cutting open part of the ovarian membrane and gently teasing out the eggs using stainless steel forceps and needles. Ripe eggs were separated from the other ovarian tissues and small previtellogenic white oocytes using dissecting tweezers, forceps and needles. The ripe eggs for each ovary were spread in the petri dish and counted. Total egg count was conducted because cichlid fishes of Lake Malawi have relatively low fecundity with large sized eggs up to more than 4 mm in diameter (Duponchelle *et al.,* 2008). After egg counting, the data were entered into a Microsoft Excel spreadsheet alongside that of gonad maturity stages.

Determination of egg sizes: After counting the eggs, a sample of 10 mature eggs from each fish with stage 4 ovary were randomly taken and the average diameter (mm) of the mature eggs was estimated using two methods depending on prevailing circumstances. The first method was undertaken by aligning the 10 sampled eggs in a single row, which was measured using a ruler to the nearest mm and divided by 10 to get average egg size for the individual fish. The second method was undertaken by using a dissecting microscope with an ocular micrometre fitted to the eye piece and calibrated to measure individual egg size to the nearest 0.1 mm. An initial comparison of the two methods to measure size of 20 eggs from one fish by using a one sample t-test in R software (R Core Team, 2018), showed that mean egg size obtained using the first method (3.125 mm) was not significantly different from the size obtained using the second method (3.113 mm) ($t = -0.85519$, $df = 19$, $p=0.4031$), hence it was decided that the two methods could be used interchangeably depending on prevailing circumstances. The first method was employed in the absence of electricity[10], while the second one was used when there was electricity power. Average egg diameter for each fish was calculated and recorded alongside the other information collected.

[10] During the time of this study there was electricity power blackout in the entire country of Malawi for a majority of the days lasting on average 16 to 20 hours a day.

4.2.3 Analysis of data

Determination of fish size at maturity: All the gonad developmental stages were grouped as either mature or immature to determine the length at maturity. Using the criteria of Núñez & Duponchelle (2008), all the male and female fish gonads of stages 3 and above were considered as mature while those of stages 1 and 2 were considered immature.

Data on fish size at maturity were sorted according to fish species and summarized as numbers of mature and immature fish per size class filtered by sex of the fish. The size classes were grouped into bins of 2 mm to 5 mm depending on size range of the fish species and number of specimens per size category. 5-mm bins were used for species of fish with wide size ranges, while 2-mm bins were used for species of fish with narrow size ranges. It was important for the number of fish per size category to be sufficient with at least eight fish per size category (Watson *et al.,* 2013), for calculation of reliable percentage of mature fish per size class.

Length of fish at maturity (defined as length at which 50% of the fish are mature) was estimated by fitting the proportion of mature fish in a length class to the logistic regression model:

$$Pi = 1/[1 + \exp(\alpha - \beta * MLi)]$$

where: *Pi* =Proportion of mature fish in a length class; *ML* = mid of the length bin; and α and β are parameters that determine the shape and location of the sigmoid curve.

According to Sparre & Venema (1998), this logistic model, which is also applicable to estimation of selectivity of a trawl net, can be rewritten as:

$Ln(1/Pi - 1) = \alpha - \beta * MLi$, which represents a straight line, with parameter α as intercept and parameter β a slope describing the linear relationship. The parameters α and β for each fish species were estimated using regression analysis within the Microsoft Excel Add-ins Data Analysis ToolPak. $Ln(1/Pi - 1)$ was computed and fit to the model as a dependent variable while ***ML*** was computed and used as an independent variable of the linear relationship. Length corresponding to 50% maturity was estimated as: $ML_{50\%} = \alpha/\beta$ (Watson *et al.,* 2013). Another parameter for this model is the difference in fish length when the proportion of mature fish is 0.75 and 0.25 as a measure of slope of the maturity ogive, which was estimated as $ML_{75\text{-}25} = 2Ln(3)/\beta$ (Watson *et al.,* 2013).

Fish species whose sample size was too small for estimation of the parameters of the logistic regression model were excluded in the model, but information about their minimum sizes at maturity was summarized.

Comparison of absolute fecundity between fish species: Data on absolute fecundity were summarized as mean number of eggs laid per species. Absolute fecundity was compared between species using the Kruskal Wallis test in R software.

Determination of the relationship between absolute fecundity and fish standard length: For each fish species, scatter plots of absolute fecundity against standard length of fish were constructed to visualise the relationship between the two variables. Since absolute fecundity is count data, simple linear regression which assumes constant variance and normal errors could not be used to determine the relationship between absolute fecundity and standard length of fish. According to Crawley (2007, page 527) the use of simple linear regression for count data may be associated with the following four challenges: prediction of negative counts, increased variance of the response variable as the mean increases, non-normal errors, and the difficulty of handling zeros in transformations. Hence the relationship between absolute fecundity and standard length of each fish species was estimated in R software using the generalized linear model of the family Poisson (to account for non-normality). This model automatically set the log link as a default function to ensure that the predicted absolute fecundity values were not below zero (Crawley 2007). The script used to model the relationship between absolute fecundity and fish standard length was:

Model <- glm(Fecundity ~ SL, family='poisson', data=df)
summary(Model)

where ***SL*** represented fish standard length in mm, ***df*** represented the dataframe for each fish species.

For species of fish with over dispersed data (i.e. glm residual deviance were greater than residual degrees of freedom), the model was refit using Quasipoisson errors instead of Poisson errors to compensate for the overdispersion (Crawley, 2007). Significance of the relationship between absolute fecundity and fish standard length was determined at p-value of 0.05. Based on the glm output parameters, the predicted lines were drawn on the graphs of absolute fecundity versus fish standard length.

Analysis of egg size data: Based on the alternative life history theory, egg size is considered as one of the traits that varies depending on existing environmental conditions that influence juvenile mortality rates such as prevailing trophic conditions for juveniles and interspecific competition for resources (Duponchelle *et al*., 2000d). Egg sizes for different fish species were compared to determine interspecific differences of egg sizes as a reflection of the quality of the juveniles for different fish species and the potential of the juveniles to survive to adult size.

Visual examination of histograms of egg diameter data suggested that the data were normally distributed and Shapiro's test of normality using R software confirmed normality of the data ($W = 0.99151$, $p = 0.3146$). Hence parametric tests were employed to compare egg diameter between different species and genera of fish.

To visualize the relationship between egg size and absolute fecundity, scatter plots of egg size against absolute fecundity were produced. While egg size data were normally distributed (Shapiro test, $W = 0.99151$, $p = 0.3146$), absolute fecundity data were not normally distributed (Shapiro test, $W = 0.98074$, $p < 0.01$). Hence nonparametric Spearman's correlation test, which does not require normality of both variables, was employed to test the association between egg diameter and absolute fecundity.

4.3 Results

4.3.1 Fish maturity

Standard length at 50% maturity: Of the 30 fish species sampled, length at 50% maturity was estimated using the logistic regression model for only 13 species (Table 4-3, Figure 4-1 and Figure 4-2). It was not possible to estimate the size at 50% maturity for the other 17 fish species because of the following reasons: For some species, the sample sizes were not large enough for reliable estimates of the parameters of the logistic regression model. For some species, not all size classes of fish were present in the specimens sampled (either only immature or only mature fish being sampled). Thirdly for some fish species the change of fish from immature to mature size class appeared to be so sudden (knife edged) making it impossible to estimate the parameters of the logistic regression model as all length classes with the proportion of either nil or 100% mature fish have to be excluded when estimating the parameters $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ for the logistic regression model (Sparre & Venema, 1998).

The estimated sizes at maturity (ML_{50}) for the 13 species ranged from 52.2 mm to 101.9 mm. Size at maturity varied between species as well as between sexes of fish belonging to the same species. Male fish had larger sizes at maturity than female fish. Slopes of the maturity ogive ($ML_{75\text{-}25}$) also varied between species and fish sexes. *M. auratus* had the smallest maturity for both females and males, while *P. taeniolatus* had the largest maturity size for both females and males (Table 4-3).

Table 4-3. Estimated parameters of the logistic regression model Pi = 1/[1 + exp(α – β*MLi)], that related the proportion of mature fish at size (Pi) to mid length (ML) for a size class. ML50% = Standard length at which 50 % of the examined fish were mature, ML75-25% = difference in standard length when P = 75% and P = 25 % which measures slope of the maturity ogive. In the column of fish sex, the letters (F) represents female while the letter (M) represents male fish. Numbers inside the brackets represent the Lower and Upper limits of the 95% confidence interval for each estimated parameter. Some species of fish have parameter estimates for only one sex category because the other sex category had insufficient fish specimens for reliable estimates of the logistic regression model parameters.

Species name	Sex	$ML_{50\%}$ (mm)	$ML_{75-25\%}$ (mm)	Model Parameters		
				α	β	P-value for estimated β
Copadichromis atripinnis	F	72.4	11.9	13.387 (5.109, 21.665)	-0.185 (-0.302, -0.068)	<0.05
Labeotropheus fuelleborni	F	72.6	8.0	19.957 (9.139, 30.775)	-0.275 (-0.417, -0.133)	<0.01
Labeotropheus fuelleborni	M	96.2	14.6	14.46 (1.833, 27.087)	-0.150 (-0.297, -0.004)	<0.05
Melanochromis auratus	F	52.2	9.5	12.057 (-41.643, 65.757)	-0.231 (-1.180, 0.717)	>0.05
Melanochromis auratus	M	61.4	6.9	19.654 (-10.926, 50.234)	-0.320 (-0.828, 0.189)	>0.05
Metriaclima barlowi	M	64.1	8.7	16.250 (-7.096, 39.596)	-0.254 (-0.575, 0.068)	>0.05
Metriaclima callainos	F	61.6	10.5	12.914 (6.627, 19.201)	-0.210 (-0.310, -0.109)	<0.01
Metriaclima callainos	M	71.2	10.5	14.840 (9.996, 19.683)	-0.208 (-0.275, -0.142)	<0.01
Metriaclima sp patricki	F	59.3	5.7	22.680 (2.684, 42.676)	-0.383 (-0.707, -0.058)	<0.05
Metriaclima sp patricki	M	69.9	8.2	18.647 (11.690, 25.603)	-0.267 (-0.371, -0.163)	<0.01
Metriaclima zebra	F	53.2	19.2	6.088 (-5.745, 17.921)	-0.115 (-0.301, 0.072)	>0.05
Metriaclima zebra	M	65.2	25.4	5.646 (-12.766, 24.057)	-0.087 (-0.351, 0.178)	>0.05
Protomelas taeniolatus	F	77.3	17.6	9.622 (0.356, 18.889)	-0.125 (-0.255, 0.006)	<0.05
Protomelas taeniolatus	M	101.9	18.5	12.115 (1.282, 22.947)	-0.119 (0.243, 0.005)	<0.05
Pseudotropheus sp williamsi mbenji	F	71.0	17.5	8.891 (-139.331, 157.113)	-0.125 (-2.165, 1.914)	>0.05
Pseudotropheus sp williamsi north	F	68.9	5.4	28.048 (-188.776, 244.871)	-0.407 (-3.395, 2.580)	>0.05
Tropheops gracilior	F	65.4	14.2	10.122 (-20.558, 40.801)	-0.155 (-0.595, 0.286)	>0.05
Tropheops gracilior	M	77.1	2.8	61.242 (37.400, 85.085)	-0.795 (-1.106, -0.483)	<0.05
Tropheops sp lilac Chindunga	F	68.1	8.6	17.329 (-15.948, 50.605)	0.254 (-0.700, 0.191)	>0.05
Tropheops sp lilac Chindunga	M	78.8	10.4	16.563 (-2.656, 35.782)	-0.210 (-0.468, 0.047)	>0.05
Tropheops sp mbenji yellow	F	72.3	12.1	13.114 (1.937, 24.290)	-0.1813 (-0.324, -0.038)	<0.05
Tropheops sp mbenji yellow	M	83.1	20.4	8.934 (-3.317, 21.185)	-0.108 (-0.247, 0.032)	>0.05

Visual inspection of the observed and predicted values of maturity ogives of the logistic regression model generally show that the model fitted well to the data for most fish species except for male *L. fuelleborni*, females for *Pseudotropheus* sp williamsi north, *Pseudotropheus* sp williamsi mbenji and *Tropheops gracilior* (Figure 4-1) and male *Tropheops* sp mbenji yellow (Figure 4-2).

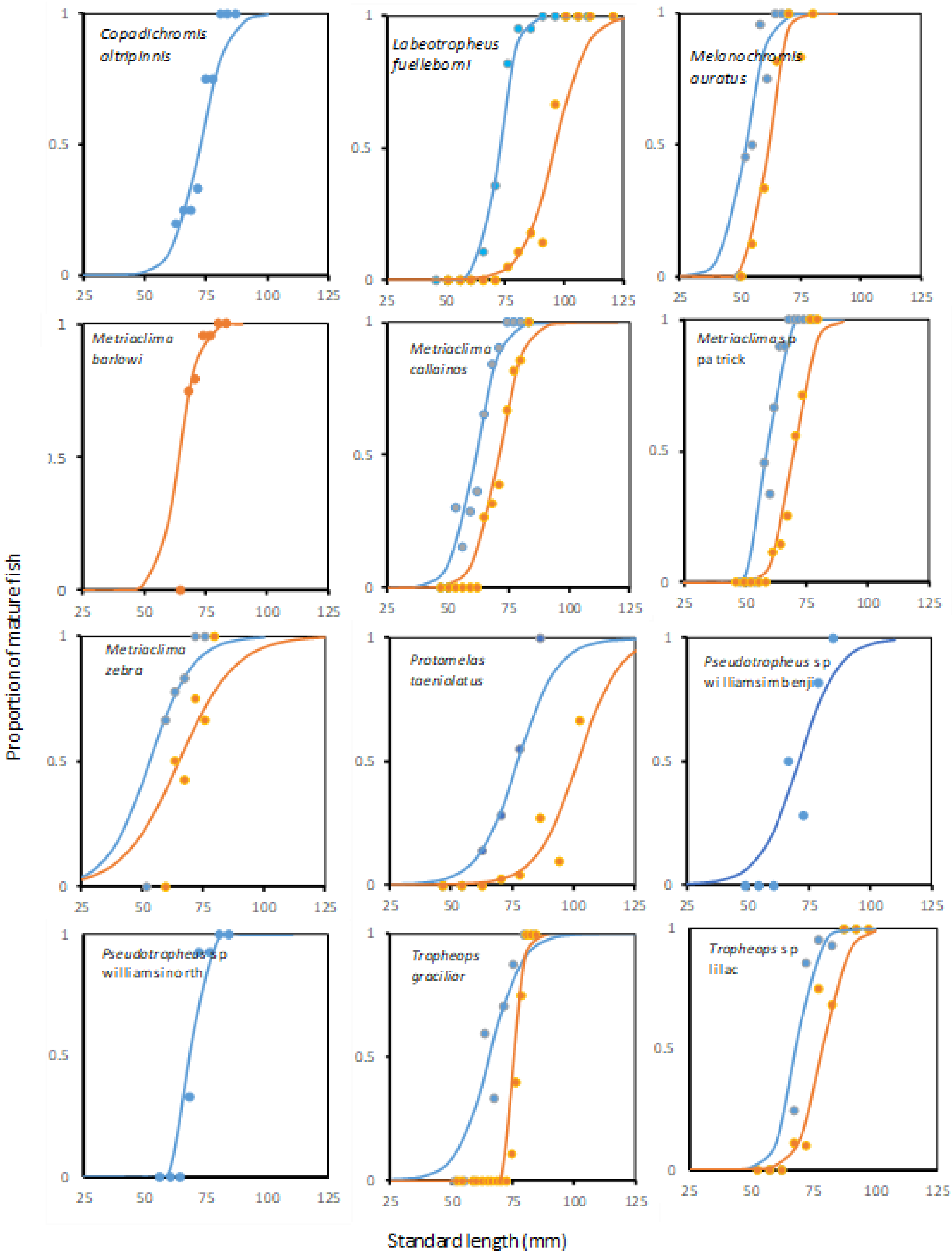

Figure 4-1. Maturity ogives *for Copadichromis atripinnis*, *Labeotropheus fuelleborni, Melanochromis auratus*, *Metriaclima barlowi*, *Metriaclima callainos*, *Metriaclima* sp patricki*, Metriaclima zebra*, *Protomelas taeniolatus*, *Pseudotropheus* sp williamsi mbenji, *Pseudotropheus* sp williamsi north, *Tropheops gracilior* and *Tropheops* sp lilac from Lake Malawi based on logistic regression model. Lines denote predicted values while dots represent observed values. Blue colour represents female fish while orange colour represents male fish.

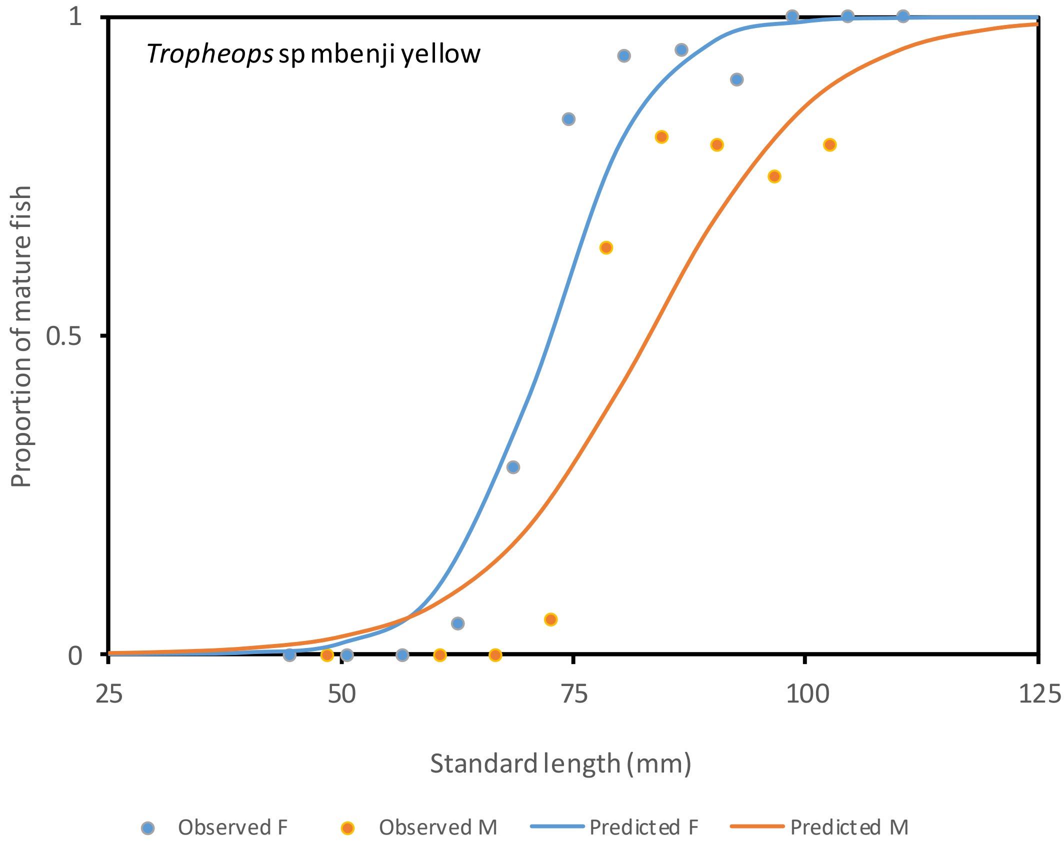

Figure 4-2 Maturity ogive for *Tropheops* sp mbenji yellow based on the logistic regression model. Observed F represents observed values for female fish, Observed M represents observed values for male fish, Predicted F represents predicted values for female fish, Predicted M represents predicted values for male fish.

Minimum size at maturity: The minimum sizes at maturity for males of fish species whose size at 50% maturity could not be estimated using the logistic regression model, ranged from 53 mm for *Labidochromis mbenjii* to 100 mm for *Petrotilapia* sp fuscous (Table 4-4). Minimum size at maturity amongst female fish ranged from 43 mm for *Labidochromis mbenjii* to 84 mm for *Petrotilapia* sp fuscous. Males of all examined fish species had larger minimum sizes at sexual maturity than females (Table 4-4).

Table 4-4. The minimum size at sexual maturity for the examined fish. Note that "-" shows no mature fish either because none of the examined specimens were mature or because the sex of fish being considered was not represented by the examined fish specimens.

Fish Species name	Minimum size at sexual maturity (mm)	
	Males	Females
Copadichromis borleyi	-	70
Cynotilapia aurifrons	55	50
Genyochromis mento	-	61
Labeotropheus trewavasae	77	70
Labidochromis ianthinus	59	54
Labidochromis mbenjii	53	43
Melanochromis heterochromis	63	55
Metriaclima barlowi	-	68
Metriaclima mbenjii	92	71
Petrotilapia genalutea	89	83
Petrotilapia sp fuscous	100	84
Pseudotropheus sp williamsi north	77	-
Pseudotropheus sp williamsi mbenji	77	-
Tropheops sp mauve yellow	95	60
Tropheops sp olive	72	60

4.3.2 Fish fecundity

Absolute fecundity: Ripe female fish were found in 22 of the examined fish species. Average of absolute fecundity of the sampled fish species ranged from 16±4.7 eggs for *Labidochromis mbenjii* to 90.5±12.0 eggs for *Petrotilapia* sp fuscous (Table 4-5). These fecundity values are lower than that of most large non *mbuna* haplochromis cichlids fishes of Lake Malawi of the genera *Buccochromis*, *Alticorpus*, *Lethrinops*, *Taeniolethrinops*, *Rhamphochromis* and *Otopharynx* (see summary of absolute fecundities of various cichlids of Lake Malawi in appendix 4.1). The results shown in Table 4-5 shows wide absolue fecundity standard deviation values relative to the mean absolute fecundity for some species such as *Metriaclima callainos*, *Petrotilapia genalutea*, *Genyochromis mento*, *Metriaclima zebra*, *Labeotropheus fuelleborni* OB and *Labeotropheus trewavasae*. This suggests wide variation of absolute fecundity for individuals of the same fish species due to their different standard lengths.

However, the absolute fecundity values found in this study are based on limited numbers of ripe female fish, which may not be representative of the sampled populations of fish. It was against ethical regulation of the University of Hull to further increase the sample sizes of fish, which could have provided a clearer picture of the fish fecundities.

Kruskal Wallis test suggested significant differences ($p<0.001$) of absolute fecundity between different fish species.

Table 4-5. Average absolute fecundity of the sampled rock-dwelling cichlid fish species of Lake Malawi.

Species name	**Number of ripe females**	**Standard Length range (mm)**	**Absolute fecundity (mean ± SD)**
Metriaclima callainos	30	52-82	32.6 ± 15.2
Labeotropheus fuelleborni[11]	28	85-105	32.4 ± 8.9
Tropheops sp mbenji yellow	22	67-92	45.9 ± 10.4
Metriaclima barlowi	17	68-74	53.9 ± 14.0
Tropheops sp lilac	15	70-88	44.3 ± 11.7
Metriaclima sp patricki	11	60-79	41.7 ± 13.3
Melanochromis auratus	10	53-71	20.9 ± 7.1
Tropheops gracilior	9	65-80	36.8 ± 10.0
Protomelas taeniolatus	9	66-78	34.3 ± 4.6
Metriaclima zebra	7	62-70	30.9 ± 10.8
Pseudotropheus sp williamsi north	7	70-80	30.0 ± 5.5
Copadichromis atripinnis	7	70-87	31.4 ± 8.3
Labidochromis mbenjii	5	43-60	16.0 ± 4.7
Pseudotropheus sp williamsi mbenji	5	74-85	46.0 ± 5.4
Labidochromis ianthinus	4	65-69	18.5 ± 3.1
Petrotilapia genalutea	3	101-105	82.7 ± 34.5
Labeotropheus fuelleborni OB[12]	3	74-110	39.0 ± 18.0
Petrotilapia sp fuscous	2	103-108	90.5 ± 12.0
Genyochromis mento	2	61-78	38.0 ± 14.1
Tropheops sp mauve yellow	2	74-78	19.5 ± 0.7
Copadichromis borleyi	2	80-91	37.5 ± 6.4
Labeotropheus trewavasae	2	81-83	24.5 ± 14.8

Fecundity length relationship: For most of the fish species examined, the number of ripe females sampled were very limited to yield meaningful relationship between fecundity and length. Scatter plots of the relationships between absolute fecundity and standard length for nine of the sampled fish species are shown in Figure 4-3, Figure 4-4, and Figure 4-5. The scatter plots suggested positive correlation between absolute fecundity and standard length of fish although the strength of the correlation appeared to vary between species. This positive correlation contributed to wide variation of absolute fecundity for some fish species in Table 4-5.

[11] All the specimens were between 85 and 95 mm except one exceptionally very large female at 105 mm
[12] Two specimens of fish were 74 and 87 mm but there was one unusually large female at 110 mm.

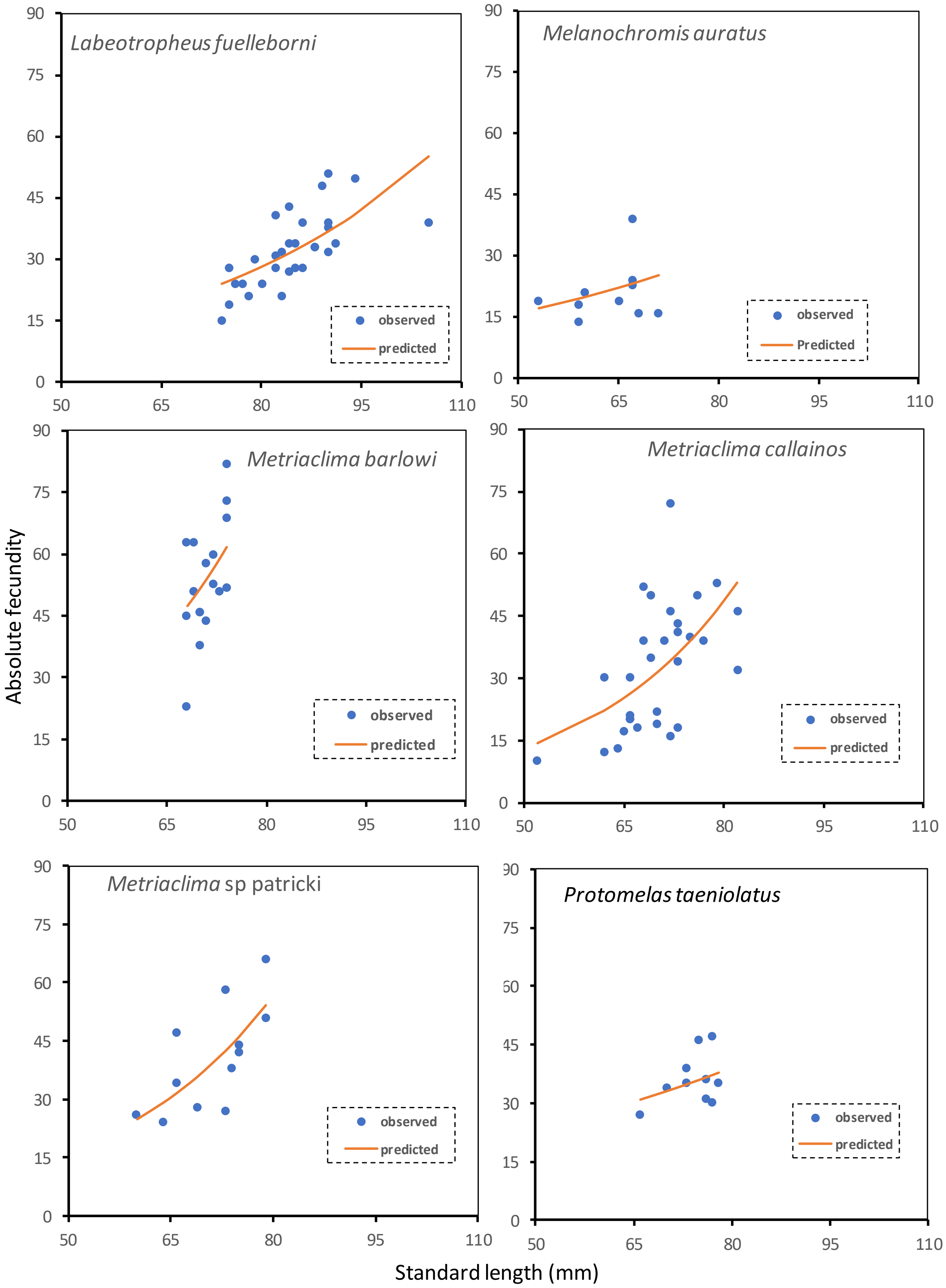

Figure 4-3. Fecundity length relationship for *Labeotropheus fuelleborni*, *Melanochromis auratus*, *Metriaclima barlowi*, *Metriaclima callainos*, *Metriaclima* sp patricki and *Protomelas taeniolatus*.

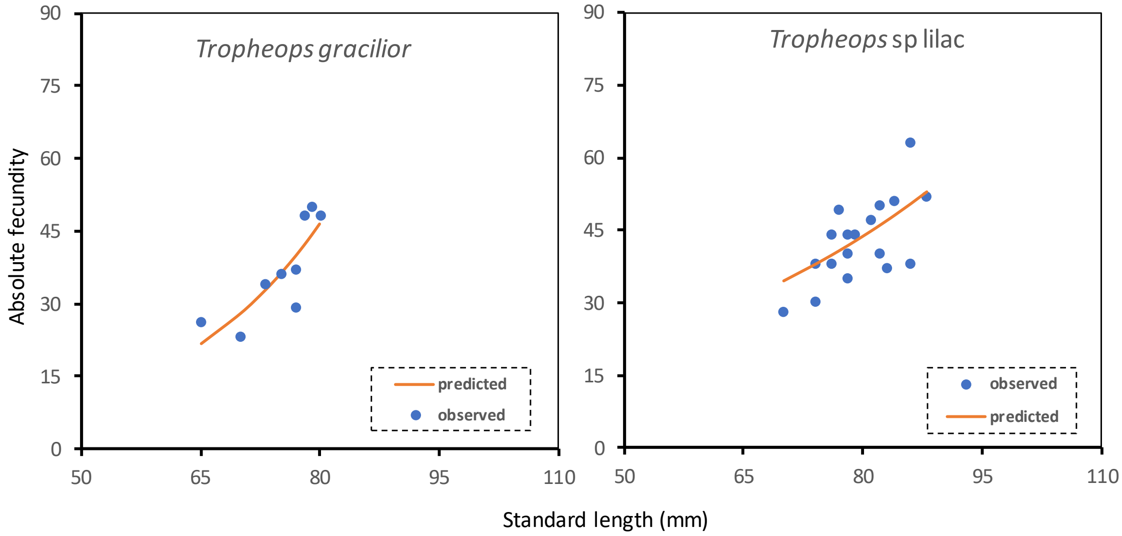

Figure 4-4. Fecundity length relationship for *Tropheops gracilior* and *Tropheops* sp lilac.

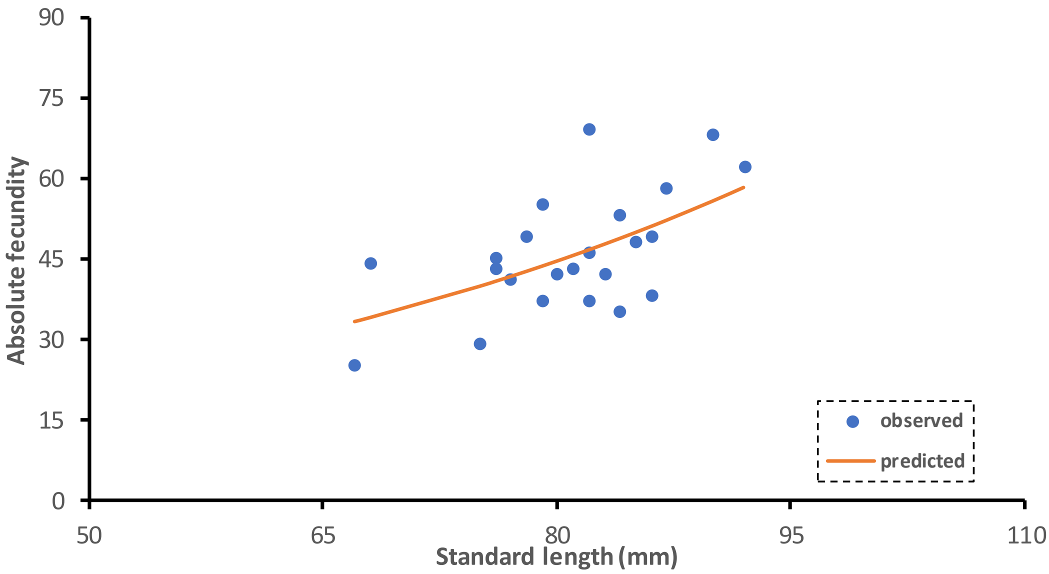

Figure 4-5. Fecundity length relationship for *Tropheops* sp mbenji yellow.

Results of the generalized linear model (glm) fit to the relationship between absolute fecundity and standard length of selected fish species are presented in Table 4-6. The GLM confirmed significant positive relationships between absolute fecundity and standard length for the following fish species: *Labeotropheus fuelleborni* ($p<0.001$), *Metriaclima callainos* ($p<0.01$), *Metriaclima* sp patricki ($p<0.05$), *Tropheops gracilior* ($p<0.001$) and *Tropheops* sp mbenji yellow ($p<0.01$). There was no evidence ($p >0.05$) to support any relationship between absolute fecundity and standard length for *Metriaclima barlowi*, *Melanochromis auratus*, *Protomelas taeniolatus* and *Tropheops* sp lilac.

Table 4-6. Outputs of the generalized linear model with Poisson errors fit to the data of absolute fecundity and standard length of different ornamental fish species of Lake Malawi. The model parameter estimates are in natural logs which were antilogged when drawing the predicted lines in Figure 4-3, Figure 4-4 and Figure 4-5.

Species name	Intercept	Slope	SE Slope	Slope p-Value
Labeotropheus fuelleborni	1.180549	0.026953	0.00462	<0.001
Melanochromis auratus	1.7099	0.0213	0.0116	>0.05
Metriaclima barlowi	0.88923	0.04370	0.02383	>0.05
Metriaclima callainos	0.393301	0.043647	0.005412	<0.01
Metriaclima sp patricki	0.74041	0.041181	0.008836	<0.05
Protomelas taeniolatus	2.27981	0.01738	0.01554	>0.05
Tropheops gracilior	-0.22410	0.05080	0.01368	<0.001
Tropheops sp lilac	1.89816	0.02350	0.01206	>0.05
Tropheops sp mbenji yellow	2.024783	0.022174	0.006968	<0.01

4.3.3 Egg sizes

Comparisons of egg diameters of different fish species: Average fish egg diameter[13] ranged from 2.7 ± 0.35 mm for *Metriaclima barlowi* to 3.9 ± 0.33 mm for *Tropheops* sp mbenji yellow (Figure 4-6). Generally standard deviation values of egg diameter for individual fish species were low relative to their average egg diameter, suggesting high uniformity of egg sizes amongst indiduals of the same species.

One-way analysis of variance showed that there were highly significant differences of egg diameter between fish species (F= 9.20, P < 0.0001). Post hoc Tukey test, which generated 105 pair combinations from the 15 species of fish compared, showed that only 17 of the species pair combinations had statistically significant different average egg diameters (p<0.05) while the rest (88 species pairs) were not statistically significant (p>0.05). The significantly different pairs included: *Tropheops* sp mbenji yellow and *Copadichromis atripinnis* (p<0.05), *M. auratus* and *L. fuelleborni* (p<0.05), *M. barlowi* and *L. fuelleborni* (p<0.0001), *Metriaclima callainos* and *L. fuelleborni* (p<0.0001), *Metriaclima barlowi* and *Labidochromis mbenji* (p<0.01), *Tropheops* sp mbenji yellow and *M. auratus* (p<0.05), *M. callainos* and *M. barlowi* (p<0.01), *Metriaclima* sp patricki and *M. barlowi* (p<0.001), *Metriaclima zebra* and *M. barlowi* (p<0.05), *Protomelas taeniolatus* and *M. barlowi* (p<0.001), *Pseudotropheus* sp williamsi north and *M. barlowi* (p<0.001), *Tropheops gracilior* and *M. barlowi* (p<0.0001), *Tropheops* sp lilac and *M. barlowi*

[13] Computed for species of fish that had more than six ripe females

(p<0.0001), *Tropheops* sp mbenji yellow and *M. barlowi* (p<0.0001), *Tropheops* sp lilac and *M. callainos*, (p<0.01), *Tropheops* sp mbenji yellow and *M. callainos* (p<0.001) and *Pseudotropheus* sp williamsi mbenji and *M. barlowi* (p<0.05).

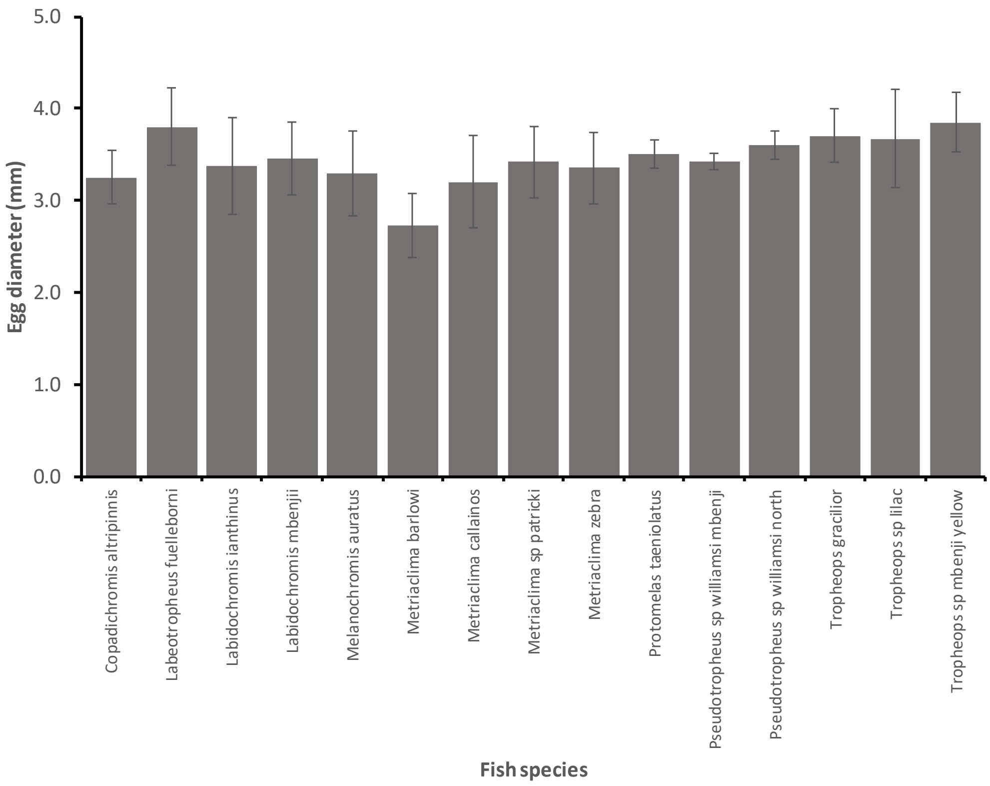

Figure 4-6. Average egg diameter (±SD) of rock-dwelling cichlid fish species sampled from Lake Malawi between August and September 2018.

Some of sampled species of fish were not included in Figure 4-6 because the samples comprised of insufficient number of ripe females for comparison of their average egg diameter with the other fish species.

The average egg diameter based on the examined genera ranged from 3.1±0.50 mm for the genus *Metriaclima* to 3.8±0.42 mm for the genus *Labeotropheus* (Figure 4-7). One-way ANOVA showed highly significant differences (F=12.38, p<0.001) of egg diameter between genera of fish. However, of the 28 pairwise combinations of the eight genera tested, Tukey test showed significantly different egg diameter for only four pairs of genera including: *Melanochromis* and *Labeotropheus* (p<0.05), *Metriaclima* and *Labeotropheus* (p<0.0001), *Tropheops* and *Melanochromis* (p<0.05) and *Tropheops* and *Metriaclima* (p<0.0001). There was no evidence for differences of egg diameter for the other 24 pairs of the genera (p>0.05).

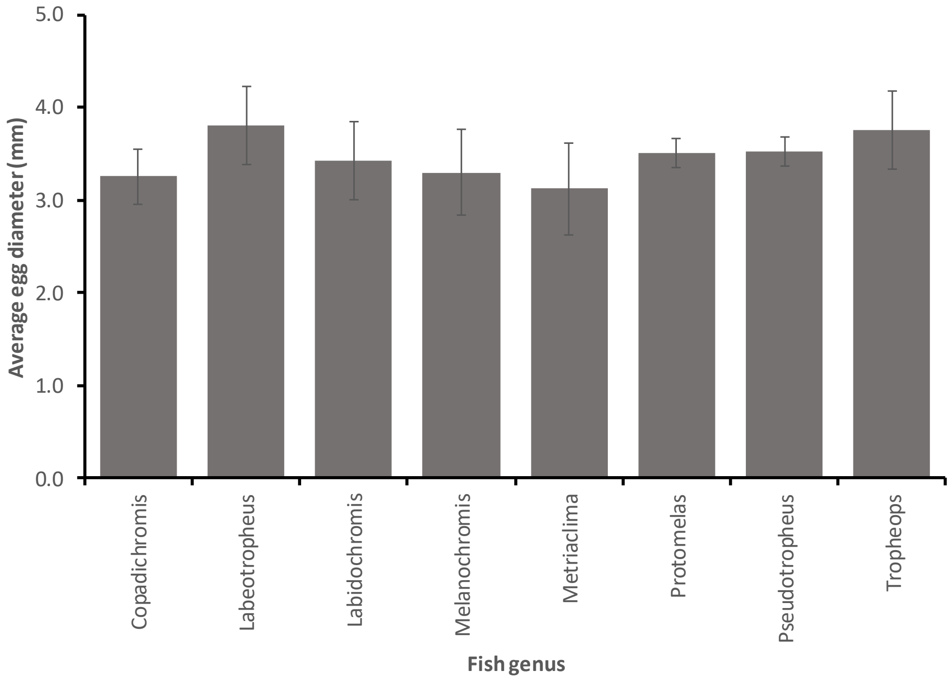

Figure 4-7. Average egg diameter (±SD) of eight genera of ornamental cichlid fish species sampled from Lake Malawi between July and September 2018.

Relationship between egg diameter and absolute fecundity:

As pointed out at the beginning of section 4.3.2, fish fecundity data presented in this study are based on limited numbers of ripe female fish. This has provided limited insights about existing relationships between egg diameter and absolute fecundity. Scatter plots of egg diameter against absolute fecundity for the limited numbers of 14 of the sampled cichlid fish species are presented in Figure 4-8 and Figure 4-9. The scatter plots suggest that there was no association between egg diameter and absolute fecundity for most fish species except *M. barlowi*, *M. callainos* and *T. gracilior* which showed negative association between egg diameter and absolute fecundity. The strength of the associations between egg diameter and absolute fecundity for individual fish species were tested using the Spearman’s correlation test the results of which are presented in the following section.

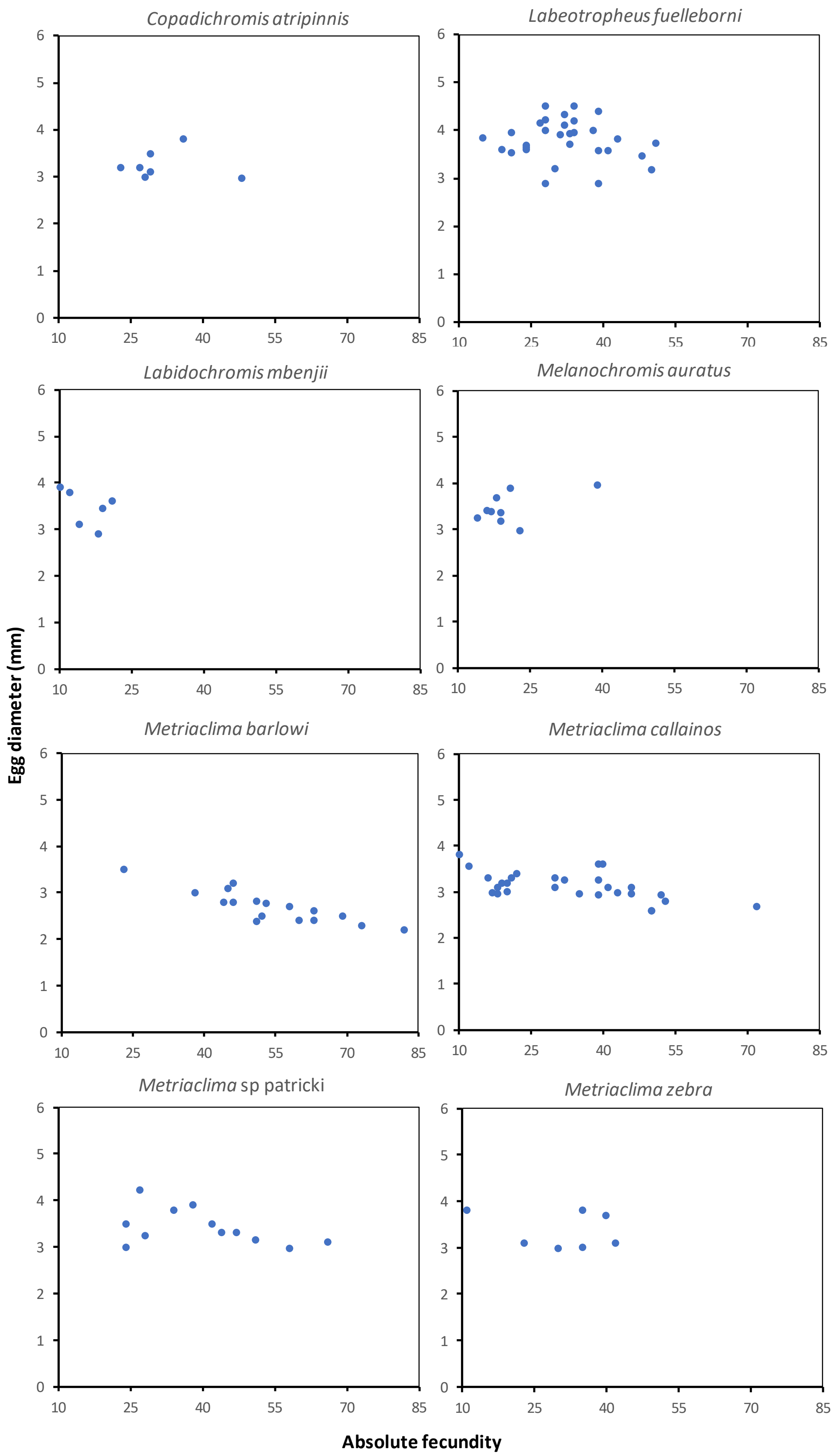

Figure 4-8. Scatter plot of egg diameter against absolute fecundity of *Copadichromis atripinnis*, *Labeotropheus fuelleborni*, *Labidochromis mbenjii*, *Melanochromis auratus*, *Metriaclima barlowi*, *Metriaclima callainos*, *Metriaclima* sp patricki, and *Metriaclima zebra*.

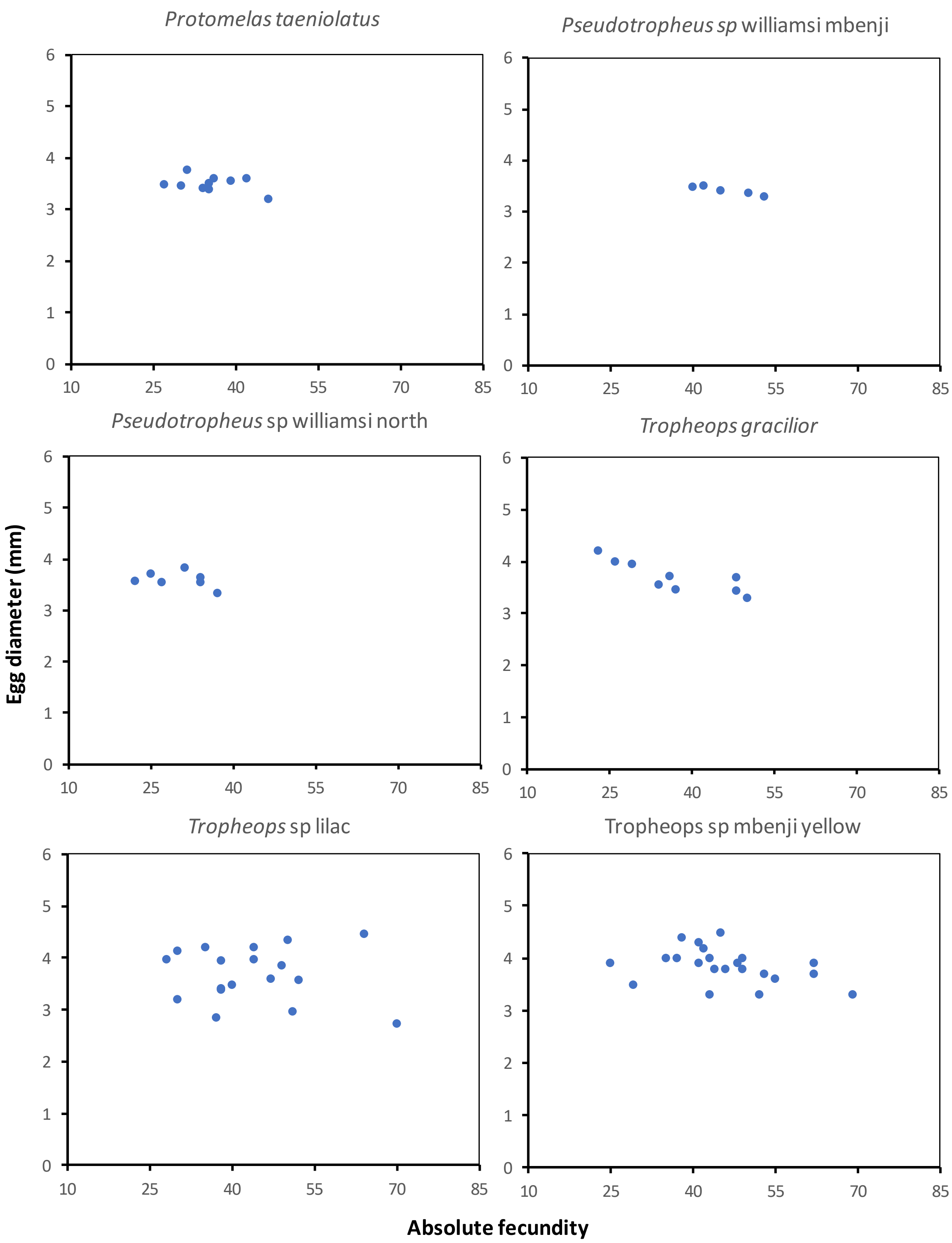

Figure 4-9. Scatter plot of egg diameter against absolute fecundity of *Protomelas taeniolatus*, *Pseudotropheus* sp williamsi mbenji, *Pseudotropheus* sp williamsi north, *Tropheops gracilior*, *Tropheops* sp lilac and *Tropheops* sp mbenji yellow.

Results of a Spearman's correlation test between egg diameter and absolute fecundity for the 14 species presented in the scatterplots in Figure 4-8 and Figure 4-9 are summarized in Table 4-7. Significant negative monotonic correlation existed between egg diameter and absolute fecundity for only four fish species including *M. barlowi* (rho(15) = -0.8352, p<0.001), *M.*

callainos (rho(26) = -0.5873, p<0.01), *T. gracilior* (rho(7) = -0.8954, p<0.01) and *Tropheops* sp mbenji yellow (rho(19) = 0.4557, p<0.05). There was no significant correlation (p>0.05) between egg diameter and absolute fecundity of the other 10 fish species (Table 4-7).

Table 4-7. Spearman's correlation of the relationship between egg diameter and absolute fecundity for fourteen cichlid fish species from Lake Malawi.

Species names	Spearman correlation coefficient (rho)	p-value
Copadichromis atripinnis	-0.1091	0.8159
Labeotropheus fuelleborni	-0.0809	0.6708
Labidochromis mbenjii	-0.4857	0.3556
Melanochromis auratus	-0.1789	0.5779
Metriaclima barlowi	-0.8352	<0.0001
Metriaclima callainos	-0.5873	<0.01
Metriaclima sp patricki	-0.4333	0.1594
Metriaclima zebra	-0.1009	0.8295
Protomelas taeniolatus	-0.0304	0.9336
Pseudotropheus sp williamsi mbenji	-0.9	0.0833
Tropheops gracilior	-0.8954	<0.01
Tropheops sp lilac	-0.0393	0.8768
Tropheops sp mbenji yellow	-0.4557	<0.05
Pseudotropheus sp williamsi north	-0.4865	0.2682

4.4 Discussion

4.4.1 Size at maturity

In this study, logistic regression models were used to estimate the standard length at sexual maturity for 13 species of fish belonging to 7 of the top 10 most commonly exported genera of ornamental fish from Lake Malawi.

The estimated size at maturity varied between species and between sexes with males of all species having larger sizes than females. The observed size differences between males and females appears to be universal for all cichlid fishes of Lake Malawi (personal observations) and it could be linked to breeding behaviour. Cichlid fishes of Lake Malawi exhibit territorial behaviour where male reproductive success is dependent on ownership of a territory to attract females that are ready to spawn (Hert, 1990; Munthali, 1996). Ownership and maintenance of a territory is dependent on winning fights or display of aggression behaviour towards both conspecific and heterospecific species (Hert, 1990). Under such circumstances larger size for males could be an important factor for ownership and maintenance of a territory.

While a few life history traits have been studied for a number of demersal and / or semi pelagic fish species of Lake Malawi caught by trawling (Thompson *et al.,* 1996; Duponchelle *et al.,* 2000a), there are limited studies of life history traits of the rock-dwelling cichlid fishes of Lake Malawi (Marsh *et al.,* 1986; Munthali & Ribbink, 1998), against which to compare the findings of the current study. Moreover, as stated in Section 4.1, previous studies of the life history traits of rock-dwelling cichlids of Lake Malawi cover only a very small proportion of these species in Lake Malawi.

However, some insights can be gained by comparing findings of the current study with a few worldwide studies of fish life history traits conducted on a wide range of fish species in a wide variety of habitats ranging from freshwater to marine systems.

In their study of pike perch [*Sander lucioperca* (Linnaeus, 1758)] in six exploited populations in southern and eastern Finland, Olin *et al.* (2018) found that maturation size was positively dependent on growth rate but decreased with an increase in fish body condition. Ferreri *et al.* (2019) found that size at maturity of horse mackerel [*Trachurus trachurus* (Linnaeus, 1758)] significantly varied between two sampling areas of the Mediterranean Sea and the authors attributed this to differences in habitat conditions between the two areas. Using annual cohort estimates of yellow perch [*Perca flavescens* (Mitchill, 1814)] size at maturity in Lake Erie, Gíslason *et al.* (2018) found wide variation of size at maturity between 1991 and 2013. Furthermore, Gíslason *et al.* (2018) found no evidence to link annual changes in size at maturity to either fishing intensity or the individual juvenile growth rates. Based on their findings, Gíslason *et al.* (2018) concluded that Lake Erie yellow perch length at maturity probably fluctuated in response to annual variation in an unknown environmental factor other than fishing intensity. Liao *et al.* (2018) investigated how the reproductive traits of three congeneric yellow catfish species (*Pelteobagrus* spp) responded to environmental changes following establishment of the Three Gorges Reservoir in the upper reach of Yangtze River by comparing fish reproductive traits responses amongst the lower, middle and upper sections of the reservoir, representing the lentic, transitional and lotic habitats. Significant differences of size at sexual maturity across the three zones of the reservoir were reported and the authors attributed the differences to genetic differences and differences of the environmental conditions. Rius *et al.* (2019) demonstrated that size at maturity of the live bearing fish, *Poecilia vivipara* Bloch & Schneider, 1801, in six coastal lagoons of South eastern Brazil, was negatively related to the density of piscivores. Furthermore, these authors noted that higher dissolved oxygen and lower salinity were associated with smaller *P. vivipara* size at maturity which was attributed to indirect effects via piscivore density.

Review of the aforementioned studies shows that fish maturity sizes vary widely between and within fish species populations depending on various factors. Some of the factors that were identified to affect fish size at maturity in the aforementioned studies may also be applicable to the rock-dwelling cichlids of Lake Malawi. For instance, amongst the fish species studied, some, such as *L. fuelleborni*, *M. zebra* and *P. taeniolatus,* have lake wide distribution (IUCN 2019), while others are widely distributed only in one region of the lake, e.g. *M. auratus*, *M. barlowi* and *Metriaclima* sp *patrick* in the southern areas of Lake Malawi and *M. callainos* and *T. gracilior* in the northern part of the lake (Konings, 2016; IUCN, 2019). Such species are likely to occupy different habitat conditions with respect to the availability of their prey. Moreover, there is variation in primary productivity in various parts of Lake Malawi. The southern part of Lake Malawi is more productive than the northern part due to stronger upwelling of nutrients (triggered by the south easterly winds) in the shallower southern part of the lake than in the deeper northern part of the lake (Bootsma & Hecky, 1999). The expectation would be for populations of fish in the southern part of the lake to have access to more food resulting in higher growth rates and better condition, which may affect their sizes at maturity. Indeed, this was partly evident from the study of Munthali & Ribbink (1998) who demonstrated that populations of *M. callainos* and *Tropheops* sp red cheek, which were translocated at Thumbi West Island in LMNP located in the southern part of the lake, had better condition than at their sites of origin in the northern part of the lake at Nkhata Bay and Likoma Island respectively. Duponchelle *et al.* (2000c) observed that the condition factor of a few rock-dwelling cichlids of Lake Malawi was positively correlated with chlorophyll a biomass. Annual variation of sizes at maturity of various rock-dwelling fish species is likely to occur depending on the prevailing environmental factors that may affect fish growth. Within the shallow depth zone of the epilimnion layer of Lake Malawi (the depth range for the rock-dwelling cichlid fishes), there is little variability of water temperature and dissolved oxygen (Vollmer *et al.,* 1999), with surface water temperature ranging from 23 ˚c to 28 ˚c (Ribbink *et al.,* 1983; Konings, 2016). However, food availability may be more variable due to inter-annual variability of primary production, which is evident from high variability of chlorophyll a concentration within Lake Malawi (Bootsma & Hecky, 1999). Furthermore, Bootsma & Hecky, (1999) reported evidence of a north-south Lake Malawi gradient of chlorophyll a concentration with the southern end having more than three times the concentration of chlorophyll a of the northern pelagic regions.

There could also be annual variability of growth rates of individual fish in a population. Duponchelle *et al.* (2000b) observed that the von Bertalanffy parameters $L\infty$ and K varied significantly between cohorts of a single population of most demersal cichlid fish species caught by trawling in the south west arm of Lake Malawi, and suggested that variability of the growth parameters was due to food availability. Similar fish growth patterns would be expected within the neighbouring populations of rock-dwelling cichlid fishes that are experiencing similar habit conditions.

It was not possible to establish size at 50% maturity for some fish species due to sample size limitations. Even for those species where the size at 50% maturity size was estimated, an increase in sample size could have improved quality of estimates of parameters of the logistic regression model of fish size at maturity. The challenge of sample size limitation for estimation of fish size or age at maturity was also raised by Duponchelle *et al.* (2000c) and Roberts & Turner (2008). Some rock-dwelling fish species in Lake Malawi have limited population and distribution patterns (Ribbink *et al.,* 1983; Konings, 2016), which can prevent increasing the sample sizes beyond a certain level and thus preclude such studies. This study has provided insights about the sizes at maturity for a few rock-dwelling cichlid fish species. However, further studies based on larger sample sizes of widely distributed and abundant rock-dwelling fish, are required to establish the spatial and temporal variability of fish life history traits within populations of individual fish species. Also, there is a fundamental need to link size at maturity against age to understand the reproductive strategies of the different species and sub-populations.

Size at maturity is one of the most important parameters of fisheries management for estimating maximum length of a fish species, minimum catch size and instituting required size restrictions for fishing gears (Hashiguti *et al.,* 2019). Gear restrictions ensure protection of spawning stock and enable 50% of the stock to spawn at least once. Rock-dwelling cichlid fishes of Lake Malawi are exploited for both the ornamental fish export trade and subsistence fishing (see Section 2.4.5 in Chapter 2). According to field observations and interviews with fish exporters, both artisanal fishers and ornamental fish exporters target mature fish and not juveniles. Thus, size at capture may not be an issue for these fisheries but rather it is the fishing intensity on some localized populations of fish species that is of concern.

There is no age information for exploited ornamental fishes of Lake Malawi which could be directly linked to maturity size of these fish species. However, estimated generation length[14] of the 70 most exported described ornamental fish species which have been included in the assessment of risk from exploitation in Chapter 5 of this thesis, ranges from one to three years. Furthermore, analysis of the fish generation length data for the 70 species indicate that a

[14] In this context generation length is defined as the average age of parents of the current cohort of fish (IUCN Standards and Petitions SubCommitee, 2017)

majority of 35 (50%) of these fish species have a generation length of one year followed by 16 (22.9%) species with a generation length of one and half years (Figure 4-10). Assuming these estimated fish generation lengths to be realistic then the age at maturity for a majority of these fish species is less than one year suggesting that most of these fish species are short lived with the ability for quick recovery from overexploitation once the exploitation pressure is reduced. Moreover, a majority of these ornamental fish species of Malawi attain a relatively small size with a modal standard length between 86 mm and 118 mm (See Figure 5-2 in Chapter 5).

However, personal observations and information existing in websites of various traders of ornamental fish suggest that in aquarium environment these fish species live for many more years ranging from 3 to 10 years depending on the care provided. Thus, further investigations are required regarding maturity ages and life spans of wild ornamental fish populations of Lake Malawi.

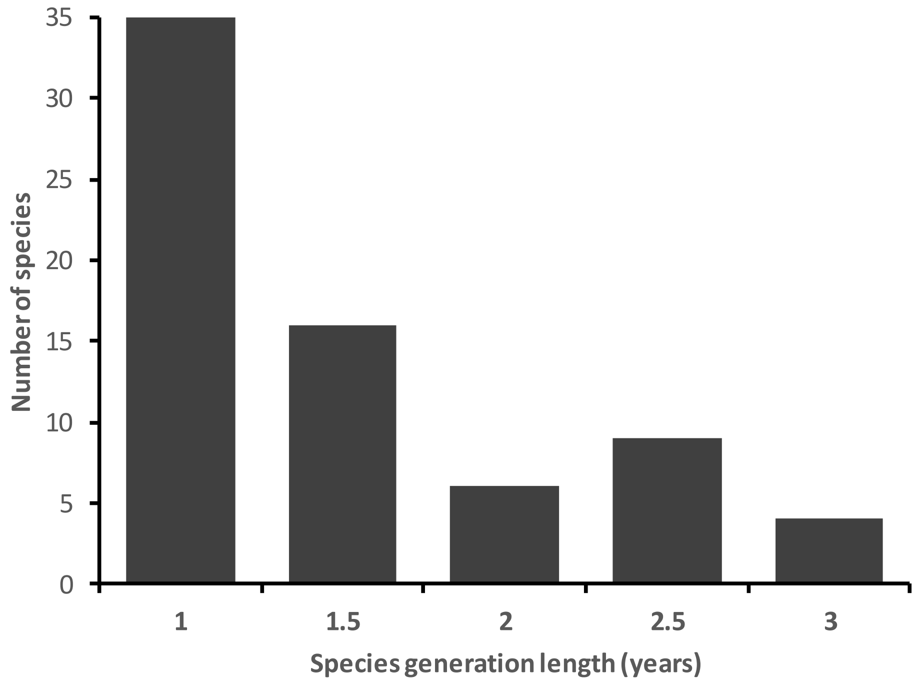

Figure 4-10. The number of commonly exploited ornamental fish species of Lake Malawi according to their estimated generation length. Generation length information was sourced from IUCN (2019). Where a two-year range of the generation length was presented an average value was computed and used in this graph.

The information about fish size at maturity established in this study matched against size of exploitation will be very useful as baseline for developing models for managing the stocks of rock-dwelling fish species of Lake Malawi.

4.4.2 Absolute fecundity and fecundity length relationships

This study showed wide variations of absolute fecundity amongst the species of fish sampled. Apart from the studies of Marsh *et al.* (1986), Thompson *et al.* (1996) and Duponchelle *et al.* (2000a), there are limited reports about absolute fecundity for Lake Malawi cichlid fishes, and the few reports that were accessed and reviewed showed that absolute fecundities vary greatly between species (Appendix 4.1).

The absolute fecundity range of 16±4.7 to 90.5±12.0 eggs obtained in this study (Table 4-5) was within the range of the reported absolute fecundity values of 2.8±2.93 eggs for *M. callainos* to 267- 627 eggs for *Buccochromis lepturus* (Appendix 4.1). There were five common species between the current study (Table 4-5) and the reviewed previous studies (Appendix 4.1), four of which showed similar absolute fecundity values (i.e. overlapping absolute fecundity ± SD values) between the current and previous studies. The species with similar fecundities include: *L. fuelleborni* (32.4 ± 8.9 eggs for the current study versus 22.5 ± 5.6 eggs and 26.9 ± 8.2 eggs for Monkey Bay and Likoma respectively); *M. auratus* (20.9 ± 7.1 eggs in this study versus 20.8 ± 5.8 eggs at Thumbi west Island), *P. taeniolatus* (34.3 ± 4.6 eggs in this study versus 29.0 ± 7.3 eggs for Monkey Bay), and *P. zebra* (30.9 ± 10.8 eggs in the current study versus 26.0 ± 6.7 eggs for Monkey Bay). There was a wide discrepancy of *M. callainos* absolute fecundity value between the current study (36.2±15.2 eggs) and the previous reports for Nkhata Bay population (2.79±2.93 eggs) and introduced population at Thumbi West Island (5.18±2.47 eggs). The similarity of fecundity values for the studies of different populations of the same fish species conducted in different areas and decades apart, suggests that absolute fecundity for these species is fairly uniform across populations and in different years. However, since absolute fecundity does not take into account size of individual fish, the values of absolute fecundity may be similar for fish that are of different weight or sizes (Munthali & Ribbink, 1998). In this study it was not possible to estimate relative fecundities of fish because it was difficult to measure weights of individual fish and ovaries due to persistent electricity blackout problems, which lead to inability to use the sensitive digital weighing scales that needed electricity to operate.

The wide discrepancy of *M. callainos* absolute fecundity between the current study and that of Munthali & Ribbink (1998) may be attributed to the differences in methodology for fecundity estimation. In the current study, fecundity was estimated based on stage 4 ovaries only while Munthali & Ribbink (1998) also included counts of eggs in the mouths of brooding females. The latter is likely to have underestimated absolute fecundity because after being laid, some eggs were very likely to have been lost to predation before they got picked into the mouths of the brooding females.

Marsh *et al.* (1986) observed that most of the few rock-dwelling cichlid fishes they studied at Monkey Bay, Thumbi West Island and Likoma Island had bimodal pattern of reproduction with the major peak occurring between August and October and a secondary peak between February and March. This was also collaborated by Munthali & Ribbink (1998) who observed that *Cynotilapia afra* and *Tropheops* sp red cheek (at Likoma Island and Thumbi West Island), and *M. callainos* (at Nkhata Bay and Thumbi West Island) bred throughout the year but with two peaks of monthly absolute fecundity during mid of the rainy season in February and at the end of the upwelling season in September. The current study was conducted between the months of August and November, which covered the major peak period observed by Marsh *et al.* (1986).

Only five of the nine fish species examined showed significant association between absolute fecundity and standard length. The positive association between these two variables supports findings of most of the previous studies. Tweddle & Turner (1977) reported a linear relationship between absolute fecundity and total length of five cichlid species of Lake Malawi – *C. mloto*, *L. parvidens*, *L. longipinnis* and *T. intermediu*s - but a power function for *M. anaphyrmus*. The positive association between fecundity and length of fish has also been reported for: *Tilapia mariae* in the Iba Oku Stream in Uyo, Nigeria (King & Etim, 2004), *Oreochromis niloticus* in man-made lakes of Côte d'Ivoire (Duponchelle *et al.,* 2000d), Arctic char in Lake Skogsfjordvatn in Norway (Smalås *et al.,* 2017) and across 26 families of freshwater and marine fishes by Elgar (1990). McKaye (1983) reported positive correlation between the number of eggs in the ovary and standard length of *Mchenga eucinostomus* at Cape Maclear in Lake Malawi only when the diameter of the largest eggs was $\geq$3.0 mm, but there was no correlation of the two variables for smaller sized eggs. In their review of reproductive characteristics of pike fish, Olin *et al.* (2018) noted that absolute fecundity not only increased with length, weight and age of fish but also depended on food supply and condition of spawners. Kamler (2005) cited studies of a few fish species in which female size explained a large part (>66%) of the relationship between absolute fecundity and female body size. Additionally, review by Kamler (2005) revealed that the relationship between absolute fecundity and female body length (L) in many fish species was described by the equation: *Absolute fecundity = a*L^b, of which the coefficients *a* and *b* vary between and within fish species depending on environmental factors. This relationship was also obtained for *Sarotherodon galilaeus* (Linnaeus, 1758) in natural lakes of Southern Benin in West Africa (Adite & Thielen, 1995).

One possible reason for not finding relationships between absolute fecundity and standard length in four fish species in the current study could be related to limited sample sizes of ripe female fish obtained. Scrutiny of the scatter point graphs (Figure 4-3,Figure 4-4, and Figure 4-5) suggests that fish species with relatively larger samples of ripe females tended to have significant associations while species with lower samples of ripe females had non-significant association between absolute fecundity and standard length. This is likely caused by all the small sized fishes being approximately the same size thus the data are clumped.

4.4.3 Variation of fish egg size

This study has shown that fish egg sizes varied between species and genera in Lake Malawi. The differences in egg size between species and genera is surprising given that the species studied have similar reproductive traits of mouth brooding the young. The large size of eggs in most of the species reflects the small number of large eggs incubated in each batch in cichlids and the parental care behaviour exhibited by most species (Konings, 2016). Also, only four of 14 species examined showed significant negative correlations between egg diameter and absolute fecundity while most of the species showed non-significant negative correlation of the two variables.

Many previous studies that are summarized in Duponchelle *et al.* (2000d), Kamler (2005) and Johnston (2018), reported that egg size was negatively correlated with absolute fecundity in many fish species. However, this is contrary to the relationship between egg size and absolute fecundity for the majority of the cichlid fish species in the current study and reflects the spawning and mouth brooding behaviour of these cichlids. This discrepancy of the current study from other studies could also be related to the error margin associated with analysis of insufficient sample sizes of the fish in this study. As pointed out in section 4.3.2, the Ethical Clearance Committee of the University of Hull approved collection of only limited sample sizes of the fish which could not provide clear insights about the investigated reproductive traits of the fish.

4.4.4 Fish life history

One possible way of visualizing all the parameters investigated in this chapter (fish maturity sizes, fecundity and eggs sizes) is from the perspective of the life history theory. It has been suggested that trade-offs of life history traits, such as egg size and fecundity, exist to maximize individual fitness (Elgar, 1990). Fitness for a given fish, measured as a product of juvenile survival and fecundity, can be maximized at an optimum egg size (Smalås *et al.,* 2017). Differences in adaptation to specific habitats could lead to differences in the trade-off between fecundity and egg size amongst different fish populations or species (Smalås *et al.,* 2017).

Cichlid fishes of Lake Malawi are mouth brooders, which are generally known to produce few but large eggs when compared to other fish species (Ribbink *et al.,* 1983; Munthali & Ribbink 1998, Duponchelle *et al.,* 2000a). One of the predictions of the life history theory is that low fecundity and large egg size should be associated with high juvenile mortality (Duponchelle *et* *al.,* 2000d). Fryer & Iles (1972 cited by Duponchelle *et al.,* 2008) suggested existence of high predation pressure on young fish in the crowded rocky shores of the African Great lakes. Larger egg sizes for cichlids may supply the developing embryo with adequate energy reserves and nutrients to enable them to hatch at a larger size which may make them less vulnerable to predation (Sargent *et al.,* 1987; Kamler, 2005; Duponchelle *et al.,* 2008) and be capable of feeding independently (Munthali & Ribbink 1998). A mouth brooding parental strategy would further increase fitness by reducing mortality of the young before they are released by the parent. Taborsky & Foerster (2004) experimentally demonstrated that females of *Ctenochromis horei* cichlid from Lake Tanganyika incubated the young for a significantly longer time (4.3 days) when a predator of the young was present during brooding than in the absence of the predator. Low fecundity and large egg size for the cichlid fishes are indications of high levels of parental investment per offspring (Duponchelle *et al.,* 2008).

4.4.5 Conclusions and recommendation for management of the ornamental fishery of Lake Malawi

This chapter has generated substantial amount of information regarding maturity sizes, fecundities and eggs sizes for a number of cichlid fish species of Lake Malawi. Additionally, size at capture may not be an issue for the ornamental fishery of Lake Malawi as the fishery appears to target mature size classes of the *mbuna* fish. The average of individual fish species absolute fecundity ranged from 16±4.7 to 90.5±12.0 eggs and about half of the studied fish species showed significant positive association between absolute fecundity and standard length. Egg sizes significantly varied between fish species and genera. The findings of this study have been compared with findings from related studies in other fish species in both freshwater and marine habitats, and widened the knowledge base on life history traits of the cichlid fishes of Lake Malawi, which can be used in future management decisions for the studied fish species.

Since the ornamental cichlid fish species included in this study are a small proportion of the targeted ornamental cichlid fishes of Lake Malawi, it is recommended that future studies should focus on life history traits of other fish species, which have never been studied before, by sampling populations from all known distribution localities. The studies should also include undescribed species (with well documented information regarding their identity), besides described species.

Future studies should explore the possibility of determining age and growth of the fish using methods such as mark recapture and length-based methods.

Chapter 5 builds on the findings of this chapter to assess the risks of exploited ornamental fish species to overexploitation.

Chapter 5 Risk from exploitation of ornamental fish species of Lake Malawi for the export trade

5.1 Introduction

Sustainability of fisheries is a common goal of fisheries management (Adrianto *et al.,* 2005; De Lara & Martinet, 2009; Rosenberg *et al.,* 2018; FAO, 2018). Fishery sustainability can be evaluated from different perspectives, including biological, ecological, economic and social dimensions (Adrianto, 2005). Currently 33.1% of the fish stocks worldwide are fished beyond biological sustainability (FAO, 2018). However, these statistics apply to marine capture fisheries for which most of the fish stock assessment information is available. By contrast, there is very limited knowledge about the status of exploited ornamental fish stocks (both marine and inland) worldwide largely because conventional fishery survey methods and management measures are not suitable for monitoring multispecies ornamental fisheries because there are no records of fish catch and effort (Dee *et al.,* 2014; Fujita *et al.,* 2013; Militz *et al.,* 2018) because there are no records of fish catch and effort. Additionally, most of the fish species involved in the ornamental fish export trade are caught in developing countries with low institutional and management capacity (Fujita *et al.,* 2013). Furthermore, most of the developed countries with higher management and enforcement capacity do not conduct stock assessments for ornamental fisheries (Dee *et al.,* 2014) perhaps because these fisheries are not a management priority.

One of the alternative options for managing fisheries with limited availability of data is the ecosystem-based fisheries management approach for which fishing is considered as one of many possible factors that can affect ecosystem functions (Hobday *et al.,* 2007; 2011; Micheli *et al.,* 2014). This is particularly pertinent in inland ornamental fisheries which are impacted by numerous externalities. One popular scientific tool developed for implementation of ecosystem-based fisheries management is ecological risk assessment for effects of fishing - ERAEF (Hobday *et al.,* 2007; 2011; Smith *et al.,* 2007; Fujita *et al.,* 2013).

5.1.1 ERAEF framework

The ERAEF framework involves a hierarchical approach that describes analysis of risk at four levels namely scoping stage, qualitative assessment, semi quantitative assessment (Productivity Sustainability Analysis (PSA)) and quantitative assessment (Figure 5-1). As one moves from lower to higher level, the analysis of risks changes from qualitative/semi quantitative to increasingly quantitative (Smith *et al.,* 2007; Hobday *et al.,* 2011).

The ERAEF approach uses a general conceptual model of how fishing impacts on ecological systems, which is used as the basis for risk assessment evaluation at each level of analysis. The approach involves evaluation of five general ecological components namely: 1) target species; 2) by-product and by-catch species; 3) Threatened, Endangered and Protected species abbreviated as TEP species; 4) habitats; and 5) ecological communities. Within these ecological components ERAEF analysis focuses on specific units that may either be species or stock of fish, habitat type, or assemblage (Hobday *et al.,* 2011). The levels in the ERAEF framework differ in the resolution at which the risk is assessed, but all levels are linked by a model based on a theoretical relationship that describes the rate of change (in abundance, amount or extent) of the unit at risk (Hobday *et al.,* 2011). One important feature of the risk assessment process is specification of the rationale behind the assessment and decisions at every step in the assessment (Hobday *et al.,* 2007).

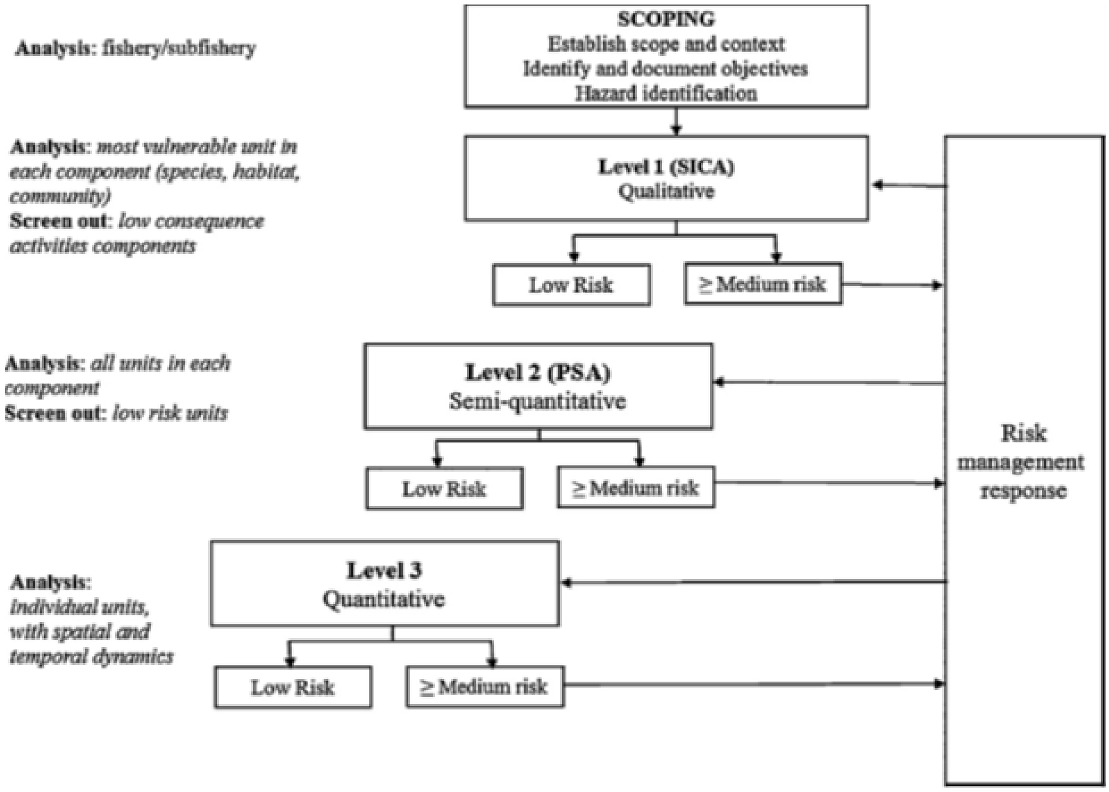

Figure 5-1. Overview of the ERAEF framework showing focus of analysis for each level in the hierarchy at the left in italics (Source: Hobday *et al.,* 2011).

The ERAEF approach has been used and modified for specific purposes by a range of international groups (see review by Hobday *et al.,* 2011). Some international groups have used only elements within the ERAEF, particularly the PSA approach (Hobday *et al.,* 2011). The flexibility of the ERAEF has resulted in its application in all types of fisheries, irrespective of size, method or species (Hobday *et al.,* 2011).

5.1.2 Productivity susceptibility analysis (PSA)

The PSA was initially developed to assess the sustainability of the bycatch in the Australian Prawn fishery (Milton, 2001; Stobutzki *et al*., 2001). With time the PSA has been modified to cater for more attributes of the ecosystem vulnerability (Patrick *et al*., 2009). The assumption of the PSA approach is that risk to a fish population is dependent on two components – the susceptibility of the fish population to the effects of fishing activities and the productivity of the population, which determines the rate at which the population will recover after potential depletion by fishing (Hobday *et al.,* 2007; 2011; Micheli *et al.,* 2014). The productivity and susceptibility attributes are scored as 1 (low), 2 (medium) or 3 (high). Productivity scores are species specific, and cut-off point values between different risk categories are determined according to fish stocks in a particular region (Salini *et al.,* 2007; Patrick *et al.,* 2009; Hobday *et al.,* 2011; Dransfeld *et al.,* 2013).

The scores are plotted and visualised on a PSA plot, which depicts an overall score as Euclidean distance from the origin, and different species under consideration can be ranked according to their overall risk (Hobday *et al.,* 2011). Species identified by the PSA analysis as high risk are further assessed using a quantitative method. However, fish species identified as high risk due to missing attributes, would require collection of information about missing attributes rather than being quantitatively analysed (Hobday *et al.,* 2011). PSA estimates relative level of risk rather than absolute level of risk, by using proxies for productivity, rather than productivity estimates as derived from quantitative assessment models (Hobday *et al.,* 2011). Furthermore, PSA does not require or assume that levels of catch or effort are available for each ecological unit impacted (Hobday *et al.,* 2011). Nevertheless, PSA allows the identification of species or habitats that are at greater potential risk due to characteristics of their biology or exposure to hazards from fishing, which is important for prioritizing remedial action or further analysis (Hobday *et al.,* 2011).

5.1.3 Suitability of PSA for assessing ornamental fish species of Lake Malawi

Chapter 2 of this thesis showed that the ornamental fish export trade in Malawi is a multispecies fishery exploiting many colourful rock dwelling fish species on the Malawian side of Lake Malawi. Some of the commonly targeted ornamental fish species for export trade are also caught by artisanal fishers for food. Additionally, it was noted that the numbers of species being exported are increasing and that many of the exported species are not yet described. Unlike the species of fish caught by the commercial food fishery, there have been no studies related to assessment of the status of targeted stocks of the ornamental fish of Lake Malawi apart from the comprehensive baseline study of Ribbink *et al.* (1983). Thus, management strategies that are based on stock assessment cannot be applied for the targeted ornamental fish stocks of Lake

Malawi. Hence, it was considered that PSA models, which are applicable for fisheries with limited data (Hobday *et al.,* 2011, Brown *et al.,* 2015), could be an alternative option for providing important insights about vulnerability to exploitation of the ornamental fish species of Lake Malawi and act as a guide for their subsequent management. The PSA has an inbuilt precautionary element of setting attributes to default high risk values in the absence of information[15]. Moreover, there is flexibility of updating the PSA model by modifying scores whenever extra fishery information is collected (Hobday *et al.,* 2007; 2011).

5.1.4 Aim and objectives

The aim of this chapter is to use the PSA model to assess the vulnerability to exploitation of commonly exploited ornamental fish species of Lake Malawi. The ultimate objectives are to rank the targeted ornamental fish species according to their relative risk (vulnerability) score; identify species which would require special management attention to ensure that the species are sustainably exploited; and recommend management measures for the exploited ornamental fish species for incorporation in the Fisheries and Aquaculture Policy in Malawi.

5.2 Methodology

5.2.1 Selection of species included in the PSA

Selection of the species included in PSA analysis was based on the the species which contributed most (≥1000 individuals) to the ornamental fish export trade from Malawi between 1998 and 2017. Both described species (Appendix 2.4) and undescribed species (Appendix 2.5) that had been exported were selected as per the following details.

In Chapter 2 it was noted that a total of 536 species were represented amongst the ornamental fishes exported from Malawi. However, only a few species predominated in the species exported, with the top 27 (22 described species and 5 undescribed species) contributing 50% of exports.

Species of fish that contributed at least 1000 individuals to the export volume between 1998 and 2017 were targeted for PSA assessment in the current study (see Appendices 2.4 and 2.5 which provide details of the number of fish exported by described and undescribed species respectively). While the cut off point number of 1000 exported individual fish may appear to be relatively low, some *mbuna* fish species have very small populations of less than 1000 fish in

[15] Though this has been blamed for making the PSA to be associated with many false positives i.e. overestimation of the number of units that are at high risk (Patrick *et al.,* 2009; Hobday *et al*., 2011)

Lake Malawi (Ribbink *et al.,* 1983; Konings, 2016). Amongst exported described fish species, 70 cichlid fish species were selected (from the species listed in Appendix 2.4) after excluding the shrimp, *Potamonautes lirrangensis*, and the Mochokidae catfish, *Synodontis njassae*, which had missing information for most of the productivity attributes[16]. Amongst the non-described fish species, 29 species were selected from the list in Appendix 2.5, after excluding the following species that had insufficient information about their identity[17] and PSA attributes: *Aulonocara* sp., *Copadichromis* sp., *Cynotilapia* sp., *Metriaclima* sp. long pelvic, mixed Malawi cichlids, *Pseudotropheus* sp., and *Tropheops* sp.

A total of 99 species, which contributed 81.0% to the total export volumes between 1998 and 2017, were selected for the PSA assessment. The full list of the of species that were selected for PSA analysis in this study is provided in Table 5-1 which has ranked the species according to their overall relative risk to exploitation for ornamental fish export trade. The 29 undescribed species that were selected can be differentiated from described species of Table 5-1 by their "not applicable" (N/A) status under the IUCN conservation status in the second column while described species take the other conservation status categories.

5.2.2 PSA traits

Hobday *et al.* (2007; 2011) defined seven productivity attributes (average age at maturity, average maximum age, fecundity, average maximum size, average size at maturity, reproductive strategy and trophic level) and six susceptibility attributes (overlap of species range with fishery, global distribution, habitat overlap with fishing gear, depth overlap with fishing gear, selectivity of fishing gear, and post-capture mortality). Patrick *et al.* (2009) defined 10 productivity attributes, by adding intrinsic rate of population growth, *r*, growth coefficient, natural mortality rate, recruitment pattern and dropping average size at maturity from the traits used by Hobday *et al.* (2007; 2011), and 12 susceptibility attributes of which seven - (areal overlap, geographic concentration, vertical overlap, seasonal migration, schooling/aggregation behaviour, morphology affecting capture, desirability/value of fishery) are related to catchability and five (management strategy, fishing mortality rate relative to natural mortality, biomass of spawners,

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[16] In addition, exploitation of these two species for ornamental export trade may not be of concern since they are distributed throughout Lake Malawi.

[17] For the 29 undescribed fish species included in the PSA, Konings (2016) has documented a lot of information about their identity, distribution and ecology which is relevant for PSA assessment. Thus, these species are treated like described species and is some cases Konings (2016) has documented many "synonyms" of the undescribed species temporary names used by Ribbink *et al*. (1983).

survival after capture and release, and fishery impact on habitat) are related to effectiveness of management.

Subsequent studies that have employed PSA have used varying numbers of the productivity and susceptibility traits, with some exclusion /additions / or substitutions of the traits to the lists used by Hobday *et al.* (2007; 2011) and Patrick *et al.* (2009), depending on the relevance of the traits to the stocks of fish under study and availability of trait information. While most of the productivity traits may be applicable for many fisheries, susceptibility traits are very often fishery specific (McCully *et al.,* 2013).

In this study, five productivity traits and four susceptibility traits for which information was available from two scientific databases, IUCN Red List (IUCN, 2019) and FishBase (Froese & Pauly, 2019) and scientific publications, were included as described in the following sub sections. Reproductive strategy was dropped amongst the productivity traits used because all the species assessed shared the same strategy of mouth brooding the young. Inclusion of a particular productivity trait is necessary only when it differs amongst the assessed species (Arrizabalaga *et al.,* 2011). Some of the susceptibility traits proposed by Patrick *et al.* (2009), such as fishing impact on habitat, seasonal migrations, schooling / aggregations and other behaviour, were found to be irrelevant for the species assessed in this study.

Productivity traits

Age at maturity and maximum age: Since data about age at maturity and maximum age for Lake Malawi cichlid fishes are not available, generation length[18] (in years) was used as a proxy for the two traits although generation length is greater than the age at first breeding and less than the age of the oldest breeding individual (IUCN Standards and Petitions Subcommittee, 2017). The generation length for each fish species was extracted from IUCN database (IUCN, 2019). The values of generation length for all the 257 described cichlid fish species exported from Malawi between 1998 and 2017 ranged from one to three years. The score of productivity was considered in this study to be the same as generation length (in years), i.e. one-year generation time was assumed to be associated with high productivity and low risk score of 1; two years generation time was assumed to be associated with medium productivity and medium risk score of 2; while 3 years generation time was assumed to have low productivity but high-risk score of 3. This scoring criterion was applied to all the described fish species selected for the PSA analysis

[18] See definition of generation length in section 4.4.1 of chapter 4 based on IUCN Standards and Petitions SubCommitee, (2017)

in this study. For undescribed fish species, the highest generation length for species in the same genus was used to assign the productivity score as a precautionary measure.

Maximum length: Information related to maximum length of fish were extracted from electronic databases (Froese & Pauly, 2019; IUCN, 2019) and peer reviewed publications. Where different maximum length values were reported for a species, largest maximum length value (which is associated with higher overfishing risk) was used as a precautionary measure (Salini *et al.,* 2007). Data for 240 ornamental cichlid species exported from Malawi (belonging to 50 genera, see Chapter 2) were reviewed and extracted from literature. Where maximum total length (***TL***) was recorded, it was converted to equivalent standard length (***SL***) in mm using the following equation that describes the relationship between ***SL*** and ***TL*** (in mm) for Lake Malawi Cichlid fishes (Duponchelle *et al.,* 2000b).

SL = 0.785 TL + 3.477

The maximum standard lengths for the 240 cichlid fish species ranged from 54 mm for *Metriaclima lanisticola* to 420 mm for *Rhamphochromis esox,* with most species having a maximum length between 54 mm and 150 mm and very few species above 203 mm. The distribution of species maximum standard length was positively skewed (Figure 5-2).

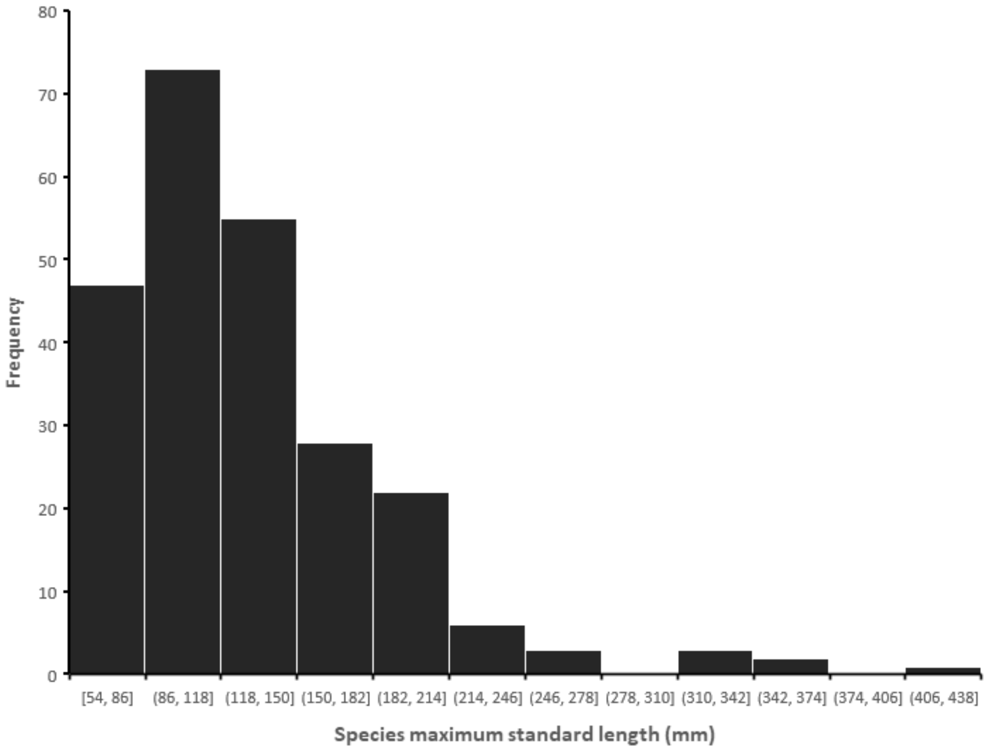

Figure 5-2. Histogram of maximum standard length of the described ornamental cichlid fish species exported from Malawi between 1998 and 2017

The cut off points of maximum standard length for the PSA scores were computed following the procedure of Salini *et al.* (2007), by log transformation of the minimum and maximum values and dividing the range into thirds followed by back transformation of the values. According to Salini *et al.* (2007), log transformation of trait values minimizes outlier biasness of the score cut off points. The computed maximum length score cut off points were as follows: score 1 - high productivity, low risk (maximum standard length ≤ 107 mm); score 2 - medium productivity, medium risk (108 mm ≤ maximum standard length ≤ 211 mm); score 3 – low productivity, high risk (maximum standard length ≥ 212 mm). These cut off points were subsequently used for scoring all the described species of fish included in the PSA of the current study. Undescribed fish species were assigned a score of the described species with the highest risk score within the same genus as a precautionary measure.

Fecundity: To compute PSA absolute cut off points for scoring absolute fecundity of Lake Malawi cichlid fishes, fecundity data compiled from literature (Appendix 4.1) and findings of Chapter 4 (Table 4-5) were combined and used. The compiled fecundity data included 89 species of Lake Malawi cichlids from 28 genera. Average absolute fecundity of the 89 species ranged from 15 eggs for *Diplotaxodon limnothrissa* to 522 eggs for *Rhamphochromis macrophthalmus*[19]. All *mbuna* cichlids (except for those belonging to the genus *Petrotilapia*) had fecundities between 15 and 53 eggs. The fecundity of species within the genus *Petrotilapia* ranged from 45 to 91 eggs, while the majority of non-*mbuna* cichlids had absolute fecundities ≥100 eggs. The absolute fecundity data followed a positively skewed distribution with a long tail to the right (i.e. Poisson distribution) (Figure 5-3).

[19] This range excluded fish reported by Munthali & Ribbink (1998) whose fecundity values were extremely low in comparison to other reports perhaps because of the latter being based on counting of eggs in the mouths of brooding fish which was assumed in this study to be unreliable due to high possibility of some eggs being lost between the time of laying and capture of mouth-brooding fish.

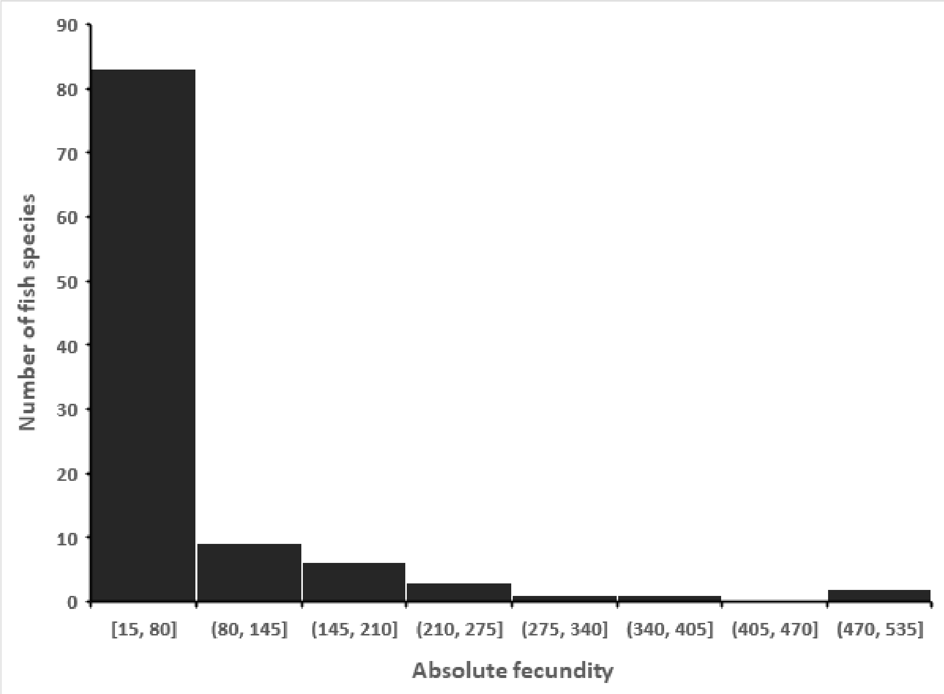

Figure 5-3. Histogram of fecundity of the ornamental cichlid fish species exported from Malawi between 1998 and 2017.

Cut-off points for PSA scoring were determined based on the criteria of Salini *et al.* (2007) by log transformation of the minimum and maximum fecundity values and dividing the range into thirds followed by back transformation of the values. The computed absolute fecundity score cut-off points were as follows: score 1 –high productivity, low risk (fecundity ≥ 159 eggs), score 2 – medium productivity, medium risk (49 ≤ fecundity ≤ 158); score 3 –low productivity, high risk (fecundity < 49 eggs).

For some of the exported fish species, fecundity studies have never been previously conducted. Hence fecundity values for such species were estimated and scored using the following methods:

- Where absolute fecundity data for other species in the same genus with similar maximum standard length[20] were available, the average absolute fecundity of such species was assigned to the species with unknown fecundities.
- For seven species (*Chilotilapia euchilus*, *Nimbochromis linni*, *Tyrannochromis macrostoma*, *Dimidiochromis compressiceps*, *Nimbochromis linni*, *Stigmatochromis modestus*, and *Eclectochromis ornatus*), there was no report about fecundity studies at both species and genus levels. Fecundity values used for scoring these species were based on the relationship between absolute fecundity and maximum standard length

[20] Information extracted from Fishbase (Foese & Pauly, 2019).

(Figure 5-4) which was estimated after Spearman's correlation showed significant positive correlation between absolute fecundity and maximum standard length of the assessed cichlid fishes of Lake Malawi (rho(55) = 0.7461, P<0.0001).

- For undescribed fish species that were included in the PSA analysis, fecundity score was assigned based on the average fecundity for described species within the same genus.

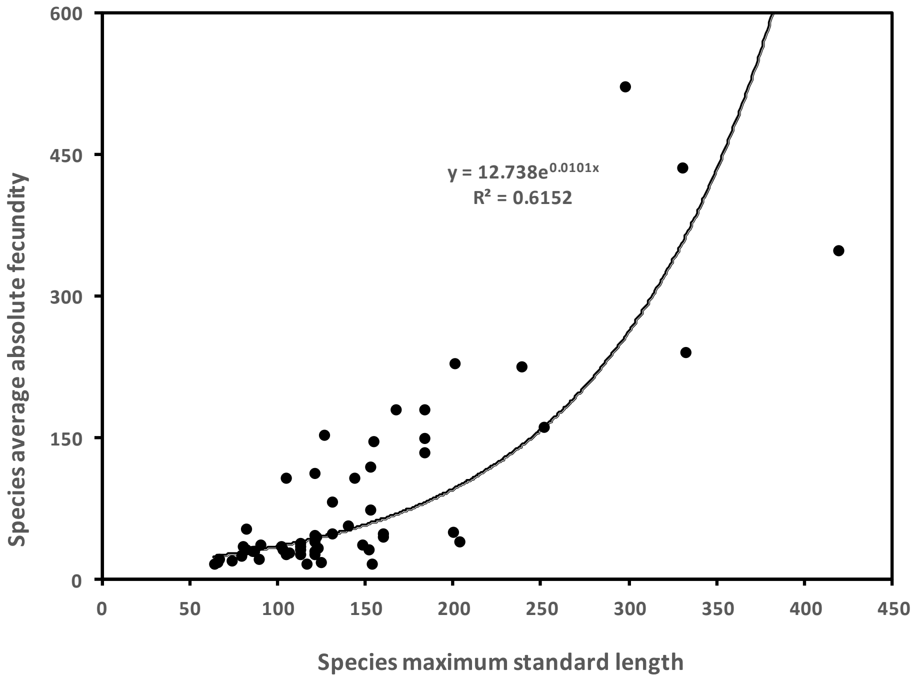

Figure 5-4. Relationship between absolute fecundity and maximum standard length of Lake Malawi cichlid fish species.

Trophic level: Information about fish trophic level was extracted from FishBase (Froese & Pauly, 2019) and reports of Darwall (2003) and Darwall *et al.* (2010) for some fish species. A total of 220 described fish species that were exported from Malawi between 1998 and 2017, belonging to 49 genera, had their trophic level information extracted and these values fell within a range of 2.0 to 4.4. The computed trophic level score cut off points based on the procedure of Salini *et al.* (2007) were as follows: score 1 (high productivity, low risk) – trophic level ≤ 2.60; score 2 (medium productivity, medium risk): 2.61≤ trophic level≤ 3.37; score 3 (low productivity, high risk): trophic level ≥ 3.38. These cut off point values were subsequently used for scoring trophic levels of the species selected for PSA in the current study. For undescribed fish species, trophic level scores were assigned based on the average trophic level value for described fish species within the same genus.

Minimum population doubling time (MPDT): In the current study, it was assumed that MPDT is related to the rate at which the individual fish species can recover from overexploitation (i.e. the productivity of the species). For each described fish species, the information about MPDT was extracted from the electronic data base (Froese & Pauly, 2019) which classifies three categories of MPDT as an estimate of the resilience of individual fish species, namely: Low resilience (MPDT value of 4.5 to 14 years), medium resilience (MPDT value of 1.4 to 4.4 years) and high resilience (MPDT of less than 15 months). These categories of the MPDT were adopted in the current study but scoring of the productivity risk for this trait was conducted as follows: Score 1 – high productivity, low risk (MPDT of less than 15 months), Score 2 - medium productivity, medium risk (MPDT value of 1.4 to 4.4 years), and Score 3 – low productivity, high risk (MPDT value of 4.5 to 14 years). For undescribed fish species, MPDT for described fish species within the same genus and attaining similar length was used for scoring their MPDT.

Susceptibility traits

Management strategy in place for the fish population (conservation actions): A review of information about described cichlid fish species exported from Lake Malawi in the IUCN database (IUCN, 2019) showed that the only notable conservation action that existed for some of the species was presence in a protected area[21]. This was therefore considered as one of the susceptibility traits for inclusion in the PSA. Susceptibility of each of the species included in the PSA was assessed with respect to the existence of the population in the protected areas of LMNP and scores were assigned as follows: Low susceptibility (Score 1): entire species population distribution range inside LMNP; Moderate susceptibility (Score 2): population distribution range found both inside and outside LMNP; High susceptibility (score 3): entire population distribution range outside LMNP.

Species depth distribution in relation to fishing gear (encounterability): An overlap between depth of a fishing gear and the fish species depth distribution range can affect the species' susceptibility to capture (Stobutzki *et al.,* 2001, Roelofs & Silcock, 2008; McCully *et al.,* 2013). Thus, depth distribution of the species was included in the PSA as an important susceptibility trait to capture by divers who use Hooker SCUBA diving gears to capture ornamental fishes of Lake Malawi within the diving depth range. According to two of the exporters of ornamental fish from Malawi interviewed, SCUBA divers can catch fish up to 40 m deep. The information about depth distribution for various fish species included in the PSA of this study was extracted from the IUCN database (IUCN, 2019) and various peer reviewed publications. Besides described fish species, Konings (2016) provided substantial ecological information about undescribed fish

[21] There was allegedly some informal effort for captive breeding for restocking rock dwelling cichlid fish whose population had drastically declined (see Chapter 2 section 2.4.6) but the programme seemed to have been unsuccessful.

species of Lake Malawi (including all those assessed in this study). Depth distribution for each species was extracted and susceptibility scores were assigned following the criteria of Okemwa *et al.* (2016) based on limits of fishing depth by SCUBA divers as follows: score of 1 (low susceptibility) - species found at depth >30 m, Score of 2 (medium susceptibility) - species found at depth between 10 and 30 m, Score of 3 (high susceptibility) - species found at depth of <10 m with unlimited SCUBA diving time. Species of fish with wide depth distribution range spanning across more than one susceptibility depth score range, were assigned the average score for their depth range. For undescribed species of fish without any report of depth in the literature, scores were assigned based on species within the same genus with the highest score value as a precautionary measure.

Market value of species: The assumption behind inclusion of market value in the PSA is that fish species with high market value are more susceptible to being overfished than those with low market value (Patrick *et al.,* 2009; McCully *et al.,* 2013; 2015). In the current study, it was assumed that ornamental fish exporters are more likely to expend more fishing effort on high value species than on less valuable species. This assumption is in line with the revelation of practices by some exporters of offering their SCUBA divers special bonus rewards as incentives to catch valuable, rare and new species of fish (see section 2.4.3).

Market value for each of the assessed fish species was calculated as average exporter price per individual fish converted to 2018 prices (see section 2.2.3 of Chapter 2 for more details about price conversions). The computed cut-off points for the three susceptibility scores following the procedure of Salini *et al.* (2007) were as follows: score 1 - Low susceptibility (average price ≤ US$6.11 per fish); score 2 - Medium susceptibility (US$6.12 ≤ average price ≤ US$11.91 per fish); score 3 - High susceptibility (average price ≥ US$11.92). The average prices for each of the species of fish included in the PSA were converted to susceptibility scores using these cut off points.

Distribution pattern of the species: Consideration of distribution patterns of a species as one of the susceptibility traits in the PSA analysis assumes that species with restricted distribution ranges are more susceptible to being overfished by various fishing gears than those with a wider distribution range (Milton, 2001; Stobutzki *et al.,* 2001; Patrick *et al.,* 2009). The information about the distribution pattern of individual fish species was obtained from the IUCN database (IUCN, 2019) for described species, and Konings (2016) and Ribbink *et al.* (1983) for undescribed fish species. Susceptibility scores and cut off points were qualitatively determined as: low susceptibility (Score of 1) for species that are widely distributed throughout Lake Malawi; Moderate susceptibility (Score of 2) for species with distribution limited to either a particular region of the lake or at a few rocky reefs/islands (4 or more rocky reefs/islands); High susceptibility (Score of 3) for fish species with limited distribution (3 or less rocky reefs/islands within Lake Malawi). Each species of fish included in the PSA was assigned a susceptibility score after thoroughly reviewing the information about its distribution range.

5.2.3 Analysis of PSA traits data

The productivity and susceptibility traits' score data were analysed using the Excel worksheets of the Marine Stewardship Council (MSC) (Marine Stewardship Council, 2018). These Excel worksheets are designed in such a way that overall productivity score, overall susceptibility score, and overall risk score are automatically generated after entering the productivity and susceptibility trait scores in the spreadsheet.

The overall productivity score for each species is estimated as arithmetic average of the individual traits scores included, while overall susceptibility score is estimated using a multiplicative approach. The multiplicative approach is considered more appropriate for estimating overall susceptibility score because low risk for any single trait acts to reduce the overall risk to a low value (Hobday *et al.,* 2011). The overall risk score, or vulnerability, (V) is estimated from the Productivity score (P) and Susceptibility score (S) as:

$$V = (P^2 + S^2)^{1/2}$$

Thus, V for each species is estimated as Euclidean distance from the point of origin of the P and S axes when plotted on a graph (Hobday *et al.,* 2011). V can take any value between 1.4 (when both P and S have minimum values of 1) and 4.24 (when both P and S have maximum possible values of 3) (Smith *et al.,* 2007; Hordyk & Carunthers, 2018). The Excel worksheets are also designed to automatically classify the overall risk score into three possible categories using two cut off points of V as follows: Low risk when V is less than 2.64. Medium risk when V is between 2.64 and 3.18 and high risk when V is above 3.18.

Based on the outputs of the Excel Worksheets, species of fish included in the PSA analysis in this study were ranked from the species with the highest to the species with the lowest relative risk of overexploitation.

5.3 Results

5.3.1 Rankings of species according to overall risk (V) score

The risk score values for the species of fish included in this study are summarised in Table 5-1. In addition, Figure 5-5 (a) and (b) show two PSA risk plots for described and undescribed species, respectively, and Figure 5-6 shows combined PSA risk plot for described and undescribed species. The overall productivity risk score values ranged from 1.4 to 2.40 with an average of 1.89 ± 0.29, while susceptibility risk score values ranged from 1.05 to 3.00 with an average of 1.57 ± 0.48. The overall risk score (***V***) ranged from 1.75 to 3.72 with an average of 2.48 ± 0.43.

Four species (*Copadichromis azureus, Aulonocara* sp maisoni, *Aulonocara* sp maulana and *Aulonocara* sp mdoka) are included in the first rank with a relative risk score value of 3.72, followed by *Aulonocara* baenschi on the second rank with a relative risk score of 3.21 and four species (*Melanochromis chipokae*, *Aulonocara nyassae*, *Aulonocara* sp sanga and *Placidochromis phenochilus*) on the third rank with a relative risk score of 3.20 (Table 5-1). The top nine species which were ranked from first to third, were in the high-risk category and they had high susceptibility score (≥2.33) but medium productivity score (1.8 <productivity < 2.2). The majority of the species at high risk had the highest score value of 3 for all susceptibility attributes included in the analysis (i.e. no management in place - species in unprotected area, found in shallow areas with unlimited diving depth, only confined to three or less rock reefs of Lake Malawi, and had high market value) (Table 5-1). Six of the nine species with high relative risk, belonged to the genus *Aulonocara,* while the other three species belonged to the genera *Copadichromis*, *Melanochromis* and *Placidochromis* (Table 5-1). Furthermore, five species in the high-risk category are described while the other four are undescribed species.

Nineteen species were ranked between 4th and 14th, and were in the medium risk category with a PSA risk score ranging from 2.64 to 3.07 (Table 5-1). Fifteen of these species are described and four are undescribed. This risk category is represented by 10 genera *(Aulonocara*, *Buccochromis*, *Chindongo*, *Cyrtocara*, *Eclectochromis, Nimbochromis*, *Placidochromis*, *Pseudotropheus*, *Tyrranochromis* and *Metriaclima*) but only the genus *Aulonocara* dominated with a representation of eight species, while the other genera were represented by either one or two species. This group comprised three categories of fish with respect to PSA traits distribution. The first group comprised the species with high susceptibility scores of 2.33 but medium productivity, medium risk scores (1.8 <productivity < 2.2) (including *Aulonocara korneliae*, *Aulonocara* sp chindunga, *Aulonocara kandeense*, *Pseudotropheus cyaneorhabdos*, *Aulonocara hueseri*, *Metriaclima* sp membe deep, and *Chindongo saulosi*). The second group had low productivity, high risk scores (2.4 < productivity score ≤ 2.6), but low susceptibility scores (<2) (including *Tyrannochromis macrostoma*, *Aulonocara rostratum*, *Buccochromis rhoadesii*, *Cyrtocara moori*, *Buccochromis heterotaenia*, *Nimbochromis linni*, and *Nimbochromis livingstoni*). This group comprised mostly sand dwellers with low productivity, high risk scores due to their relatively large size, higher generation length and high trophic levels compared with colourful rock dwelling cichlids. The third group had medium values for both productivity scores (2 ≤

productivity score ≤ 2.2) and susceptibility scores (1.73 ≤ susceptibility score ≤ 2.10), including *Aulonocara* sp mbenji, *Aulonocara maylandi*, *Placidochromis* sp jalo, *Eclectochromis ornatus* and *Aulonocara ethelwynnae*.

A total of 71 species were ranked from 15th to 47th, and were in the low risk category with a PSA risk score range of 1.75 to 2.62. This group of species had low scores for both productivity risk attributes (1.4 ≤ productivity score ≤ 2.2) and susceptibility attributes (1.05 ≤ susceptibility score ≤1.88). The group is represented by 50 described species and 21 undescribed species. Fish in this category were from 23 genera of fish with the described species having representation in all the 23 genera, whereas undescribed species were represented by only five of the 23 genera (*Protomelas*, *Pseudotropheus*, *Metriaclima, Cynotilapia* and *Tropheops*).

The PSA plots showed that described species had more scattered risk score points than undescribed species (Figure 5-5), mainly because described species were represented by a higher diversity of species and genera than undescribed species. However, some described and undescribed species of fish in all the three risk categories had identical productivity and susceptibility risk score values (Table 5-1), and this resulted in less points than the number of species in both the separate (Figure 5-5) and combined (Figure 5-6) plots of described and undescribed species.

Table 5-1. Summary of scores of the productivity and susceptibility attributes for various species assessed. IUCN CS = IUCN conservation status, N/A under IUCN CS means the species is undescribed. GL = generation length in years, MPDT = minimum population doubling time, Fec = Fecundity, SL = Maximum standard length, TL = Trophic level, Prod Score = Productivity score, Cons = Conservation, Enc DD = Encounterability with respect to diving depth, Dist Pat = Distribution pattern, Susc = Susceptibility score

Species name	**IUCN CS**	**GL**	**MPDT**	**Fec**	**SL**	**TL**	**Prod score**	**Cons**	**Enc DD**	**Dist pat**	**Market value**	**Susc score**	**PSA risk Score**	**Risk Category**	**Risk score ranking**
Copadichromis azureus	NT	2	1	3	2	3	2.20	3	3	3	3	3.00	3.72	High	1
Aulonocara sp maisoni	N/A	2	2	2	2	3	2.20	3	3	3	3	3.00	3.72	High	1
Aulonocara sp maulana	N/A	2	2	2	2	3	2.20	3	3	3	3	3.00	3.72	High	1
Aulonocara sp mdoka	N/A	2	2	2	2	3	2.20	3	3	3	3	3.00	3.72	High	1
Aulonocara baenschi	CR	1	2	2	1	3	1.80	3	2.5	3	3	2.66	3.21	High	2
Melanochromis chipokae	CR	2	1	3	2	3	2.20	3	3	3	2	2.33	3.20	High	3
Aulonocara nyassae	NT	2	2	3	1	3	2.20	3	2	3	3	2.33	3.20	High	3
Aulonocara sp sanga	N/A	2	2	2	2	3	2.20	3	3	3	2	2.33	3.20	High	3
Placidochromis phenochilus	EN	3	1	3	2	2	2.20	3	3	2	3	2.33	3.20	High	3
Aulonocara korneliae	LC	2	2	2	1	3	2.00	3	3	3	2	2.33	3.07	Med	4
Aulonocara sp chindunga	N/A	2	2	2	2	2	2.00	3	3	3	2	2.33	3.07	Med	4
Aulonocara sp mbenji	N/A	2	2	2	2	3	2.20	3	2.5	3	2	2.10	3.04	Med	5
Aulonocara kandeense	CR	2	2	2	1	2	1.80	3	3	3	2	2.33	2.94	Med	6
Pseudotropheus cyaneorhabdos	CR	1	1	3	1	3	1.80	3	3	3	2	2.33	2.94	Med	6
Aulonocara hueseri	LC	1	2	2	1	3	1.80	3	3	3	2	2.33	2.94	Med	6
Aulonocara maylandi	CR	2	2	2	2	3	2.20	3	2	3	2	1.88	2.89	Med	7
Placidochromis sp Jalo Reef	N/A	3	1	3	2	2	2.20	3	2	3	2	1.88	2.89	Med	7
Tyrannochromis macrostoma	LC	3	2	2	3	3	2.60	2	2	1	2	1.18	2.85	Med	8
Aulonocara rostratum	LC	3	2	2	2	3	2.40	3	2.5	1	3	1.54	2.85	Med	8
Metriaclima sp membe deep	N/A	1	1	3	1	2	1.60	3	2	3	3	2.33	2.82	Med	9

Table 5-1 (continued)

Species name	IUCN CS	GL	MPDT	Fec	SL	TL	Prod score	Cons	Enc DD	Dist. Pat	Market value	Susc. score	PSA risk score	Risk Category	Risk score ranking
Cyrtocara moori	VU	2	3	2	2	3	2.40	2	2.5	1	3	1.35	2.75	Med	10
Buccochromis rhoadesii	LC	3	2	1	3	3	2.40	2	2.5	1	3	1.35	2.75	Med	10
Buccochromis heterotaenia	LC	3	2	1	3	3	2.40	2	2	1	3	1.28	2.72	Med	11
Nimbochromis linni	LC	3	2	2	2	3	2.40	2	2	1	3	1.28	2.72	Med	11
Nimbochromis livingstonii	LC	3	2	2	2	3	2.40	2	2	1	3	1.28	2.72	Med	11
Chindongo saulosi	CR	1	1	3	1	1	1.40	3	3	3	2	2.33	2.71	Med	12
Eclectochromis ornatus	LC	3	1	2	2	3	2.20	3	2.5	1	3	1.54	2.68	Med	13
Aulonocara ethelwynnae	NT	1	2	3	1	3	2.00	3	2.5	2	2	1.73	2.64	Med	14
Chilotilapia euchilus	LC	3	2	1	3	2	2.20	2	3	1	3	1.43	2.62	Low	15
Dimidiochromis compressiceps	LC	3	1	2	2	3	2.20	2	3	1	3	1.43	2.62	Low	15
Stigmatochromis modestus	LC	3	1	2	2	3	2.20	2	3	1	3	1.43	2.62	Low	15
Copadichromis verduyni	LC	2	1	3	1	2	1.80	3	2	3	2	1.88	2.60	Low	16
Protomelas sp steveni	N/A	2	1	2	2	2	1.80	3	3	2	2	1.88	2.60	Low	16
Protomelas sp steveni imperial	N/A	2	1	2	2	2	1.80	3	3	2	2	1.88	2.60	Low	16
Protomelas fenestratus	LC	2	1	3	2	2	2.00	3	3	1	3	1.65	2.59	Low	17
Copadichromis trewavasae	LC	2	1	3	1	3	2.00	3	2	2	2	1.58	2.55	Low	18
Copadichromis borleyi	LC	2	1	3	2	3	2.20	2	3	1	2	1.28	2.54	Low	19
Mylochromis lateristriga	LC	3	1	2	2	3	2.20	2	3	1	2	1.28	2.54	Low	19
Placidochromis milomo	LC	3	1	3	2	2	2.20	2	2	1	3	1.28	2.54	Low	19
Sciaenochromis fryeri	LC	2	1	3	2	3	2.20	2	2	1	3	1.28	2.54	Low	19
Taeniolethrinops furcicauda	LC	3	2	2	2	2	2.20	3	2	1	2	1.28	2.54	Low	19
Copadichromis mloto	DD	2	1	3	2	3	2.20	2	2	1	2	1.18	2.49	Low	20
Pseudotropheus sp polit	N/A	1	1	3	1	2	1.60	3	2	2	3	1.88	2.46	Low	21
Metriaclima sp elongatus ornatus	N/A	1	1	3	2	2	1.80	3	3	3	1	1.65	2.44	Low	22

Table 5-1 (continued)

Species name	IUCN CS	GL	MPDT	Fec	SL	TL	Prod score	Cons	Enc DD	Dist. Pat	Market value	Susc. score	PSA risk score	Risk Category	Risk score ranking
Metriaclima sp zebra gold	N/A	1	1	3	2	2	1.80	3	2	2	2	1.58	2.39	Low	23
Lethrinops microstoma	LC	2	1	2	2	3	2.00	2	3	1	2	1.28	2.37	Low	24
Protomelas taeniolatus	LC	2	1	3	2	2	2.00	2	3	1	2	1.28	2.37	Low	24
Protomelas virgatus	LC	2	1	3	2	2	2.00	2	3	1	2	1.28	2.37	Low	24
Aulonocara saulosi	LC	2	2	3	1	2	2.00	3	2	1	2	1.28	2.37	Low	24
Cynotilapia axelrodi	LC	1	1	3	1	3	1.80	3	2.5	3	1	1.54	2.37	Low	24
Metriaclima lombardoi	LC	1	2	3	1	2	1.80	3	2.5	3	1	1.54	2.37	Low	24
Pseudotropheus interruptus	NT	1	1	3	1	3	1.80	3	2.5	3	1	1.54	2.37	Low	24
Cynotilapia sp mbamba	N/A	1	1	3	1	3	1.80	3	2.5	3	1	1.54	2.37	Low	24
Aulonocara stuartgranti	LC	2	2	2	1	3	2.00	2	2.5	1	2	1.23	2.35	Low	25
Fossorochromis rostratus	LC	3	1	2	2	2	2.00	2	2.5	1	2	1.23	2.35	Low	25
Petrotilapia tridentiger	LC	1	2	2	2	3	2.00	2	2.5	1	2	1.23	2.35	Low	25
Labidochromis flavigulis	LC	1	1	3	1	2	1.60	3	3	3	1	1.65	2.30	Low	26
Metriaclima mbenjii	LC	1	1	3	1	2	1.60	3	3	3	1	1.65	2.30	Low	26
Metriaclima hajomaylandi	LC	1	1	3	1	3	1.80	3	2	3	1	1.43	2.30	Low	26
Labidochromis joanjohnsonae	NT	1	1	3	1	3	1.80	2	3	3	1	1.43	2.30	Low	26
Metriaclima sp elongatus	N/A	1	1	3	2	2	1.80	3	3	2	1	1.43	2.30	Low	26
Metriaclima sp elongatus bee	N/A	1	1	3	2	2	1.80	3	3	2	1	1.43	2.30	Low	26
Tropheops sp red cheek	N/A	1	2	3	2	2	2.00	2	3	1	1	1.13	2.29	Low	27
Melanochromis loriae	LC	1	1	3	2	3	2.00	2	2.5	1	1	1.10	2.28	Low	28
Tropheops sp yellow	N/A	1	2	3	2	2	2.00	2	2	1	1	1.08	2.27	Low	29
Placidochromis electra	LC	2	1	2	2	2	1.80	3	2.5	1	2	1.35	2.25	Low	30
Chindongo flavus	NT	1	1	3	1	3	1.80	1	2.5	3	2	1.35	2.25	Low	30
Metriaclima sp zebra long pelvic	N/A	1	1	3	2	2	1.80	3	2.5	2	1	1.35	2.25	Low	30

Table 5-1 (continued)

Species name	IUCN CS	GL	MPDT	Fec	SL	TL	Prod score	Cons	Enc DD	Dist. Pat	Market value	Susc. score	PSA risk score	Risk Category	Risk score ranking
Pseudotropheus sp elongatus	N/A	1	1	3	1	2	1.60	2	3	2	2	1.58	2.25	Low	30
Metriaclima pulpican	LC	1	1	3	1	1	1.40	3	2.5	2	2	1.73	2.22	Low	31
Protomelas sp thick lips	N/A	2	1	2	2	2	1.80	2	2	3	1	1.28	2.21	Low	32
Labeotropheus fuelleborni	LC	1	2	3	1	2	1.80	2	3	1	2	1.28	2.21	Low	32
Tropheops tropheops	LC	1	2	3	2	1	1.80	2	3	1	2	1.28	2.21	Low	32
Metriaclima sp zebra BB	N/A	1	1	3	2	2	1.80	2	3	2	1	1.28	2.21	Low	32
Metriaclima sp zebra blue	N/A	1	1	3	2	2	1.80	2	3	2	1	1.28	2.21	Low	32
Metriaclima sp zebra OB	N/A	1	1	3	2	2	1.80	2	3	1	2	1.28	2.21	Low	32
Metriaclima sp zebra patricki	N/A	1	1	3	2	2	1.80	2	3	2	1	1.28	2.21	Low	32
Cynotilapia sp edward type	N/A	1	1	3	1	3	1.80	3	2	2	1	1.28	2.21	Low	32
Metriaclima sp zebra gold brown	N/A	1	1	3	2	2	1.80	3	2	2	1	1.28	2.21	Low	32
Pseudotropheus perileucos	LC	1	1	3	1	1	1.40	3	3	3	1	1.65	2.16	Low	33
Labeotropheus trewavasae	LC	1	2	3	1	2	1.80	2	2	1	2	1.18	2.15	Low	34
Labidochromis freibergi	LC	1	1	3	1	2	1.60	2	3	3	1	1.43	2.14	Low	35
Pseudotropheus sp aceii	N/A	1	1	3	1	2	1.60	3	3	2	1	1.43	2.14	Low	35
Metriaclima barlowi	LC	1	1	3	1	3	1.80	2	3	1	1	1.13	2.12	Low	36
Cynotilapia afra	LC	1	1	3	1	3	1.80	2	2	1	1	1.08	2.10	Low	37
Metriaclima greshakei	NT	1	1	3	2	1	1.60	3	1.5	3	1	1.31	2.07	Low	38
Metriaclima zebra	LC	1	1	3	2	1	1.60	2	3	1	2	1.28	2.05	Low	39
Metriaclima pyrsonotos	LC	1	1	3	1	1	1.40	2	2.5	2	2	1.48	2.03	Low	40
Pseudotropheus johannii	LC	1	2	3	1	1	1.60	3	3	1	1	1.20	2.00	Low	41
Chindongo socolofi	LC	1	1	3	1	1	1.40	3	3	2	1	1.43	2.00	Low	41
Labidochromis caeruleus	LC	1	1	3	1	1	1.40	3	2	1	3	1.43	2.00	Low	41
Metriaclima estherae	LC	1	1	3	1	1	1.40	3	3	1	2	1.43	2.00	Low	41

Table 5-1 (continued)

Species name	**IUCN CS**	**GL**	**MPDT**	**Fec**	**SL**	**TL**	**Prod score**	**Cons**	**Enc DD**	**Dist. Pat**	**Market value**	**Susc. score**	**PSA risk score**	**Risk Category**	**Risk score ranking**
Metriaclima callainos	LC	1	1	3	1	2	1.60	2	2.5	1	1	1.10	1.94	Low	42
Metriaclima sp zebra pearly	N/A	1	1	3	1	2	1.60	2	2.5	1	1	1.10	1.94	Low	42
Metriaclima flavifemina	LC	1	1	3	1	2	1.60	1	2	1	2	1.08	1.93	Low	43
Otopharynx auromarginatus	LC	2	1	1	2	1	1.40	2	2.5	1	2	1.23	1.86	Low	44
Metriaclima lanisticola	LC	1	1	3	1	1	1.40	2	2	1	2	1.18	1.83	Low	45
Metriaclima aurora	LC	1	1	3	1	1	1.40	2	3	1	1	1.13	1.80	Low	46
Melanochromis auratus	LC	1	1	3	1	1	1.40	2	1.5	1	1	1.05	1.75	Low	47

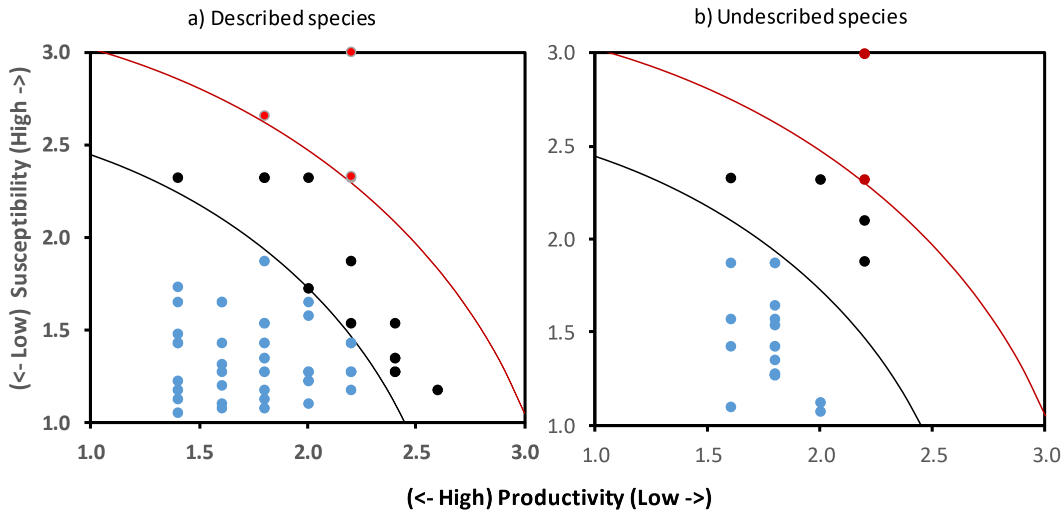

Figure 5-5. PSA risk score plot for commonly exported (a) described and (b) undescribed ornamental fish species from Lake Malawi. Black line represents risk score value of 2.64 and red line represents risk score value of 3.18 as cut-off points between different risk categories. Blue points to the left of black line represent species with low risk scores, black points between the black and red lines represent species with medium risk scores and red points to the right of the red line represent species with high risk score values. The total number of data points is different from the number of species assessed since species with ties of both susceptibility and productivity scores (and overall risk score) are depicted as a single point in the plot.

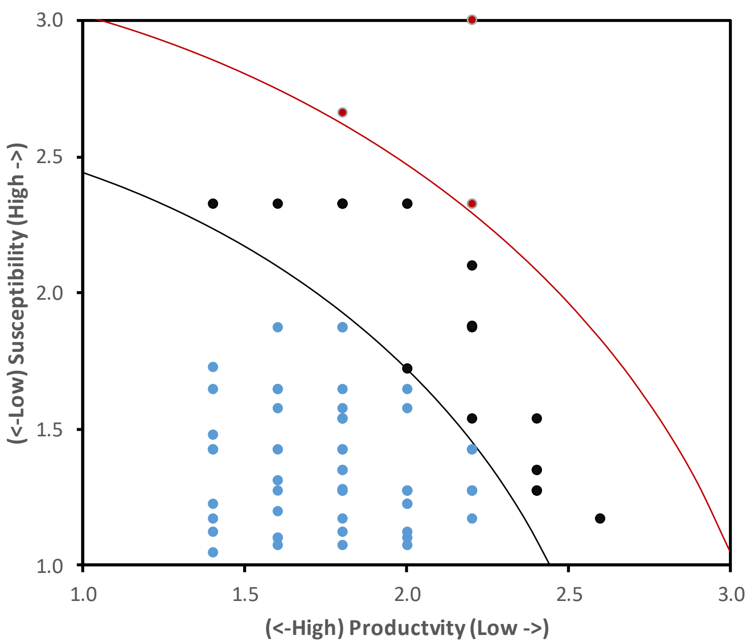

Figure 5-6. PSA risk score plot for commonly exported ornamental fish species of Lake Malawi (described and undescribed combined). Black line represents risk score value of 2.64 and red line represents risk score value of 3.18, as cut-off points between different categories of risk scores. Blue points represent species with low risk scores, black points represent species with medium risk scores and red points represent species with high risk score values.

5.3.2 Correlation between conservation status and PSA ranking

Amongst the five described fish species with high relative risk score, IUCN (2019) classified two species as near threatened, another two species as critically endangered and one species as endangered. In this group there was no representation of species classified to be of least concern. Of the 15 described species in the medium risk category, nine were classified by IUCN (2019) as of least concern, four as critically endangered, one as vulnerable, and one as near threatened. Of the 50 described species belonging to the low risk category, one was classified by IUCN (2019) as data deficient, 45 were classified to be of least concern and four were classified to be near threated. Overall, the proportion of fish classified in the four IUCN categories of concern (near threatened, vulnerable, endangered, and critically endangered) decreased with the decrease in the species PSA risk score ranking, while the proportion of species classified to be of least concern increased with a decrease in the species PSA risk score ranking (Figure 5-7). This suggests a correlation between the PSA assessment applied in the current study and the IUCN assessment criteria. Moreover, one factor that IUCN (2019) used as a basis for determining species conservation status (but not considered in this study) was species susceptibility to being caught by subsistence fishers. This factor was not considered in this study for two reasons: firstly, it was not possible to determine this information for undescribed fish species and secondly there was no information about the quantities of fish caught to form the basis for cut-off points of susceptibility of the species to being overfished by subsistence fishers.

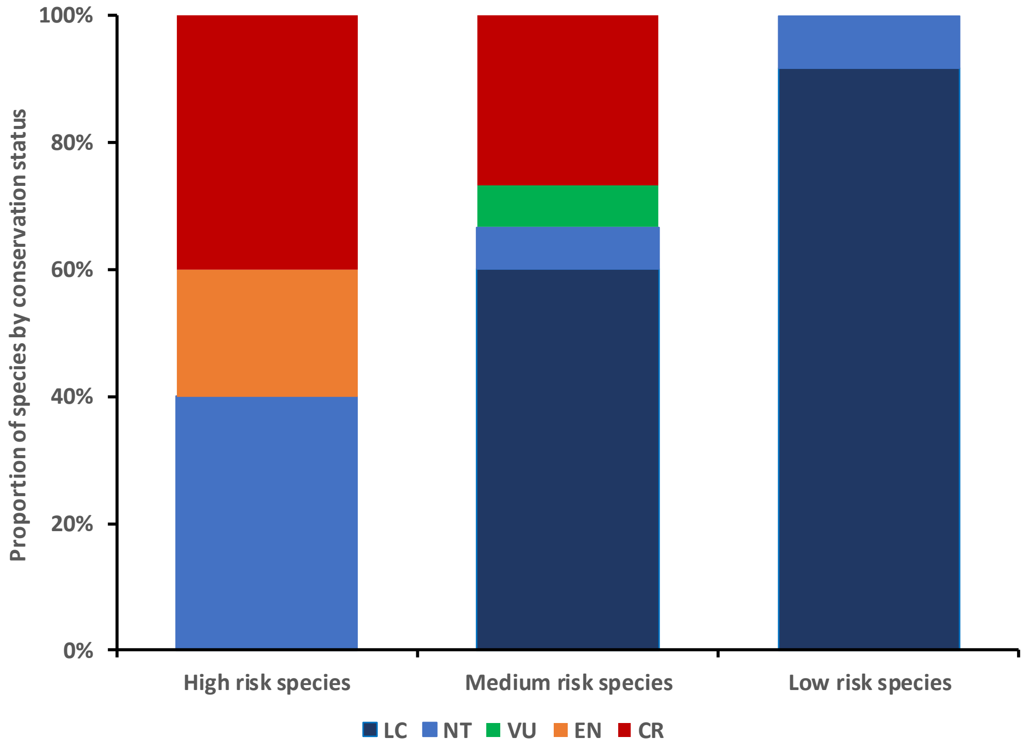

Figure 5-7 The proportion of exported described ornamental fish species from Lake Malawi belonging to different IUCN conservation status categories by their risk score ranking. LC = least concern, NT = near threatened, VU = vulnerable, EN = endangered, CR = critically endangered.

The box and whisker plot of overall productivity and susceptibility scores by IUCN conservation status are presented in Figure 5-8. The results show a general decrease in the average susceptibility score for fish species as the IUCN risk category decreases from critically endangered to species of Least Concern. However, the pattern for productivity score is not clearly defined showing an initial increase of the average score value as the IUCN conservation risk category decreases from critically endangered to vulnerable followed by a decrease of the average productivity score as the IUCN risk category decreases further from vulnerable to least concern. These results demonstrate that the susceptibility score of this study has a stronger correlation with the IUCN (2019) risk assessment criteria than the productivity score.

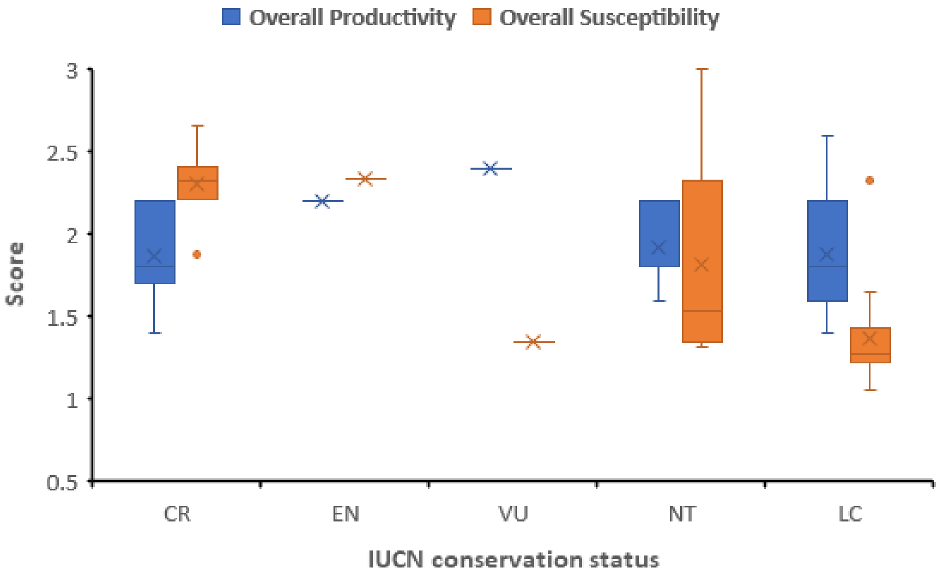

Figure 5-8. Box and whisker plots of productivity and susceptibility scores against IUCN risk category. CR = critically endangered, EN = Endangered, VU = Vulnerable, NT = near threatened, LC = Least Concern. Note that for EN and VU, there were only single values for both Productivity and Susceptibility scores, hence shown as points in the graph.

5.4 Discussion

This chapter used PSA tools to assess the relative risk to exploitation of commonly exploited ornamental fish species of Lake Malawi and rank them according to their relative risk scores. Not all the productivity and susceptibility attributes of the original PSA of Hobday *et al.* (2007, 2011) and the modified PSA version of Patrick *et al.* (2009) were used because the required information for some productivity attributes was not available and some of the susceptibility attributes were not relevant for the ornamental fishery of Lake Malawi. Moreover, there appears to be lack of consensus regarding the PSA attributes that may be universally ideal for use in different types of fisheries (Fujita *et al.,* 2013), although most of the attributes used for scoring productivity and susceptibility traits were vetted by the Vulnerability Evaluation Work Groups created by the U.S. National Oceanic and Atmospheric Administration's National Marine Fisheries Service (Patrick *et al.,* 2009). The PSA has been commonly modified to suit specific fish stocks and fisheries management areas (Arrizabalaga *et al.,* 2011; Brown *et al.,* 2013, Fujita *et al.,* 2013; McCully *et al.,* 2013; McCully Phillips *et al.,* 2015; Furlong-Estrada *et al.,* 2017). Furthermore, Hordyk & Carruthers (2018) are of the view that the PSA scoring system could be over-parameterized and that addition of unrelated or correlated attributes to the PSA could reduce the capacity of PSA to predict relative risk to exploitation. Identification of relevant traits for scoring productivity and susceptibility of individual fish species assessed in the current study was based on existing literature. Productivity attributes were mostly obtained from IUCN (2019) and FishBase (Froese & Pauly, 2019), while susceptibility traits were based on those previously applied to ornamental fisheries including the Queensland Marine Aquarium Fishery in Australia (Roelofs & Silcock, 2008), a combination of marine coral reef fisheries in different parts of the world (Fujita *et al.,* 2013) and the marine aquarium fishery in Kenya (Okemwa *et al.,* 2016).

One assumption made when conducting PSA in this study was that fishing for ornamental trade is the only risk factor to the ornamental fish species of Lake Malawi. Other threats presented in Chapter 2 (Figure 2-15), including subsistence fishing, sedimentation, water pollution, habitat destruction and population size, were not included in the PSA because information about such threats was not available for most of the assessed ornamental fish species. Factoring such information in the PSA assessment may change the risk scores and rankings of the assessed fish species. In Section 2.4.5, it was suggested that subsistence fishing of the targeted ornamental fish species of Lake Malawi is probably underreported. The subsistence fishery is probably posing more risk to the targeted fish species than the ornamental fishery. Assessment of cumulative risk of both fisheries on these stocks using the method developed by Micheli *et al.* (2014) could illuminate the combined impacts of the two fisheries on the exploited fish species. Micheli *et al.* (2014) demonstrated that different fisheries targeting the same stocks can have significant cumulative impacts on the targeted fish species when a cumulative risk assessment method is used. However, a cumulative risk assessment approach could not be conducted in the current study because of information gaps for scoring risk caused by the subsistence fishery (i.e. fishing gear used, depth of fishing, fishing localities, species composition and other information that may affect fish susceptibility to capture). Despite not including some of these components in this study, a few important insights can be gained.

Results of the current study showed that the majority (71) of the assessed ornamental fish species of Lake Malawi had low relative risk to overexploitation. Nineteen species had medium relative risk while nine species had high relative risk of overexploitation. The nine fish species with high risk score had high susceptibility score and medium productivity score. The 19 fish species with medium risk score comprised a mixture of three categories including: species with high susceptibility score but low productivity scores; species with medium scores for both susceptibility and productivity, and species with high productivity score but low susceptibility score. Amongst the 71 fish species ranked to be of low risk, 61 species had productivity score values higher than their susceptibility scores.

This study demonstrated positive correlations between PSA risk categories and IUCN (2019) assessment criteria despite the two criteria being different. The IUCN criteria for classification of biological taxa into their conservation status categories is based on five quantitative criteria that define biological indicators of populations that are threatened with extinction. The criteria include: 1) population size reduction – measured over the longer of 10 years or 3 generations, 2) geographic range in the form of either extent of occurrence and/or area of occupancy, 3) small population size and decline, 4) very small or rescricted population, and 5) quantitative analysis indicating the probability of extinction in the wild (IUCN Standards, and Petitions Committee, 2019). Each of these five criteria has defined cut off points for categorizing a taxon into specific conservation threats (i.e. least concern, near threatened, vulnerable, endangered, critically endangered). Least concern applies for taxa without plausible threats and the level of threats increases from this category to critically endangered (IUCN Standards, and Petitions Committee, 2019). In addition to these categories of concervation threat, taxa known only from their type localities without information on their current status are classified as data deficient (IUCN Standards, and Petitions Committee, 2019). The PSA analysis employed in the current study was based on five productivity traits of the assessed fish species (including generation length as a proxy for age at maturity and maximum age, maximum length, fecundity, trophic level and minimum population doubling time) and four susceptibility traits (management strategy in place, species distribution depth in relation to fishing gear, market value of exported ornamental fish species and distribution of the species. This shows that the IUCN criteria are different from the PSA criteria used in the current study. The two models use different data sets except the distribution patterns of the species which is factored in both models though differently and using totally different definitions of cut off points to define the PSA risk scores and the IUCN conservations status categories.

The positive correlation between PSA risk categories and IUCN conservation status has also been reported in studies of different marine fish stocks (Patrick *et al.,* 2009; McCully *et al.,* 2013; Osio *et al.,* 2015; Lucena-Frédou *et al.,* 2017). This correlation justifies the application of the PSA to assess the relative risk to exploitation of Lake Malawi ornamental fish species. However, there were a few outliers to the observed correlations. Firstly, PSA scored four critically endangered and one vulnerable species as having medium risk scores instead of the expected high-risk scores under the assumption of a perfect match between the two criteria for risk assessment. Secondly within the 50 fish species scored by PSA to have low risk, four species were classified by IUCN as near threatened species. Assuming a perfect match between the PSA and IUCN risk assessment criteria, the four species should have been scored as medium risk species. Hordyk & Caruthers (2018) reported that PSA is a good predictor of risk in the lowest and highest risk range but poor predictor in the middle risk range. The few species that showed a mismatch of the PSA risk score and IUCN conservation status support the report of Hordyk & Caruthers (2018), and these few species can partly be explained by the variation in the individual productivity and susceptibility trait scores (Table 5-1). For instance, although species like *Aulonocara kandeense*, *Pseudotropheus cyaneorhabdos* and *Chindongo saulosi* are critically endangered, with high susceptibility score of 2.33, their productivity scores were less than 2 resulting in medium risk score. Alternatively, *Cyrtocara moori* and *Aulonocara ethelwynnae*, which are classified by IUCN (2019) as vulnerable and near threatened respectively, have medium to high (2 to 2.4) productivity scores but low susceptibility scores (1.35 to 1.73) resulting in a medium risk score. On the other hand, *Aulonocara maylandi* is classified as critically endangered by IUCN (2019) but has medium scores for both productivity (2.2) and susceptibility (1.8) resulting in medium risk score.

The results of this study also showed that susceptibility trait scores had a higher influence on the relative risk rankings of different fish species than productivity trait scores. Similar trends are shown in PSA reports for other fisheries including: elasmobranch bycatch in the shrimp trawl fishery of Costa Rica (Cortés *et al.,* 2010; Clarke *et al.,* 2018), elasmobranchs and teleosts caught in the fisheries of the northern European seas (McCully *et al.,* 2013), Atlantic pelagic elasmobranchs species (Cortés *et al.,* 2015), species caught in the marine aquarium fishery of Kenya (Okemwa *et al*., 2016), and species caught by artisanal fishers along the seascape of in Kilwa and Mafia districts of Tanzania (Chande *et al.,* 2019). In their evaluation of PSA as a tool for determining fish stocks' risk to exploitation, Hordyk & Caruthers (2018) concluded that susceptibility score is of greater importance in determining overall risk to the fish stock than productivity score, which is consistent with findings of the current study. However, one exceptional situation was reported for Alaska ground fish fisheries stocks of which productivity traits had more influence on PSA risk scores than susceptibility traits (Ormseth & Spencer 2011).

The fact that susceptibility contributed more to fish species being in the high-risk category than productivity traits, provides opportunities for a wide scope of management interventions to reduce the risk of exploitation of species (Cope *et al.,* 2011, Brown *et al.,* 2013). For example, through interventions such as creation of sanctuary areas and fishing gear restriction, which are aimed at conserving species, the susceptibility score of targeted ornamental fish species could be reduced thereby reducing the overall risk score.

The following options have been proposed for management of species with medium to high risk score based on PSA results: further quantitative risk assessment, further research and data collection where information is lacking, and some management response to mitigate the risk to these fish species (Hobday *et al.,* 2011; Brown *et al.,* 2013; Cortés *et al.,* 2015; McCully Phillips *et al.,* 2015; Lucena-Frédou *et al.,* 2017). In addition, it has been suggested that irrespective of the overall risk score value, species of fish with high susceptibility scores deserve the same management attention as those in the medium and high-risk categories (Cope *et al.,* 2011; Brown *et al.,* 2013). In the current study, 28 fish species with high susceptibility scores were either in the medium or high-risk category and all were ranked between 1 and 14 (with ties of ranks for some species). For these fish species of concern, available quantitative risk assessment methods (e.g. Zhou & Griffiths, 2008; Zhou *et al.,* 2009; 2011; 2012; 2016) cannot be applied as a next step because these methods require more information about the assessed fish stocks (including fishing effort, fish abundance, and fish mortality rate) than PSA, which is currently not available for Lake Malawi cichlid fishes. The feasible options could therefore be to undertake further research and data collection and implementation of some management response to mitigate the risk to exploitation. Further research could focus on collection of data about the population sizes (and life history traits such as size and age at maturity, fecundity, and fish growth parameters) of fish species with medium and high relative risk (and undescribed fish species whose life history traits were estimated based on their genera) and relating the population size to the numbers of fish exploited and exported. Some productivity trait scores for undescribed species estimated in this study based on the genera the fish belong to, may change when the PSA is updated with species specific information collected (Arrizabalaga *et al.,* 2011; Cope *et al.,* 2011). Alternatively, Apel *et al.* (2013) and Fujita *et al.* (2013) proposed a five-step framework as a management guide for ornamental coral reef fisheries with varying amount and types of data by combining three different data-poor assessment and management methods[22], which may be applicable to the management of ornamental fishery of Lake Malawi. The steps in the proposed framework are: assessment of ecosystem risk of fishing using quantitative ecosystem thresholds or ERAEF; assessment of vulnerability to fishing using PSA; estimation of relative levels of depletion and/or exploitation using density ratios or other fish export information; prioritisation of precautionary management by identifying stocks that require reduced fishing pressure and stocks that can sustain increased fishing pressure; and prioritisation of species for further assessment and management based on vulnerability, exploitation status and economic importance. The tools that were demonstrated by Fujita *et al.*

[22] The methods include: 1) coral reef threshold identification which relates attributes of the coral reef state (e.g. macroalgae cover, grazing intensity and coral cover) to fish diversity and abundance, 2) The productivity sustainability analysis, 3) Determining depletion/exploitation status which uses fish density as a proxy for fish biomass and therefore a measure of coral reef status and “health” of the reef system.

(2013) for application of the proposed framework to management of the ornamental fishery of Indonesia, showed that less data are required than for quantitative risk assessment methods of Zhou & Griffiths (2008) and Zhou *et al.* (2009; 2011; 2012 & 2016). Further application of this framework for management of Lake Malawi ornamental fishery is discussed in section 6.2 of Chapter 6.

Management responses to mitigate the risk to fish species with high relative risk and exported in high numbers, should be considered urgent for Lake Malawi. Although one of the weaknesses of PSA is the inability to generate specific management reference points for sustainable exploitation levels of fish stocks (Apel *et al.,* 2013; Fujita *et al.,* 2013; McCully Phillips *et al.,* 2015), it is conceivable for management to reduce fishing effort or completely ban fishing of fish species that have high PSA risk scores and are highly sought after in the ornamental fish export trade. The correlation between IUCN risk assessment criteria and PSA risk ranking of the current study validates the use of PSA as a basis for taking some management actions for species with medium to high relative risk to exploitation. Moreover, this study has shown that fish species with medium to high relative risk have very high susceptibility scores (due to limited distribution range, being found in unprotected areas and in shallow waters which are easily accessible to SCUBA divers with no diving time limit, and the species are of high market value), which predisposes them to being overexploited. Reduction of fishing effort for these fish species could be combined with research on the exploited species populations to act as a basis for setting sustainable levels of exploitation of the species. The research could be based on the framework and tools proposed by Apel *et al.* (2013) and Fujita *et al.* (2013), by assessing the required information of the components of their framework such as assessment of stock depletion status by using underwater visual estimates of fish densities (using SCUBA diving gear) inside and outside the protected area of Lake Malawi and assessment of priority stocks. This research is urgently needed considering that currently there is no limit to the quantity of any ornamental fish species that can be exploited from Lake Malawi. Fujita *et al.* (2013) recommended two possible options for ornamental fish species that are highly vulnerable and subject to high exploitation levels including light fishing with careful monitoring and banning capture of the species. These two options are suitable for the vulnerable ornamental fish species of Lake Malawi. Thus, exportation of ornamental fish species with low relative risk could be encouraged while banning exportation of the vulnerable species.

5.5 Conclusions and recommendations

The findings of this study showed that of the 99 species of fish assessed and ranked using PSA, 9 species had high relative risk, 19 species had medium relative risk while 71 species had low relative risk to exploitation for ornamental fish trade. Susceptibility traits had higher contribution to the high-risk scores than productivity traits. A positive correlation was observed between fish species PSA risk scores and IUCN assessment criteria.

Based on the findings, the following recommendations are made:

- Fish species that were found to be of high risk, and all those not included in the PSA but are in the categories of high-risk concern on the IUCN criteria (near threatened, vulnerable, endangered, critically endangered), should be banned from ornamental fish trade exportation. These species include *Copadichromis azureus*, *Aulonocara* sp maisoni, *Aulonocara* sp maulana, *Aulonocara* sp mdoka, *Aulonocara baenschi*, *Melanochromis chipokae*, *Aulonocara nyassae*, *Aulonocara* sp sanga, *Placidochromis phenochilus*, *Metriaclima usisyae*, *Nyassachromis boadzulu*, *Pseudotropheus brevis*, *Labidochromis zebroides*, *Nyassachromis brevis*, *Mchenga conophoros*, *Metriaclima flavicauda*, *Copadichromis nkatae*, *Trematocranus microstoma* and *Serranochromis robustus*. Banning of exportation of these species should be backed by national legislation and fishery management policy in Malawi.
- Strict enforcement of the ban will be required during inspection and approval[23] of every ornamental fish export consignment.
- All the people involved in enforcement (Fisheries Department personnel and Custom Clearance personnel) should be trained in fish identification and fish names used, including both scientific and trade names used in the ornamental fish trade.
- Sustainable exploitation of ornamental fish species that were found to be of low exploitation risk for export trade should be promoted. These species include those ranked in the PSA from 15 to 47, with the exception of *Chindongo flavus*, which is only found in LMNP around Chinyankhwazi Island[24] and 13 other species whose distribution range in Lake Malawi is not widespread including: *Copadichromis verduyni*, *Cynotilapia*

[23] By both Fisheries Department Personnel and Customs Clearance Inspectors of the export consignment.
[24] Included in the PSA because the export data collected in this study indicated that it was commonly exported up to 2011 after which it has never been exported

axelrod, *Metriaclima lombardoi*, *Pseudotropheus interruptus*, *Cynotilapia* sp mbamba, *Labidochromis flavigulis*, *Metriaclima mbenji*, *Metriaclima hajomaylandi*, *Metriaclima joanjohnsonnae*, *Protomelas* sp thick lips, *Pseudotropheus perileucos*, *Labidochromis freibergi*, and *Metriaclima greshakei*. Exploitation of these 13 species will require close monitoring of the populations and more research to establish exploitation level that could be sustained based on comparisons of fish relative abundance in well protected areas of LMNP with fished areas of similar habitat types. Based on research findings, the PSA may be revisited to revise some of the productivity and susceptibility trait values and exportation quota can be established for these ornamental fish species.

The recommendations made in this chapter are further articulated in the proposed management framework for the ornamental fishery of Lake Malawi in section 6.5 of Chapter 6.

Chapter 6 Discussions, conclusions and recommendations

6.1 Introduction

The overall aim of this research was to investigate potential impacts of ornamental fish export trade on the fish species of Lake Malawi. The specific objectives were: identification of ornamental fish species exported from Malawi since 1998 (with respect to export volumes and value, collection localities in Lake Malawi, IUCN conservation status and export destinations); comparison of populations of exploited ornamental fish species inside and outside the protected areas of Lake Malawi; investigation of exported fish species maturity sizes and fecundities; and assessment of the relative risk of fish to exploitation. Based on findings of this study, recommendations are made regarding management of the ornamental fishery of Lake Malawi and a framework for the ornamental fisheries conservation plan is proposed.

The ornamental fish export trade in Malawi targets colourful endemic cichlid fishes found in localised rocky outcrops of Lake Malawi. The number of licenced exporters of ornamental fish from Malawi has varied between one and four exporters during the past two decades (Chapter 2). The exporters employ SCUBA divers to catch the fish in different localities of the lake with the numbers of fish caught varying between localities (Chapter 2). On average about 24996 ornamental fish are exported annually from Malawi.

6.2 Impacts of ornamental fish trade on the exploited populations

The high diversity of ornamental fishes exported from Malawi (Chapter 2) is consistent with reported ornamental fish exploitation patterns of targeting both abundant and rare fish species (Pinnegar & Murray, 2019). The potentially negative impact of the ornamental fish export trade on exploited fish in Lake Malawi relates to representation of 22 threatened and 21 near threatened amongst the exported fish species. This exploitation for the ornamental trade is exacerbated by the subsistence fishery commonly targeting the same species and large numbers of fish being removed indiscriminately by small seine nets, gillnets and hooks and lines. **This unregulated exploitation necessitates the need for Malawi Fisheries Policy to incorporate management measures for threatened ornamental fish species**. The other concern noted from the current study is the exploitation of many undescribed fish species with unknown population sizes to guide their management. **These results suggest the need for more investment in taxonomy and systematics of cichlid fishes of Lake Malawi to formally describe these fish species and determine the exploitation pressures on their extant populations.** The other notable finding (Chapter 2) is that collection of ornamental fishes is concentrated in a few specific areas, some of which are small rocky reefs that may not have the capacity to support high fishing effort. This is critical because many fish species appear to be confined to very restricted localities and this will increase the susceptibility of the discrete populations and their overall risk to overfishing. **It is therefore recommended to monitor the populations of ornamental fish in the most commonly fished rocky reefs of Lake Malawi including: Chilumba Area, Nkhata Bay, Likoma and Chizumulu Islands, Mbenji Island, Chindunga Rocks and Mozambique Border**.

The relatively constant volume and value of ornamental fish exported from Malawi between 1998 and 2017, after accounting for apparent extreme fluctuations, was contrary to expectations of a continuously decreasing pattern of ornamental fish export volumes due to competition from fish captively bred in the Far East, South America and the Czech Republic (Watson, 2000; King, 2019). It is possible this stable trend for export of Lake Malawi cichlid fishes is due in part to continuous discovery of new fish species (Konings, 2016), which get advertised in the ornamental fish export market promotional material. To promote the aquarium fish trade in Malawi, it was planned to increase the number of licensed ornamental fish exporters in Malawi from three to twelve in the Implementation, Monitoring and Evaluation Strategy of the Malawi Government Fisheries and Aquaculture Policy (Malawi Government, 2016b). This proposed increase of licensed exporters is not supported by findings of this study, as interviews with current ornamental fish exporters in Malawi revealed that they were not operating at their maximum capacity. Thus, **stakeholders in the ornamental fish export trade may require promotional measures that would increase effective demand for ornamental fish species from Malawi**.

At present, export price may be the major determining factor of demand for ornamental fish from Malawi, as revealed by interviews with exporters of ornamental fish in Malawi who stated that many of the importers complained about ornamental fish from Malawi being relatively expensive compared with those from other countries. This could partly be attributed to competition with lower prices from captively bred fish sources (Watson, 2000; Raghavan *et al*., 2013; Evers *et al*., 2019; King 2019). One exporter also revealed that the other main competitors are exporters from Tanzania, whose export prices are lower than those for exporters in Malawi because of better flight connections from Tanzania to ornamental fish importing countries. Fish exporters also revealed that mortality risk during transportation was one of the factors that influenced their decision to export fish to specific countries. This is linked to mortality increasing with the time it takes for fish to arrive at the export destination, which is dependent on existing flight connections to the export destinations. Watson (2000) also alluded to poor services and delays by customs clearance of export consignments as a challenge for exportation of ornamental fish, which interviewed exporters concurred with. **Thus, one way to ensure exporters of ornamental fish from Malawi compete favourably with those from other countries is to improve services of the customs and border controls so that clearance of ornamental fish export consignments is expedited rapidly.**

Definitive conclusions regarding comparisons of ornamental fish species composition and abundance between protected and non-protected areas (Chapter 3) could not be drawn without accounting for the sources of overdispersion of the data set. **It is recommended that future research into fish population ecology be undertaken using more rigorous sampling to account for possible causes of overdispersion of the data at the microhabitat level - as discussed in Chapter 3. The sampling should combine the use of video footages and SCUBA divers using strip transects to estimate fish species composition and abundance.** Additionally, the impact of the ornamental fish trade on exploited fish populations could not be directly determined through comparisons of individual fish species' populations inside and outside protected areas because most of the exported fish species have limited distribution ranges, being found either only in protected area or only outside protected areas. **To determine the impacts of fish exploitation on individual fish species, long-term monitoring of populations of the key export species at their known localities is recommended. At each known distribution locality for commonly exported fish species, permanent quadrants (strip transects) should be established where fish population could be periodically (e.g. annually) assessed through SCUBA diving techniques to determine relative population density changes.** In addition, there **is need for collaboration between the Department of Fisheries and Lake Malawi ornamental fish exporters and hobbyists who have more information regarding the population trends of various ornamental fish species of Lake Malawi**. Such collaboration could guide the Department of Fisheries to verify the existing information on cichlid forum websites about the disappearance of some cichlid species of Lake Malawi in the natural environment, as discussed in Section 2.4.6 of Chapter 2.

The size of the rocky areas being a significant determinant of fish assemblage structure, with larger rocky areas being associated with higher species diversity and fish abundance than smaller rocky areas suggests that fish species confined to small rocky areas are likely to be more vulnerable to overexploitation from the ornamental trade. This concern has consistently been raised by other researchers (see review by Wood, 2001). **It is recommended that small rocky**

areas harbouring unique fish species should form part of the regular monitoring programmes to follow fish population trends.

Chapter 4 has shown that most of the investigated ornamental fish species of Lake Malawi mature at small sizes between 50 mm and 100 mm standard length and they have relatively low absolute fecundity ranging from 16 to 90 eggs. However, the sampled fish were a very small proportion of the species of fish in Lake Malawi with known life history traits. Moreover, the sample sizes for some of the fish species were too small to draw definitive conclusions about their reproductive traits. **Future studies should focus on life history traits of fish species, which have never been studied before, by sampling populations from all known distribution localities. The studies should also include undescribed species (with well documented information regarding their identity), besides described species**.

The use of PSA tools (Chapter 5) to assess the relative risk of commonly targeted fish species of Lake Malawi to exploitation for the ornamental fish export trade indicated that 28 of the 99 species of fish included in the risk assessment were of management concern, since they had medium to high risk of exploitation, while 71 species were of low risk. Options for management of fish species with medium to high risk were discussed (Chapter 5), and include undertaking further quantitative risk assessment, further research and data collection where information is lacking, and implementation of measures to mitigate the risk to fish species. However, not all of these options would be applicable for managing Lake Malawi ornamental fish species because some of them require more information about the exploited fish populations than is available. The framework of Apel *et al*. (2013) and Fujita *et al*. (2013) discussed in (Section 5.4), proposed five steps as a management guide for ornamental coral reef fisheries. These were: i) assessment of ecosystem risk of fishing using quantitative ecosystem thresholds or ERAEF; ii) assessment of vulnerability to fishing using PSA; ii) estimation of relative levels of depletion and/or exploitation using density ratios or other fish export information; iv) prioritisation of precautionary management by identifying stocks that require reduced fishing pressure and stocks that can sustain increased fishing pressure; and v) prioritisation of species for further assessment and management based on vulnerability, exploitation status and economic importance. All steps except the first (i) are applicable for management of the ornamental fishery of Lake Malawi[25].

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[25] The first step may not be currently applicable for Lake Malawi ornamental fishery because of lack of information related to fish age and growth and mortality which is required for computation of quantitative ecosystem thresholds.

Moreover, the ecosystems for the two fisheries (coral reefs and rocky areas of Lake Malawi) share many common attributes (as revealed by numerous publications about these ecosystems) – e.g. both ecosystems are characterised by shallow depths, have high species diversity, have many algae grazing fish species, are important for tourism development, and support fisheries important for subsistence economies. Assessment of fish vulnerability using PSA is the second step of the framework of Fujita *et al*. (2013), which was conducted in Chapter 5. Information about the third step, which relates to estimation of relative levels of fish depletion and/or exploitation using density ratios, can easily be collected by divers using underwater transect techniques through SCUBA diving, as employed by Ribbink *et al*. (1983) and Genner *et al*. (2004; 2006). For exported ornamental fish species of Lake Malawi, which are relatively small, SCUBA divers using underwater transects can collect better quality fish density data at species level than using underwater video footage (see Chapter 3). Density ratios could be estimated by comparing densities in well protected sites of Lake Malawi National Park and exploited sites outside the protected areas. The fourth and fifth steps involve prioritization of management actions based on analysis of information collected in the first three steps. **It is therefore recommended that management plans for ornamental fish species of Lake Malawi should be based on a combination of the use of PSA and estimates of relative levels of depletion and/or exploitation using density ratios to prioritise precautionary management of stocks according to the framework of Fujita *et al*. (2013).**

All the described species of fish of medium to high PSA score (Table 5-1) were amongst the top 71 most commonly exported fish species of the list in Appendix 2.4. Additionally, it was noted that 30% of the top 30 most exported ornamental fish species were of conservation concern based on IUCN (2019) (Chapter2). Since PSA risk score was positively correlated with IUCN risk assessment criteria, **fish management decisions that relate to IUCN risk criteria could also be applied to the PSA criteria and this application could be extended to undescribed fish species that are not included in the IUCN risk assessment criteria.** Undescribed fish species categorised by PSA to have high risk are very likely to be of conservation concern if these species were to be assessed according to IUCN risk assessment criteria.

Twenty of the species of fish that were not included in the PSA due to their relatively low export volumes are classified by IUCN (2019) in the categories of conservation concern (near threatened, vulnerable, endangered and critically engendered) (see Appendix 2.4). The fact that relatively few numbers have been exported for each of these species does not make these species less vulnerable to exploitation by ornamental fish trade. In Lake Malawi it is very easy for both abundant and rare species to be caught simultaneously since many targeted *mbuna* fish species can be confined in a small rocky area. Moreover, with the incentives provided to divers to catch rare but valuable species (see section 2.4.3 in Chapter 2), divers would be willing to catch the last individual fish of the rare species they encounter in the same localities. **It is therefore recommended that control measures be put in place about exploitation of ornamental fish species with limited distribution and classified by IUCN to be of conservation concern**.

Three categories of fish species found to be of medium to high risk (in Chapter 5) can be identified based on their threats stated in the IUCN (2019) data base. The first category comprises species threatened by subsistence and/or commercial food fisheries, which include *Aulonocara nyassae*, *Cyrtocara morii*, *Buccochromis rhoadesii*, *Buccochromis heterotaenia* and *Eclectochromis ornatus*. The second category comprises species of fish threatened by both ornamental fishing and subsistence and/or commercial food fisheries, which include *Copadichromis azureus*, *Placidochromis phenochilus*, *Melanochromis chipokae*, *Tyrannochromis macrostoma* and *Aulonocara rostratum*. The third category includes fish species threatened (or that can potentially be threatened) by the ornamental fish trade only, such as *Aulonocara baenschi*, *Aulonocara korneliae*, *Aulonocara hueseri*, *Aulonocara kandeense*, *Pseudotropheus cyaneorhabdos*, *Aulonocara maylandi*, *Chindongo saulosi*, *Aulonocara ethelwynnae*, *Nimbochromis linnii*, and *Nimbochromis livingstonii*. All species in the first category, except *Aulonocara nyassae,* are widely spread in Lake Malawi. However, in the second group, *C. azureus*, *P. phenochilus*, and *M. chipokae* are of limited distribution while *T. macrostoma* and *A. rostratum* have lake-wide distribution (IUCN, 2019). In the third group, all species are of very limited distribution, except for *N. linni* and *N. livingstonii,* which are widespread in the lake (IUCN, 2019). All fish species with limited distribution are more likely to be vulnerable to any form of exploitation than species with widespread distribution, which are very unlikely to be overfished by the SCUBA divers currently employed by the ornamental fish exporters. Thus, although few species with widespread distribution (*T. macrostoma*, *A. rostratum*, *N. linni*, and *N. livingstonii*) were of medium risk score (due to their high productivity scores), ornamental fishing would not pose much threat to such species. **It is recommended that measures need to be put in place to regulate subsistence and commercial fishing activities that threaten specific ornamental fish species**.

One possible option for management of ornamental fish species of conservation concern is captive breeding of such species by the fish exporters. However, the success of such an option could be dependent on the following three factors: 1) existence of enough demand for the species so that the exports should be able to offset investment and running costs for captive breeding programme; 2) access to reliable electricity supply[26] to run the fish breeding facilities; 3) breeders of cichlids overseas with better facilities, such as in the Far East and USA, not being able to outcompete such a captive breeding programme overtime. **To minimize costs of captive breeding of ornamental fishes, solar power could be harnessed and used to provide electricity for the breeding facilit**y. This reduction in costs of breeding the fish could result in reduced fish export price thereby reducing the chances of being outcompeted by breeders of cichlids overseas.

6.3 Global strategies for management of ornamental fisheries

Many strategies have been used for management of marine coral reef ornamental fisheries, which were categorised by Dee *et al*. (2014) into international agreements that regulate ornamental fish trade and country level regulations and management.

At the international level, Dee *et al*. (2014) summarized the mechanisms and limitations of many existing international agreements. For instance, IUCN provides information about individual species conservation status and extinction risks but does not have regulatory authority. Another example is the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) that regulates international trade for listed species, but only a few of the species involved in the ornamental export trade are listed because of the complicated process for listing new species (Dee *et al*., 2014). According to the reviews by Dee *et al*. (2014) and King (2019), there are many other challenges associated with international agreements with regards to operationalization of the rules, standardization of management protocols, and enforcement of the set rules. These challenges are not only affecting coral reef ornamental fisheries but also freshwater fish species. For instance, none of the cichlid species of Lake Malawi is on the CITES list (CITES, 2019).

Several national-level fishery management regulations are used, which may vary from country to country (Dee *et al*., 2014; King, 2019). These regulations employ many management measures, of which Dee *et al*. (2014) identified the following to be suitable for managing ornamental fisheries: gear restriction, total bans, effort control, total allowable catch, rights-based fisheries management, spatial closures and zoning, size limits and regulations on import and export practices. Some of these regulations are also applicable to management of ornamental fishes of Lake Malawi. For instance, Lake Malawi National Park protects some of the ornamental fish

[26] Electricity supply in Malawi, which is from hydropower, is currently very erratic

species. Management rules applicable to food fisheries of Lake Malawi (closed season and ban of some fishing gears such as small mesh sized fishing nets) also offer some protection to ornamental fish species because of the overlap of the ornamental and food fish fisheries.

Based on a review of reports about the use of these fisheries' management measures in different marine coral wildlife exporting and importing countries, Dee *et al*. (2014) provided information about successes and limitations of the measures that could guide management of other ornamental fisheries, like that of Lake Malawi. Besides the challenges associated with international agreements for regulation of ornamental fish trade (e.g. lack of regulations enforcement), other issues are prevalent, including corruption, lack of stock assessment, poor data collection and conflicts between different fisheries groups. A number of these challenges also affect Lake Malawi ornamental fisheries (Chapter 5 and this chapter).

6.4 Strategies for management of ornamental fish species of Lake Malawi

According to IUCN (2019), two strategies are used for management of individual ornamental fish species exploited from Lake Malawi: protection of the populations of some species by Lake Malawi National Park and a restocking programme for some fish species initiated by Stuart Grant Cichlid Conservation Fund. The former strategy has some positive impacts on the protection of the species of fish (Chapter 3), where it was demonstrated that protected areas provide significantly higher species diversity metric values than unprotected areas. However, for the restocking programme the positive impacts are yet to be demonstrated. Moreover, implementation of this programme, cannot be successful if there are no measures in place to allow the populations of the stocked fish species to recover before being exploited. The rocky areas of Lake Malawi reported to have been restocked with the fish are open access areas to fishing so that the stocked fish are likely to be caught by fishers soon after stocking. Most people, including the artisanal fishers and the technical staff in the Department of fisheries, are not aware of the restocking programme. Moreover, there are negative effects of restocking of wild fish populations with captively bred fishes, including loss of genetic diversity, inbreeding, reduction in fitness of the fish, disease introductions, and poor adaptation of stocked fish (see section 2.4.6 of Chapter 2). **There is need for research about the impacts of the ornamental fish stocking in Lake Malawi. Before any further stocking efforts are conducted the Department of Fisheries and the scientific community from various institutions should be involved to help predict and mitigate the negative impacts of the programme.**

IUCN (2019) has recommended several other fish species-specific conservation actions for Lake Malawi, which may be grouped into three categories as follows: habitat management, policy and legislation, species management and trade management. Furthermore, IUCN (2019) recommended monitoring of the exploited fish population trends.

The findings of the current study suggest the need for improvements in the strategies used for management of the ornamental fishery in Malawi. **Research and monitoring of the ornamental fishery, which is crucial for sustainability of the fishery, requires collaboration by various stakeholders**. The Department of fisheries research unit and other research institutions (e.g. academic and international researchers) could be involved in primary research of the fish populations, including fish classification and taxonomic studies, distribution and population sizes, life history traits, assessment of anthropogenic impacts on exploited fish populations (impacts of artisanal and commercial fishing on ornamental fish populations, effect of various forms of pollution on ornamental fish populations), and general biology and ecology of the fish. For cost effectiveness there will be a **need for synergistic implementation of monitoring and research programmes** amongst various stakeholders. Ornamental fish exporters could be mandated to provide regular information about their fishing including number of fishing trips per given time period, numbers of diving teams involved in the trips, fish species composition and numbers of fish caught in each trip. The other aspects that could be included in the fishing reports is whether fishers were able catch all their target species and numbers, and specification of targeted species that they did not catch. Such reports could provide the currently missing information about catch and effort of the ornamental fishery as well as an indication of fish species that are possibly overfished. **The Department of Fisheries in Malawi should establish mechanisms for collaboration with the ornamental fish hobbyists and other informal institutions such as the Stuart Grant Trustee on Fish Conservation**. Since these stakeholders are also concerned about overexploitation of the ornamental fish resources, collaborative efforts between these stakeholders and the Department of Fisheries on conservation and management of ornamental fish resources of Lake Malawi could be easily implemented.

There is need for investment in ornamental fish taxonomic and classification studies to resolve issues associated with exploitation of many undescribed fish species, some of which were found to have high risk of exploitation by PSA (Chapter 5). These studies will require collaboration between local scientists in Malawi and international researchers who have contributed substantially to the classification and taxonomy of Lake Malawi fishes.

According to the Implementation, Monitoring and Evaluation Strategy for operationalization of the National Fisheries and Aquaculture Policy 2016-2021, aquarium fish trade was to be promoted as one of the outputs for enhancing public private partnerships and investment in capture fisheries (Malawi Government, 2016b). In addition, the target was to increase the total number of licenced ornamental fish exporters from three in 2016 to twelve by 2021. Findings of this study suggest that it may not be feasible to licence more exporters of ornamental fish from Malawi unless demand for the fish increases. Some of the **ways that could help to increase demand of ornamental fish from Malawi include advertising abundant ornamental fish species with low exploitation risk and improvement of quality of services of inspection** and clearance of export consignments (to minimize delays which lead to increased mortality).

The findings in different chapters of this thesis justify the need to implement species-specific conservation actions recommendations of IUCN (2019) and build them into a conservation management framework.

6.5 A framework for the conservation plan for the ornamental fishery of Lake Malawi

The findings of the research conducted in this thesis have resulted in a number of conclusions and recommendations regarding sustainability of the ornamental fishery of Lake Malawi (presented in Chapters 2 to 5 and in section 6.2 to 6.4 of this chapter). The recommendations relate to the needs for the following broad action points: development of capacity of the Department of Fisheries to manage ornamental fishery, conducting research on many aspects of the ornamental fishery of Lake Malawi, monitoring of the populations of the exploited fish species, promotion of export of abundant ornamental fish species, implementation of measures to ensure recovery of threatened and overexploited ornamental fish species, and introducing measures to ensure sustainable exploitation of the ornamental fish species. In order to conceptualize how these broad actions would contribute to the sustainability of the ornamental fishery in Malawi, the action areas have been summarised as outputs in a logical framework format (Table 6-1). The overall objective of the proposed logical framework is to manage the ornamental fisheries in Malawi in a biologically, ecologically, economically and socially sustainable manner. The purpose is to ensure optimum and sustainable benefits from the ornamental fisheries in relation to revenue generations, creation of employment and conservation of biodiversity, which are in line with the goal of the National Fisheries and Aquaculture Policy (Malawi Government 2016a).

The suggested logical framework approach differs from the Implementation, Monitoring and Evaluation Strategy of the National Fisheries and Aquaculture Policy (Malawi Government, 2016b), in which promotion of the ornamental fisheries is considered as one of the strategies for achieving the objective of promoting public private partnerships and investment in capture fisheries. The ornamental fisheries issues that have emerged from the current study justify the need for the Fisheries and Aquaculture Policy to pay greater attention to management of the ornamental fisheries beyond a mere strategy for accomplishing an objective. Owing to the uniqueness of the issues discussed in this thesis, the management of the ornamental fisheries needs to be considered in the Fisheries and Aquaculture Policy as either an independent objective requiring its own strategies or as a separate Fishery Policy Priority Area with its own objectives and strategies for accomplishment.

Table 6-1. Logical framework for the proposed conservation plan for the ornamental fishery of Lake Malawi

	Intervention logic	**Indicators of achievement**	**Verifications**	**Assumptions**
Overall objective	Develop sustainable ornamental fishery in Malawi.	Effective management systems for the fishery established	Evaluation reports	Fishery prioritized by the Department of Fisheries
Purpose	Optimum and sustainable fishery benefits including: • Generation of revenue for the exporters and the government • Creation of employment • Conservation of biodiversity of Lake Malawi	• Ornamental fish export trends • Number of people employed in the fishery • Exploited fish population status	• Fishery monitoring reports	• Improved fish exportation services • Compliance to fishery management measures put in place
Outputs	1. Capacity of the Department of Fisheries to conduct ornamental fishery research, manage and monitor developed 2. Detailed research about ornamental fish of Lake Malawi conducted 3. Exports of abundant fish species promoted 4. Measures for recovery of threatened ornamental fish species introduced 5. Monitoring system for the ornamental fish export trade improved 6. Measures to ensure sustainable exploitation of the ornamental fish species developed and implemented		Evaluation reports, periodic (monthly / quarterly/annual) review meetings Research reports Ornamental fish export returns Monitoring reports Evaluation reports	

Table 6.1 continued

Strategic goals and activities	***1. Enhance the capacity of the Department of Fisheries to undertake ornamental fish research*** • Source research funding • Training research staff in underwater research techniques and taxonomy of the ornamental fish species of Lake Malawi • Strengthen collaborative research between Department of Fisheries and other research institutions (e.g. academic institutions) • Introduce ornamental fish issues in the curriculum of Malawi College of Fisheries. ***2. Conduct research in ornamental fishes of Lake Malawi*** • Conduct collaborative fish taxonomic research on undescribed species with renowned cichlid fish taxonomists • Assess the populations of the commonly exploited ornamental fish using standard transect methods with SCUBA diving techniques. • Assess relative levels of ornamental fish depletion and/or exploitation using density ratios in in protected and unprotected areas	***Inputs:*** *Resource people* • Trainers/consultants and researchers in various aspects of the ornamental fishery research and management (e.g. cichlid taxonomy, fish ecology, novel techniques for assessment of fish populations, impact studies of restocking ornamental fish in Lake Malawi). • Certified and experienced SCUBA dive masters to train fishery research teams in SCUBA diving		***Assumptions*** Approval of the programme by the Department of Fisheries and the Malawi Government Funding for implementation of activities secured and no financial mismanagement Easily accessible expertise for providing guidance in implementation of specific activities Willingness of collaborators in the specific activities to participate

Table 6.1 continued

	• Assess the potential for exporting captively bred threatened ornamental fish species (with an option to use solar energy as an alternative power source for the system). • Assess impacts of restocking captively bred threatened ornamental fish species into Lake Malawi • Research on ornamental fish population ecology - life history traits, age and growth, recruitment patterns • Investigate the lake wide extent/volumes of artisanal fishing of the ornamental fish species ***3. Promote export trade for abundant ornamental fish species with low exploitation risk*** • Advertise the abundant fish species for the ornamental fish export market • Encourage fish exporters to export the abundant fish species • Improve customs clearance services to avoid delays of ornamental fish export consignments	*Equipment* • Boat with systems for communicating with other people on the mainland and with safety kit (life jackets) • SCUBA diving equipment (compressor, diving cylinders, diving computer, regulators, fins, weights) • Reliable 4x4 cars, for field research, execution of fishery management measures, and outreach programmes with the fishery community • Solar energy systems for feasibility studies of captive breeding of threatened ornamental fish species for export trade • computers • Life jackets		

Table 6.1 continued

	4. Put in place management measures for recovery of overexploited (endangered species and species with high risk of exploitation) • Ban exportation of threatened fish species and species with high exploitation risk of exploitation • Lists of banned fish species for export to be produced and used by inspectors of export consignments (Department of Fisheries' inspectors and Customs clearance staff) before exportation • Train inspectors of the export consignments in identification of ornamental fish species of Lake Malawi • Develop short ornamental fish conservation course for the fisher community • Establish bylaws to control fishing of threatened ornamental fish • Undertake outreach campaigns to sensitize the fishing community about the endangered ornamental fish species ***5. Improve the monitoring system for the ornamental fish exports***	*Operating funds for*: • execution of fishery research activities • implementation of fishery management measures • monitoring the ornamental fishery activities • maintenance of equipment *Training* • Fisheries research personnel (at post graduate level – MSc and PhD levels) • Short courses for fishing community and personnel in Department of Fisheries		

Table 6.1 continued

	• Develop an electronic data base of fish export returns where all information should be entered • Make a provision for the exporters to submit information about fishing trips and number of fishes caught by fishing trip (besides the information they are already providing in export returns) • Annually analyse fish export information to determine trends of exports and species which might be at risk • Compile a list of names of exported fish species including scientific names, common names and trade names to be used for monitoring the fishery. • Annually monitor the populations of ornamental fish in heavily fished rocky reefs and institute appropriate adaptive fishery management measures depending on fish population trends • Improve collaboration and flow of information about ornamental fish between Department of Fisheries, fish exporters and fish hobbyists. • Conduct annual review meetings with various stakeholders	*Networking and collaboration with other stakeholders (locally and internationally)* • Research dissemination meetings and workshops attendance • Presentation of seminars in academic and other research institutions		

Table 6.1 continued

	6. Institute measures to ensure sustainable exploitation of the ornamental fish species • Source funding for implementation of fishery measures • Promote rotational harvesting of ornamental fish • Put in place measures to prevent further translocations of fish within Lake Malawi • Use PSA and IUCN risk assessment criteria to develop fisheries management measures for individual fish species and regularly update the PSA scores when new information collected. • Regulate subsistence and commercial fishing activities which negatively impact the ornamental fish species of Lake Malawi			

6.5.1 Institutional and Policy framework for fishery management in Malawi

The responsibility to manage fisheries in Malawi is vested in the Department of Fisheries (DoF) guided by the National Fisheries and Aquaculture Policy (Malawi Government 2016a) and the Implementation, monitoring and evaluation strategy for this Policy (Malawi Government 2016b). Within the DoF are four sections, namely: Fisheries Planning and Development, Fisheries Extension and Training, Fisheries Research, and General Administrative Support.

The DoF currently falls under the Ministry of Agriculture, Irrigation and Water Development (MoAIWD) which embraces eight technical Departments (Agriculture Extension Services, Agriculture Research, Animal Health and Industry, Crops Development, Land Resource and Conservation, DoF, Department of Irrigation, Department of Water) and Agriculture Planning Services (Figure 6-1). However, within the umbrella of the MoAIWD, the DoF, Irrigation and Water Development departments have not yet been merged with the District Agriculture offices (Figure 6-1).

The MoAIWD is guided by the National Agriculture Policy (NAP) whose goal is “to achieve sustainable agriculture transformation that will result in significant growth of the agriculture sector, expanding incomes for farm households, improved food and nutrition security for all Malawians, and increased agricultural exports” (Malawi Government, 2016c). The NAP is linked to other national development policy instruments such as Malawi’s Vision 2020 (National Economic Council Malawi, 1998) and the Malawi Growth and Development Strategy III (Malawi Government, 2017). Fisheries management is covered under the NAP objective “to increase sustainably the production and consumption of livestock, aquaculture and capture fisheries by 50%” (Malawi Government, 2016c). To operationalise the NAP, the National Agriculture Investment Plan (NAIP) was developed as a framework to guide investment in the Malawi Agriculture sector between 2018 and 2023 (Malawi Government, 2018). The NAIP is aligned to the UN Sustainable Development Goals (SDGs) (United Nations, 2015), as well as the CAADP Compact (Malawi Government, 2010) and African Union Malabo Declaration (African Union, 2016), and its implementation requires collaboration with policies and strategies for other sectors including development partners, civil society, farmer organizations and the private sector (Malawi Government, 2018). The NAIP uses a matrix structure with four Programmes and 16 intervention areas, and capture fisheries management is mainly covered under the programme “Resilient livelihoods and agriculture systems” in the intervention area of “Natural resource management and climate change” (Malawi Government, 2018).

The aforementioned institutional and policy framework shows that the DoF in Malawi is well placed to undertake its mandated responsibilities.

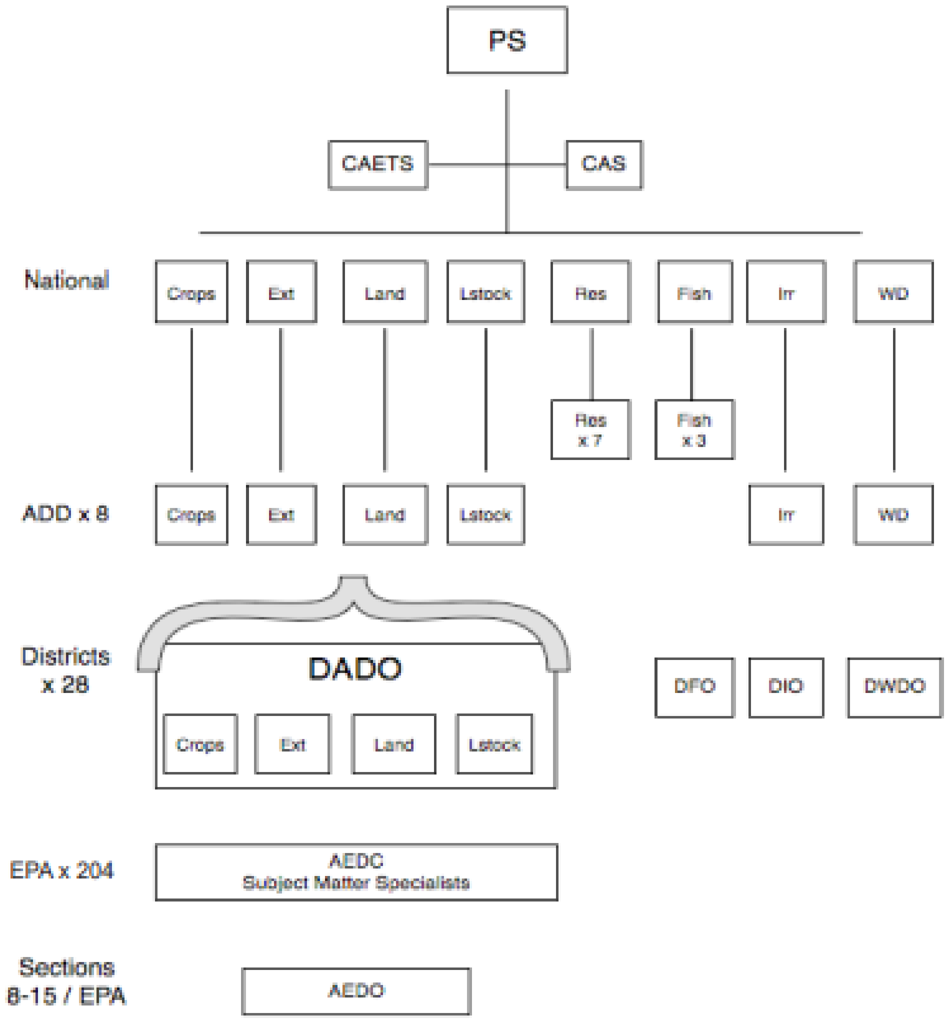

Figure 6-1. Organizational structure of the Ministry of Agriculture, Irrigation and Water Development. PS = Principal Secretary, CAETS = Controller of Agricultural and Extension Technical Services, CAS = Controller of Agricultural Services and Institutions, Crops= Department of Crops, Ext = Department of Agriculture Extension Services, Land = Department of Land Resources and Conservation, Lstock = Department of Animal Health and Livestock, Res = Department of Agricultural Research Services, Fish = Department of Fisheries, Irr = Department of Irrigation, WD = Water Department. ADD = Agriculture Development Division, DADO = District Agricultural Development Officer, DFO = District Fisheries Officer, DIO = District Irrigation Officer, DWDO = District Water Development Officer. EPA = Extension Planning Area, AEDC = Agriculture Extension Development Officer, AEDO = Agriculture Extension Development Officer (Source: Malawi Government, 2018)

6.5.2 Implementation of the proposed action plan for the ornamental fishery of Lake Malawi

The activities relating to each of the broad action points that would contribute to the outputs of the proposed logical framework (Table 6-1) are outlined in an implementation plan with a time frame ranging from one to five years and with outputs and indicators for these activities included (Table 6-2). The action points are presented in the proposed implementation plan as goals, each with a list of activities.

Such a plan which this thesis has recommended for the DoF in Malawi, can be easily implemented using the current structure of the DoF under the Ministry of Agriculture and Natural Resources in Malawi if it can be prioritized by the DoF. The other assumptions for successful implementation of the plan include securing of funding, accessing guidance services of technical expertise in implementation of some activities, and willingness of collaborators to participate.

The proposed action plan has focussed on identifying the activities required for sustainable management of the ornamental fishery of Lake Malawi. However, for implementation of the proposed actions there is need for more detail such as the budget for each of the planned action, the responsibility within the four sections of the DoF, the MoAIWD and/or amongst other stakeholders. Such details can be included once DoF and various stakeholders buy into the proposed action plan after disseminating findings of this thesis to various stakeholders.

Table 6-2. Implementation plan of the proposed actions for the management of the ornamental fisheries of Lake Malawi

Goal/actions	Priority	Time frame	Outputs	Indicators
***Goal 1**: Enhance the capacity of the Department of Fisheries to undertake ornamental fisheries research*				Value of research funding secured Number of research staff able to undertake underwater fishery research Number of collaborative research activities implemented
I. Source research funding	High	1-2 years	Capacity of the Department of Fisheries to conduct ornamental fishery research, manage and monitor fishery activities developed Detailed research about ecology and life history traits of individual ornamental fish species conducted Collaborative research projects between Department of Fisheries and other institutions being implemented Populations and sustainable catch levels of ornamental fish species established	
II. Training research staff in underwater fishery research techniques and taxonomy of the ornamental fish species of Lake Malawi	high	2-5 year		
III. Strengthen collaborative research between Department of Fisheries and other research institutions (e.g. academic institutions)	High	2-3 years		
IV. Introduce issues of ornamental fish trade in the curriculum of Malawi College of Fisheries.	High	2-4 years		

Table 6.2 continued

Goal/actions		Priority	Time frame	Outputs	Indicators
Goal 2: Conduct research on ornamental fishes of Lake Malawi					
I.	Conduct collaborative fish taxonomic research with renowned cichlid fish taxonomists to describe the undescribed fish species	High	5 years	Taxonomic problems of ornamental fish species sorted out Detailed research about ecology and life history traits of individual ornamental fish species conducted Populations and sustainable catch levels of ornamental fish species established Impacts of restocking ornamental in Lake Malawi assessed Collaborative research projects between Department of Fisheries and other institutions being implemented	Number of collaborative research activities implemented Reports about each of the research activities conducted
II.	Assess the populations of the commonly exploited ornamental fish using standard transect methods with SCUBA diving techniques, with consideration of existing microhabitat factors.	High	1–2 years		
III.	Assess relative levels of ornamental fish depletion and/and or exploitation using density ratios in protected and unprotected areas	Medium/high	1-3		
IV.	Assess the potential for exporting captively bred threatened ornamental fish species (with an option to use solar energy as an alternative power source for the system).	Medium	3-5 years		
V.	Assess impacts of restocking captively bred threatened ornamental fish species into Lake Malawi	Medium/high	2-4 years		

Table 6.2 continued

Goal/actions	Priority	Time frame	Outputs	Indicators
VI. Investigate ornamental fish population ecology - life history traits, age and growth, recruitment patterns	Medium	2-4 years	Quantities of ornamental fish caught by the artisanal fishery established and impacts on fish populations assessed	
VII. Investigate the lake wide extent of artisanal fishing of the ornamental fish species and the quantities of ornamental fish species caught	High	1-2 years		
Goal 3: Promote export trade for abundant ornamental fish species with low exploitation risk				
I. Advertise the abundant fish species for the ornamental fish export market	Medium	1 years	Ornamental fishery management systems instituted Measures to minimize delays of ornamental fish export consignments in place Exports of abundant fish species promoted	Fish export returns from exporters Reports of export volumes of the abundant ornamental fish species
II. Encourage fish exporters to export the abundant fish species	Medium	Continuous		
III. Improve customs clearance services to avoid delays of ornamental fish export consignments	High	1-2 years		
Goal 4: Identify and implement management measures for recovery of threatened (endangered or at high risk of exploitation) species				

Table 6.2 continued

Goal/actions	Priority	Time frame	Outputs	Indicators
I. Ban exportation of threatened fish species and species with high exploitation risk of exploitation	High	Continuous	Ornamental fishery management systems (measures) instituted Measures for recovery of threatened ornamental fish species introduced Export of abundant fish species promoted	Research reports about population trends of the threatened ornamental fish species
II. Lists of banned fish species for export to be produced and used by inspectors of export consignments (Department of Fisheries' inspectors and Customs clearance staff) before exportation	High	1 year		
III. Train inspectors of the export consignments in identification of ornamental fish species of Lake Malawi including those on the export ban	High	1-2 years		
IV. Develop short ornamental fish conservation course for the fisher community	Medium	1-3 years		
V. Establish bylaws to control fishing of threatened ornamental fish by artisanal fishers	High	1 year		
VI. Undertake outreach campaigns to sensitize the fishing community about the endangered ornamental fish species	Medium	Continuous		
Goal 5: Improve the monitoring system for the ornamental fish exports				

Table 6.2 continued

Goal/actions	Priority	Time frame	Outputs	Indicators
I. Develop an electronic data base of fish export returns where all information should be entered	High	Continuous	Capacity of the Department of Fisheries to conduct ornamental fishery research, manage and monitor fishery activities developed Populations and sustainable catch levels of ornamental fish species established Improved ornamental fishery monitoring system	Monitoring reports Review meetings' reports
II. Make a provision for the exporters to submit information about fishing trips and number of fishes caught by fishing trip (besides the information they provide in export returns)	High	Continuous		
III. Compile a list of names of exported fish species used including scientific names, common names and trade names to be used for monitoring the fishery.	high	1 year		
IV. Annually analyse fish export information to determine trends of exports and species which might be at risk	Medium	Continuous		
V. Annually monitor the populations of ornamental fish populations in heavily fished rocky reefs and institute appropriate adaptive fishery management measures depending on fish population trends	Medium	Continuous		
VI. Improve collaboration and flow of information about populations of ornamental fish species of	Medium	Continuous		

Table 6.2 continued

Goal/actions		Priority	Time frame	Outputs	Indicators
	Lake Malawi between Department of Fisheries, fish exporters and fish hobbyists.				
VII.	Conduct annual review meetings with various stakeholders	Medium	Continuous		
Goal 6: Institute measures to ensure sustainable exploitation of the ornamental fish species					
I.	Source funding for implementation of fishery measures	High	1-2 years	Ornamental fishery management systems (measures) instituted Capacity of the Department of Fisheries to conduct ornamental fishery research, manage and monitor fishery activities developed Populations and sustainable catch levels of ornamental fish species established	Number of ornamental fishery management measures implemented Reports about compliance levels to the ornamental fishery measures
II.	Promote rotational harvesting of ornamental fish	Medium	1-3 years		
III.	Put in place measures to prevent further translocations of fish within Lake Malawi	High	1-2 years		
IV.	Use PSA and IUCN risk assessment criteria to develop fisheries management measures for individual fish species and regularly update the PSA scores when new information collected.	High	Continuous		

Table 6.2 continued

Goal/actions	Priority	Time frame	Outputs	Indicators
V. Put in place measures to regulate subsistence and commercial fishing activities which negatively impact the ornamental fish species of Lake Malawi	High	2-4 years		

6.6 Conclusions

This thesis has demonstrated that the ornamental fish export trade in Malawi is based on diverse ichthyofauna which are represented by many described and undescribed cichlid fish species collected from various localities of Lake Malawi. Most of the exported fish species are of least conservation concern, but 21 threatened, 12 critically endangered, 5 endangered and 5 vulnerable species were amongst the exported fish which might be negatively affected by exploitation for ornamental fish trade. Artisanal fishers also target these ornamental fishes using different fishing gears such as gillnets, small seine nets and hook and lines, which might negatively affect the threatened fish species. There were no significant differences of overall fish abundance between protected and non-protected sites but protected sites showed significantly higher values of species diversity metrics than non-protected areas. Size of rocky reefs had significant effect on fish assemblage structure in Lake Malawi with larger rocky reefs being associated with higher abundance and species diversity. Most of the sampled ornamental fish species mature at relatively small size, have low absolute fecundities and lay relatively large egg sizes, which is typical for mouth brooding fish. PSA analysis showed that 28 of the 99 species assessed are potentially at high risk of being overfished by the ornamental fishery alone and this coupled with their exploitation by the artisanal fishery may further increase their overfishing risk.

The conclusions and recommendations from the findings of this thesis suggest the need for many action points for sustainability of the ornamental fishery of Lake Malawi, which are grouped under six broad categories including: i) development of capacity of the Department of Fisheries to manage the ornamental fishery, ii) conducting research on many aspects of the ornamental fishery of Lake Malawi iii) monitoring of the populations of the exploited ornamental fish species iv) promotion of exports of abundant ornamental fish species v) implementation of measures to ensure recovery of threatened and overexploited ornamental fish species and vi) introduction of measures to ensure sustainable exploitation of the ornamental fish species. These measures will require the following: approval by the Department of Fisheries and the Malawi Government, funding for implementation, expertise for implementation of specific activities and participation of collaborators in many specific activities. Thus, implementation of these actions will require discussions and planning meetings amongst stakeholders to work out how these actions will be achieved, by whom and what their modalities will be.

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Appendices

Appendix 2.1 Ornamental fish export certification document that accompanies the export consignment to importing countries after inspection by an officer from the Department of Fisheries in Malawi. The certificate number, details of the exporter, the invoice and importer have been redacted in order to conform to confidentiality of the information.

ACCOMPANYING DOCUMENT FOR IMPORT OF ORNAMENTAL FISHES INTO GERMANY

Certificate number:- [redacted] AirWayBill Number 125 6677 6743

Exporters full details	[redacted]

Description of the species which are sent - FRESHWATER FISHES

Country of Origin	Malawi - Central Africa

Scientific name	Common name (If available)	Quantity
See invoice attached to this document	See Invoice [redacted]	1,672
	Total Quantity	1672 Fishes

Above shipment will be sent to:-

Importers full details	[redacted]

Total number of boxes	Flight number/details	Date of arrival
16	BA2064 LLW/LGW 1100/2200 BA 2716 LGW/FRA 1340/1630	Sat 13 October 2001 Sun 14 October2001(FRA)

We hereby guarantee that all above details on species, numbers and origin are correct.

Name of certifying authority	Signature and official stamp	Date and place
District Fisheries Officer Senga Bay, Salima District		

Appendix 2.2. A sample of fish export returns that exporters of fish submit to the Department of Fisheries. Names of the exporter and importer have been redacted in order to conform to confidentiality of information.

[redacted]

PROFORMA INVOICE [redacted] - THURSDAY 13 March 2003

LLW - NBO with Air Kenya NBO/FRA with Lufthansa AW 02.6 2448 33.02

CONSIGNEE - [redacted] FRANKFURT AIRPORT

[redacted]

Packing water details:- pH 8.3 Degrees 25.0

Packing - New polystyrene cartons 52 x 48 x 34cms

Code	Number	Species	Price/Fish	TOTAL - EURO
100	16	Aulon. baenschi/benga	8.00	128.00
220	32	Aulon. kandeense	8.50	272.00
270	28	Aulon. mbenji	6.00	168.00
280	28	Aulon. maylandi	7.90	221.20
360	21	Aulon. st. usisya	8.00	168.00
370	21	Aulon. st ngara/mdoka	11.00	231.00
505	49	Aulon. maleoni	12.00	588.00
962	12	Labeo. fuelleborni red top chipoka	3.50	42.00
963	24	Labeo. fuelleborni OB chipoka	5.00	120.00
980	32	Labeo. fuelleborni katale	8.00	256.00
1480	64	Melano. joanjohnsonae	2.00	128.00
1490	47	Melano. johanni eastern	2.00	94.00
2070	63	Metria. barlowi mbenji	3.00	189.00
2396	44	Pseudo. sp.	6.00	264.00
2536	126	Pseudo. saulosi	5.00	630.00
2600	27	Metria. lombardoi	4.00	108.00
3240	22	Metria zebra chilumba	4.00	88.00
3260	165	Metria. callainos	2.50	412.50
3276	36	Metria. zebra gold mundola	4.50	162.00
3285	27	Metria. zebra gold kawanga	4.50	121.50
4860	17	Proto. fenestratus eastern	8.00	136.00
6880	16	Coped. azureus mbenji	9.00	144.00
6910	12	Proto. sp. thick lips mbenji	8.00	96.00
9999	24	Metria zebra	6.00	144.00
6080	16	Cryto. moori med	16.00	256.00
	969		EURO	5167.20
LESS Allowance following on prepayment			EURO	1033.44
			EURO	4133.00
PLUS Packaging at EURO15.00/Box (17)			EURO	255.00
			EURO	4388.00
PLUS Estimated air freight on KQ (Kenya Airways) sector LLW/NBO			EURO	400.00
			EURO	4788.00

FISHERIES DEPARTMENT
[illegible]03- 2003
P.O. [illegible] SENGA BAY.
SALIMA

Appendix 2.3. Genera and families of ornamental fish that were exported from Malawi between 1998 and 2017. Names of genera were validated using IUCN (2019) Red List of threatened species.

Genus	**Family**	**Number exported**	**% exported**
Metriaclima	Cichlidae	130515	26.107
Aulonocara	Cichlidae	82587	16.520
Pseudotropheus	Cichlidae	40675	8.136
Cynotilapia	Cichlidae	39177	7.837
Copadichromis	Cichlidae	27575	5.516
Melanochromis	Cichlidae	20412	4.083
Protomelas	Cichlidae	19093	3.819
Labeotropheus	Cichlidae	18883	3.777
Tropheops	Cichlidae	13764	2.753
Chindongo	Cichlidae	11938	2.388
Labidochromis	Cichlidae	11419	2.284
Placidochromis	Cichlidae	7217	1.444
Lethrinops	Cichlidae	7030	1.406
Nimbochromis	Cichlidae	6086	1.217
Mylochromis	Cichlidae	5635	1.127
Tyrannochromis	Cichlidae	4716	0.943
Buccochromis	Cichlidae	3622	0.725
Otopharynx	Cichlidae	3446	0.689
Chilotilapia	Cichlidae	3225	0.645
Stigmatochromis	Cichlidae	3212	0.643
Petrotilapia	Cichlidae	3189	0.638
Eclectochromis	Cichlidae	3119	0.624
Taeniolethrinops	Cichlidae	3031	0.606
Synodontis	Mochokidae	2733	0.547
Dimidiochromis	Cichlidae	2394	0.479
Fossorochromis	Cichlidae	2215	0.443
Potamonautes	Potamonautidae	2104	0.421
Sciaenochromis	Cichlidae	1955	0.391
Cyrtocara	Cichlidae	1753	0.351
Tramitichromis	Cichlidae	1567	0.313
Champsochromis	Cichlidae	1203	0.241
Mastacembelus	Mastacembelidae	1001	0.200
Rhamphochromis	Cichlidae	1001	0.200
Astatotilapia	Cichlidae	842	0.168
Taeniochromis	Cichlidae	823	0.165
Lichnochromis	Cichlidae	784	0.157
Hemitaeniochromis	Cichlidae	772	0.154
Aristochromis	Cichlidae	727	0.145
Nyassachromis	Cichlidae	712	0.142
Iodotropheus	Cichlidae	639	0.128
Mchenga	Cichlidae	569	0.114

Appendix 2.3 (Continued)

Genus	Family	Number exported	% contribution export volume
Trematocranus	Cichlidae	523	0.105
Chiloglanis	Mochokidae	498	0.100
Ctenopharynx	Cichlidae	497	0.099
Naevochromis	Cichlidae	443	0.089
Hemitilapia	Cichlidae	351	0.070
Barbus	Cyprinidae	315	0.063
Abactochromis	Cichlidae	265	0.053
Labeo	Cyprinidae	240	0.048
Exochochromis	Cichlidae	226	0.045
Caprichromis	Cichlidae	196	0.039
Gephyrochromis	Cichlidae	96	0.019
Caridina	Atyidae	90	0.018
Serranochromis	Cichlidae	89	0.018
Bagrus	Bagridae	46	0.009
Genyochromis	Cichlidae	40	0.008
Pseudocrenilabrus	Cichlidae	30	0.006
Aplocheilichthys	Poeciliidae	25	0.005
Oreochromis	Cichlidae	20	0.004
Malawispongia	Malawispongiidae	16	0.003
Clarias	Claridae	15	0.003
Coptodon	Cichlidae	10	0.002
Corematodus	Cichlidae	10	0.002
Protopterus	Protopteridae	3	0.001
Snails	Unknown	15	0.003
unidentified cichlids	Cichlidae	2499	0.500

Appendix 2.4. Described species of aquarium fish exported from Malawi between 1998 and 2017. LC = Least concern, NA = Not applicable, NT = Near threatened, CR = Critically endangered, DD = Data deficient, EN = Endangered, VU = Vulnerable, NE = Not evaluated. Species names and their conservation status were validated using IUCN (2019) Red list of threatened species.

Species name	**IUCN Conservation status**	**Total number exported**
Cynotilapia afra (Günther, 1894)	LC	30336
Aulonocara stuartgranti Meyer & Riehl, 1985	LC	25828
Metriaclima zebra (Boulenger, 1899)	LC	19952
Metriaclima callainos (Stauffer & Hert, 1992)	LC	17039
Melanochromis auratus (Boulenger, 1897)	LC	12085
Labeotropheus fuelleborni Ahl 1926	LC	11940
Chindongo saulosi (Konings, 1990)	CR	8990
Pseudotropheus johannii Eccles 1973	LC	8382
Metriaclima lombardoi (Burgess, 1977)	LC	8344
Metriaclima pyrsonotos Stauffer, Bowers, Kellogg & McKaye, 1997	LC	7759
Aulonocara baenschi Meyer & Riehl, 1985	CR	7280
Copadichromis borleyi (Iles, 1960)	LC	7059
Aulonocara maylandi Trewavas, 1984	CR	6900
Labeotropheus trewavasae Fryer 1956	LC	6827
Metriaclima barlowi (McKaye & stauffer, 1986)	LC	6137
Metriaclima hajomaylandi (Meyer & Schartl, 1984)	LC	4992
Copadichromis mloto (Iles, 1960)	DD	4578
Tyrannochromis macrostoma (Regan, 1922)	LC	4371
Protomelas taeniolatus (Trewavas, 1935)	LC	4369
Labidochromis joanjohnsonae Johnson, 1974	NT	4337
Metriaclima aurora (Burgess, 1976)	LC	4333
Melanochromis chipokae Johnson, 1975	CR	4297
Copadichromis azureus Konings, 1990	NT	4213
Aulonocara hueseri Meyer & Riehl & Zetzsche, 1987	LC	4196
Pseudotropheus cyaneorhabdos (Bowers & Stauffer, 1997)	CR	3609
Pseudotropheus interruptus (Johnson, 1975)	NT	3558
Metriaclima pulpican (Tawil, 2002)	LC	3246
Aulonocara kandeense Tawil & Allgayer, 1987	CR	3183
Metriaclima estherae (Konings, 1995)	LC	3183
Copadichromis trewavasae Konings, 1999	LC	3092
Nimbochromis linni (Burgess & Axelrod, 1975)	LC	3091
Aulonocara korneliae Meyer & Riehl & Zetzsche, 1987	LC	2864
Synodontis njassae Keilhack, 1908	LC	2733
Eclectochromis ornatus (Regan, 1922)	LC	2730
Chilotilapia euchilus (Trewavas, 1935)	LC	2724
Cynotilapia axelrodi Burgess, 1976	LC	2548
Labidochromis freibergi Johnson, 1974	LC	2532
Aulonocara ethelwynnae Meyer & Riehl & Zetzsche, 1987	NT	2370
Fossorochromis rostratus (Boulenger, 1899)	LC	2215

Appendix 2.4 (Continued)

Species name	**IUCN Conservation status**	**Total number exported**
Potamonautes lirrangensis Rathbun, 1904	LC	2104
Taeniolethrinops furcicauda (Trewavas, 1931)	LC	2057
Placidochromis electra (Burgess, 1979)	LC	2054
Copadichromis verduyni Konings, 1990	LC	1980
Mylochromis lateristriga (Günther, 1864)	LC	1971
Nimbochromis livingstonii (Günther, 1894)	LC	1766
Cyrtocara moorii Boulenger, 1902	VU	1753
Placidochromis milomo Oliver, 1989	LC	1705
Protomelas fenestratus (Trewavas, 1935)	LC	1674
Melanochromis loriae Johnson, 1975	LC	1664
Dimidiochromis compressiceps (Boulenger, 1908)	LC	1591
Protomelas virgatus (Trewavas, 1935)	LC	1482
Labidochromis caeruleus Fryer, 1956	LC	1476
Metriaclima flavifemina Konings & Stauffer, 2006	LC	1473
Buccochromis rhoadesii (Boulenger, 1908)	LC	1453
Otopharynx auromarginatus (Boulenger, 1908)	LC	1402
Aulonocara nyassae Regan, 1922	NT	1360
Sciaenochromis fryeri Konings, 1993	LC	1353
Metriaclima greshakei (Meyer & Förster, 1984)	NT	1341
Lethrinops microstoma Trewavas, 1931	LC	1312
Aulonocara saulosi Meyer & Riehl & Zetzsche, 1987	LC	1267
Pseudotropheus perileucos (Bowers & Stauffer, 1997)	LC	1207
Petrotilapia tridentiger Trewavas, 1935	LC	1202
Stigmatochromis modestus (Günther, 1894)	LC	1195
Chindongo socolofi (Johnson, 1974)	LC	1182
Labidochromis flavigulis Lewis, 1982	LC	1133
Buccochromis heterotaenia (Trewavas, 1935)	LC	1133
Metriaclima lanisticola (Burgess, 1976)	LC	1119
Metriaclima mbenjii Stauffer, Bowers, Kellogg & McKaye, 1997	LC	1110
Aulonocara rostratum Trewavas, 1935	LC	1102
Tropheops Tropheops Regan, 1922	LC	1066
Placidochromis phenochilus (Trewavas, 1935)	EN	1066
Chindongo flavus (Stauffer, 1988)	NT	1000
Stigmatochromis woodi (Regan, 1922)	LC	999
Lethrinops albus Regan, 1922	LC	986
Tramitichromis lituris (Trewavas, 1931)	LC	975
Champsochromis caeruleus (Boulenger, 1908)	LC	968
Taeniolethrinops praeorbitalis (Regan, 1922)	LC	945
Buccochromis lepturus (Regan, 1922)	LC	942
Metriaclima chrysomallos Stauffer, Bowers, Kellog & McKaye, 1997	NT	935
Protomelas similis (Regan, 1922)	LC	876
Labidochromis chisumulae Lewis, 1982	LC	855
Astatotilapia calliptera (Günther, 1894)	LC	842
Copadichromis cyaneus (Trewavas, 1935)	LC	826

Appendix 2.4 (Continued)

Species name	**IUCN Conservation status**	**Total number exported**
Taeniochromis holotaenia (Regan, 1922)	LC	824
Tropheops macrophthalmus Ahl, 1927	LC	798
Lichnochromis acuticeps Trewavas, 1935	LC	784
Metriaclima fainzilberi (Staeck, 1976)	LC	770
Placidochromis johnstoni (Günther, 1894)	LC	766
Nimbochromis polystigma (Regan, 1922)	LC	764
Melanochromis dialeptos Bowers & Stauffer, 1997	LC	762
Mastacembelus shiranus Günther, 1896	LC	759
Pseudotropheus livingstonii (Boulenger, 1899)	LC	752
Protomelas spilonotus (Trewavas, 1935)	LC	727
Aristochromis christyi Trewavas, 1935	LC	727
Lethrinops auritus (Regan, 1922)	LC	720
Eclectochromis lobochilus (Trewavas, 1935)	LC	709
Copadichromis chrysonotus (Boulenger, 1908)	LC	704
Copadichromis quadrimaculatus (Regan, 1922)	LC	703
Chindongo minutus (Fryer, 1956)	LC	694
Copadichromis geertsi Konings, 1999	LC	652
Iodotropheus sprengerae Oliver & Loiselle, 1972	NT	639
Copadichromis virginalis (Iles, 1960)	NT	635
Metriaclima usisyae Li, Konings & Stauffer, 2016	CR	624
Labidochromis gigas Lewis, 1982	LC	585
Dimidiochromis kiwinge (Ahl, 1926)	LC	517
Metriaclima cyneusmarginatum Stauffer, Bowers, Kellogg & McKaye, 1997	NT	510
Chilotilapia rhoadesi Boulenger, 1908	LC	501
Trematocranus placodon (Regan, 1922)	LC	500
Chiloglanis neumanni Boulenger, 1911	NA	498
Hemitaeniochromis spilopterus (Trewavas, 1935)	LC	482
Lethrinops marginatus Ahli, 1926	LC	471
Protomelas annectens (Regan, 1922)	LC	462
Mylochromis melanonotus (Regan, 1922)	LC	453
Aulonocara jacobfreibergi (Johnson, 1974)	LC	453
Melanochromis vermivorus Trewavas, 1935	NT	444
Naevochromis chrysogaster (Trewavas, 1935)	LC	440
Lethrinops micrentodon (Regan, 1922)	DD	428
Stigmatochromis pleurospilus (Trewavas, 1935)	DD	418
Tropheops romandi Colombé, 1979	LC	394
Mylochromis guentheri (Regan, 1922)	LC	386
Mylochromis spilostichus (Trewavas, 1935)	LC	360
Nimbochromis venustus (Boulenger, 1908)	LC	360
Mylochromis gracilis (Trewavas, 1935)	LC	353
Hemitilapia oxyrhynchus Boulenger, 1902	LC	351
Tyrannochromis nigriventer Eccles, 1989	LC	345
Ctenopharynx pictus (Trewavas, 1935)	LC	339
Otopharynx lithobates Oliver, 1989	LC	317

Appendix 2.4 (Continued)

Species name	**IUCN Conservation status**	**Total number exported**
Mylochromis sphaerodon (Regan, 1922)	LC	314
Copadichromis jacksoni (Iles, 1960)	LC	311
Pseudotropheus perspicax (Trewavas, 1935)	LC	310
Abactochromis labrosus (Trewavas, 1935)	LC	310
Metriaclima emmiltos Stauffer, Bowers, Kellogg & McKaye, 1997	LC	309
Lethrinops furcifer Trewavas, 1931	LC	301
Copadichromis pleurostigma (Trewavas, 1935)	LC	297
Nyassachromis prostoma (Trewavas, 1935)	LC	284
Hemitaeniochromis urotaenia (Regan, 1922)	LC	283
Copadichromis ilesi Konings, 1999	LC	278
Nyassachromis boadzulu (Iles, 1960)	EN	269
Aulonocara aquilonium Konings, 1995	LC	265
Sciaenochromis ahli (Trewavas, 1935)	LC	262
Labeo cylindricus Peters, 1852	LC	240
Champsochromis spilorhynchus (Regan, 1922)	LC	235
Exochochromis anagenys Oliver, 1989	LC	226
Sciaenochromis psammophilus Konings, 1993	LC	225
Rhamphochromis longiceps (Günther, 1864)	VU	224
Mylochromis incola (Trewavas, 1935)	LC	214
Mylochromis plagiotaenia (Regan, 1922)	LC	213
Tramitichromis brevis (Boulenger, 1908)	LC	206
Melanochromis simulans Eccles, 1973	LC	201
Mchenga flavimanus (Iles, 1960)	LC	199
Lethrinops lethrinus (Günther, 1894)	LC	194
Aulonocara gertrudae Konings, 1995	LC	190
Mylochromis mola (Trewavas, 1935)	LC	190
Mylochromis mollis (Trewavas, 1935)	LC	189
Mchenga thinos (Stauffer, LoVullo & McKaye, 1993)	LC	172
Metriaclima glaucos Ciccotto, Konings & Stauffer, 2011	NT	168
Pseudotropheus crabro (Ribbink & Lewis, 1982)	LC	167
Caprichromis liemi (McKaye & Mackenzie, 1982)	LC	163
Aulonocara koningsi Tawil, 2003	LC	157
Otopharynx heterodon (Trewavas, 1935)	LC	156
Mylochromis labidodon (Trewavas, 1935)	LC	153
Mylochromis subocularis (Günther, 1894)	LC	149
Dimidiochromis dimidiatus (Günther, 1864)	LC	147
Mylochromis anaphyrmus (Burgess & Axelrod, 1973)	LC	145
Mylochromis epichorialis (Trewavas, 1935)	LC	142
Dimidiochromis strigatus (Regan, 1922)	LC	139
Otopharynx decorus (Trewavas, 1935)	LC	139
Mchenga cyclicos (Stauffer & LoVullo & McKaye, 1993)	NT	135
Rhamphochromis esox (Boulenger, 1908)	VU	133
Ctenopharynx nitidus (Trewavas, 1935)	LC	129
Labidochromis pallidus Lewis, 1982	LC	128
Tramitichromis intermedius (Trewavas, 1935)	LC	127

Appendix 2.4 (Continued)

Species name	**IUCN Conservation status**	**Total number exported**
Metriaclima xanstomachus (Stauffer & Boltz, 1989)	NT	126
Tropheops gracilior (Trewavas, 1935)	LC	123
Mylochromis ericotaenia (Regan, 1922)	LC	121
Otopharynx argyrosoma (Regan, 1922)	LC	120
Stigmatochromis pholidophorus (Trewavas, 1935)	LC	112
Petrotilapia microgalana Ruffing, Lambert & Stauffer, 2006	LC	110
Nimbochromis fuscotaeniatus (Regan, 1922)	VU	108
Aulonocara brevinidus Konings, 1995	LC	106
Pseudotropheus williamsi (Günther, 1894)	NT	98
Gephyrochromis lawsi Fryer 1957	LC	96
Copadichromis insularis Stauffer & Konings, 2006	LC	94
Mylochromis formosus (Trewavas, 1935)	LC	93
Labidochromis strigatus Lewis, 1982	LC	90
Caridina nilotica (P. Roux, 1833)	LC	90
Serranochromis robustus (Günther, 1864)	CR	89
Copadichromis likomae (Iles, 1960)	LC	89
Cynotilapia zebroides (Johnson, 1975)	LC	85
Chindongo cyaneus (Stauffer, 1988)	NT	84
Cynotilapia aurifrons (Tawil, 2011)	LC	83
Lethrinops parvidens Trewavas, 1931	LC	75
Copadichromis pleurostigmoides (Iles, 1960)	LC	70
Copadichromis atripinnis Stauffer & Sato, 2002	LC	68
Aulonocara auditor (Trewavas, 1935)	DD	67
Pseudotropheus Galanos Stauffer & Kellogs, 2002	NT	64
Pseudotropheus brevis (Trewavas, 1935)	EN	61
Labidochromis zebroides Lewis, 1982	EN	59
Buccochromis nototaenia (Boulenger, 1902)	LC	58
Lethrinops leptodon Regan, 1922	LC	58
Melanochromis baliodigma Bowers & Stauffer, 1997	LC	54
Tropheops microstoma (Trewavas, 1935)	NT	53
Pseudotropheus benetos (Bowers & Stauffer, 1997)	LC	52
Mchenga eucinostomus (Regan, 1922)	LC	49
Otopharynx ovatus (Trewavas, 1935)	LC	48
Bagrus meridionalis Günther, 1894	CR	46
Chindongo ater (Stauffer, 1988)	NT	45
Genyochromis mento Trewavas, 1935	LC	40
Lethrinops longimanus Trewavas, 1931	LC	38
Protomelas triaenodon (Trewavas, 1935)	LC	35
Caprichromis orthognathus (Trewavas, 1935)	LC	33
Protomelas marginatus (Trewavas, 1935)	LC	32
Protomelas labridens (Trewavas, 1935)	LC	32
Tramitichromis variabilis (Trewavas, 1931)	LC	30
Pseudocrenilabrus philander (Weber, 1897)	LC	30
Ctenopharynx intermedius (Günther, 1864)	LC	29
Protomelas kirkii (Günther, 1894)	LC	29

Appendix 2.4 (Continued)

Species name	**IUCN Conservation status**	**Total number exported**
Lethrinops altus Trewavas, 1931	LC	26
Mylochromis ensatus Turner & Howarth, 2001	LC	26
Nyassachromis breviceps (Regan, 1922)	CR	25
Nyassachromis microcephalus (Trewavas, 1935)	LC	22
Otopharynx brooksi Oliver, 1989	LC	20
Chindongo bellicossus Li, Konings & stauffer, 2016	LC	20
Pseudotropheus elegans Trewavas, 1935	LC	18
Copadichromis chizumuluensis Stauffer & Konings, 2006	LC	17
Protomelas insignis (Trewavas, 1935)	LC	16
Malawispongia echinoides Brien, 1972	NE	16
Clarias ngamensis Castelnau, 1861	LC	15
Lethrinops turneri Ngatunga & Snoeks, 2003	LC	15
Melanochromis heterochromis Bowers & Stauffer, 1993	LC	15
Mchenga conophoros (Stauffer & LoVullo & McKaye, 1993)	CR	14
Copadichromis trimaculatus (Iles, 1960)	LC	13
Copadichromis mbenjii Konings, 1990	LC	13
Lethrinops longipinnis Eccles & Lewis, 1978	LC	12
Labidochromis vellicans Trewavas, 1935	LC	12
Lethrinops lunaris Trewavas, 1931	LC	12
Lethrinops macrochir (Regan, 1922)	LC	11
Melanochromis melanopterus Trewavas, 1935	LC	11
Buccochromis spectabilis (Trewavas, 1935)	LC	11
Coptodon rendalli (Boulenger, 1897)	LC	10
Corematodus taeniatus Trewavas, 1935	LC	10
Metriaclima flavicauda Li, Konings & Stauffer, 2016	VU	10
Mylochromis balteatus (Trewavas, 1935)	LC	9
Taeniolethrinops laticeps (Trewavas, 1931)	LC	8
Trematocranus microstoma Trewavas, 1935	EN	8
Labidochromis ianthinus Lewis, 1982	LC	7
Labidochromis mbenjii Lewis, 1982	LC	7
Pseudotropheus purpuratus Johnson, 1976	LC	6
Labidochromis lividus Lewis, 1982	LC	4
Metriaclima phaeos Stauffer, Bowers, Kellog & McKaye, 1997	LC	4
Protomelas pleurotaenia (Boulenger, 1901)	LC	3
Protopterus annectens (Owen, 1839)	LC	3
Rhamphochromis woodi Regan, 1922	LC	3
Lethrinops macrophthalmus (Boulenger, 1908)	LC	3
Labidochromis mylodon Lewis, 1982	LC	3
Copadichromis nkatae (Iles, 1960)	CR	2
Melanochromis robustus Johnson, 1985	NT	2

Appendix 2.5. Undescribed species (some referred to by their trade names) that were exported from Malawi between 1998 and 2017

Undescribed species names	**number exported**
Pseudotropheus sp elongatus[27]	13173
Metriaclima sp zebra gold[28]	10099
Metriaclima sp zebra BB	6334
Metriaclima sp zebra OB	5271
Aulonocara sp mbenji	4642
Aulonocara sp maulana	4031
Tropheops sp red cheek	3801
Aulonocara sp maisoni	3427
Pseudotropheus sp aceii	3403
Protomelas sp thick lips	3209
Aulonocara sp mdoka	3127
Protomelas sp steveni	2924
Tropheops sp	2699
Metriaclima sp zebra pearly	2435
Pseudotropheus sp polit	2401
Metriaclima sp elongatus	2453
Metriaclima sp elongatus ornatus	2146
Cynotilapia sp mbamba	1998
Mixed Malawi cichlids	2499
Metriaclima sp membe deep	1941
Cynotilapia sp	1903
Metriaclima sp zebra long pelvic	1840
Metriaclima sp zebra patricki	1834
Aulonocara sp chindunga	1685
Protomelas sp steveni imperial	1502
Aulonocara sp sanga	1407
Metriaclima sp long pelvic	1378
Metriaclima sp zebra blue	1324
Pseudotropheus sp	1335
Aulonocara sp	1287
Placidochromis sp Jalo Reef	1259
Cynotilapia sp edward type	1244
Metriaclima sp zebra gold brown	1152
Metriaclima sp elongatus bee	1087
Tropheops sp yellow	1026

[27] Fish previously identified by this name are now split into four genera including the following three other genera: *Metriaclima* sp elongatus, *Tropheops* sp elongatus, and *Cynotilapia* sp elongatus. Probably these genera are included amongst the fish exported as *Pseudotropheus* sp elongatus (Konings 2016).
[28] This was probably confused with other closely related species according to Konings (2016)

Appendix 2.5 (continued)

Undescribed species names	**number exported**
Copadichromis sp	1021
Lethrinops sp red cap	968
Metriaclima sp zebra red dorsal yellow chin	953
Metriaclima sp lime	894
Aulonocara sp maleri	818
Aulonocara sp walteri	803
Tropheops sp red fin	798
Aulonocara sp yellow collar	779
Metriaclima sp	722
Aulonocara sp galireya reef	668
Metriaclima sp zebra gold OB	665
Rhamphochromis sp	633
Metriaclima sp zebra orange	628
Petrotilapia sp	626
Metriaclima sp zebra m/cat	520
Aulonocara sp cobue	514
Protomelas sp	508
Pseudotropheus sp ndumbi gold	502
Tropheops sp OB	484
Lethrinops sp	462
Metriaclima sp zebra OB big blotch	459
Otopharynx sp cave	448
Cynotilapia sp red top	445
Tropheops sp yellow chin	423
Aulonocara sp chitseko	416
Stigmatochromis sp tolae	400
Tropheops sp elongatus	390
Lethrinops sp yellow collar	386
Lethrinops sp orange top	365
Metriaclima sp long pelvic red top	351
Tropheops sp lilac	334
Barbus sp	315
Otopharynx sp torpedo	311
Petrotilapia sp retrognathus	299
Metriaclima sp callainos OB	289
Pseudotropheus sp elongatus ornatus	286
Metriaclima sp zebra white top	264
Tropheops sp membe	250
Mastacembelus sp rosette	242
Aulonocara sp nkhata bay	234
Petrotilapia sp giant yellow	232

Appendix 2.5 (continued)

Undescribed species names	**number exported**
Pseudotropheus sp chailosi bee	230
Pseudotropheus sp aggressive yellow fin	220
Metriaclima sp zebra hermani	215
Pseudotropheus sp elongatus brown	214
Otopharynx sp	213
Metriaclima sp yellow chin	210
Protomelas sp hertae	207
Tramitichromis sp	198
Tropheops sp mauve yellow	195
Copadichromis sp staufferi	190
Otopharynx sp spots	182
Metriaclima sp maisoni	180
Petrotilapia sp orange pelvic	180
Petrotilapia sp yellow chin	179
Protomelas sp kirki	175
Aulonocara sp jalo	173
Copadichromis sp kadango redfin	172
Melanochromis sp blackwhite auratus	172
Placidochromis sp	168
Tropheops sp weed	164
Melanochromis sp lepidophage	162
Pseudotropheus sp chailosi	162
Tropheops sp black dorsal	162
Copadichromis sp yellow jumbo	159
Metriaclima sp daktarin	156
Cynotilapia sp white top	149
Placidochromis sp gisseli	148
Labidochromis sp	135
Metriaclima sp msobo	135
Tropheops sp red cheek dwarf	133
Melanochromis sp	131
Protomelas sp mbenji thick lips	127
Metriaclima sp zebra yellow chin	124
Aulonocara sp mbowe	122
Melanochromis sp blotch	118
Petrotilapia sp chitimba thick bars	118
Aulonocara sp mkondowe	116
Aulonocara sp masasa	112
Metriaclima sp red zebra	112
Metriaclima sp black mask hermani	108
Tropheops sp chitimba yellow	106
Copadichromis sp goldfin	104
Labeotropheus sp super orange	103

Appendix 2.5 (continued)

Undescribed species names	**number exported**
Nyassachromis sp	96
Pseudotropheus sp elongatus gold bar	95
Metriaclima sp zebra Chilumba	93
Cynotilapia sp elongatus	92
Metriaclima sp black dorsal	91
Metriaclima sp zebra OB M/cat	89
Aulonocara sp red shoulder mtengula	88
Aulonocara sp dwarf maulana	87
Petrotilapia sp ruarwe red fin	83
Cynotilapia sp lions cove	79
Sciaenochromis sp nyassae	79
Aulonocara sp yellow head	78
Cynotilapia sp yellow dorsal	78
Metriaclima sp zebra black dorsal	77
Lethrinops sp purple	75
Aulonocara sp zunga	75
Copadichromis sp white blaze	70
Metriaclima sp zebra chilumba BB	68
Tropheops sp gold chisumulu	67
Aulonocara sp albert	65
Mylochromis sp	65
Cynotilapia sp mbamba yellow head	64
Protomelas sp red empress	61
Protomelas sp black belly	56
Petrotilapia sp ruarwe	54
Protomelas sp tiger	54
Copadichromis sp jumbo yellow	53
Metriaclima sp chesese	53
Copadichromis sp virgatus	49
Tropheops sp dwarf	47
Protomelas sp johnstoni solo	46
Pseudotropheus sp deep	46
Aulonocara sp chitimba	45
Metriaclima sp zebra pearly white	45
Placidochromis sp blue otter	45
Pseudotropheus sp kingsizei	45
Lethrinops sp yellow head	43
Metriaclima sp red dorsal yellow chin	42
Aulonocara sp kande yellow	40
Pseudotropheus sp orange	40
Tropheops sp red dorsal	40
Lethrinops sp nyassae	38
Stigmatochromis sp torpedo	38

Appendix 2.5 (continued)

Undescribed species names	**number exported**
Aulonocara sp blue yellow	36
Labidochromis sp Gome	36
Petrotilapia sp yellow ventral	36
Pseudotropheus sp elongatus blue	226
Tropheops sp yellow gular	35
Aulonocara sp jumbo	34
Metriaclima sp callainos pearly white	34
Petrotilapia sp chitande	34
Sciaenochromis sp	34
Cynotilapia sp lion	33
Protomelas sp steveni black belly	33
Protomelas sp thick bars	33
Metriaclima sp hermini chiwi	32
Ortopharynx sp torpedo blue	31
Cynotilapia sp black dorsal	30
Metriaclima sp pearly white zebra	30
Metriaclima sp shauri	30
Tramitichromis sp circle	30
Tropheops sp kakusa	29
Metriaclima sp chilumba	28
Aulonocara sp benga	26
Pseudotropheus sp Katale	26
Aplocheilichthys sp	25
Buccochromis sp	25
Mylochromis sp kande	25
Protomelas sp oxyrhynchus	25
Aulonocara sp mazinzi	24
Otopharynx sp margrette	24
Tropheops sp masasa	24
Tropheops sp ndumbi gold	24
Mylochromis sp deep	23
Pseudotropheus sp elongatus ndumbi gold	22
Labidochromis sp blue bar	22
Taenio*Lethrinops* sp	21
Copadichromis sp 3 spot masinje	20
Oreochromis sp	20
Otopharynx sp heterodon royal blue	20
Tropheops sp golden head	20
Labidochromis sp politica	18
Protomelas sp fire blue	18
Pseudotropheus sp ensatus	18
Pseudotropheus sp Maisoni Reef	18
Pseudotropheus sp pale white	18

Appendix 2.5 (continued)

Undescribed species names	**number exported**
Stigmatochromis sp king cave	18
Aulonocara sp bakiri wreck	15
Copadichromis sp verduyni dwarf	15
Melanochromis sp pearl	15
Snails	15
Stigmatochromis sp guttatus	15
Tropheops sp brown	15
Aulonocara sp charo	14
Lethrinops sp orange head	14
Metriaclima sp zebra blue OB	14
Stigmatochromis sp silver torpedo	14
Pseudotropheus sp elongatus red top	13
Tropheops sp blue	13
Metriaclima sp orange	12
Mylochromis sp macrorhynchus	12
Petrotilapia sp small blue	12
Protomelas sp imperial black belly	12
Protomelas sp spilonotus blue	12
Protomelas sp spilonotus yellow	12
Tropheops sp m/cat	12
Metriaclima sp callainos white mottled blue	11
Metriaclima sp zebra brown	11
Petrotilapia sp Chimwalani	11
Copadichromis sp maison reef	10
Cynotilapia sp mbweca	10
Lethrinops sp black dorsal	10
Metriaclima sp zebra OB elongatus	10
Mylochromis sp yellow black line	10
Otopharynx sp margrette blotch	10
Tropheops sp kakusa red fin	10
Tropheops sp likoma	10
Tropheops sp hora red fin	10
Labeotropheus sp katale	9
Nyassachromis sp taeniolatus	9
Tropheops sp blue Mbenji	9
Aulonocara sp chiofu	8
Mylochromis sp silver torpedo	8
Protomelas sp steven imperial	8
Nyassachromis sp mtengula	7
Aulonocara sp Big Mouth	6
Copadichromis sp 1 spot	6
Metriaclima sp hermanni black mask	6
Mylochromis sp insignis	6

Appendix 2.5 (continued)

Undescribed species names	**number exported**
Petrotilapia sp red fin ruarwe	6
Rhamphochromis sp nyassae	6
Aulonocara sp deep	5
Copadichromis sp kawanga	5
Copadichromis sp three spot	5
Hemitaeniochromis sp paedophage	5
Otopharynx sp torpedo blue	5
Placidochromis sp long deep	5
Protomelas sp thick bars	5
Protomelas sp spilonotus ovatus	5
Aulonocara sp magrette	4
Labeotropheus sp likoma	4
Lethrinops sp chiponde	4
Metriaclima sp callainos m/cat	4
Petrotilapia sp fuscus	4
Aulonocara sp masimbwe	3
Lethrinops sp round head	3
Metriaclima sp zebra gold m/cats	3
Metriaclima sp zebra white morph	3
Mylochromis sp torpedo blue	3
Petrotilapia sp gold ventral	3
Protomelas sp taiwan Reef	3
Stigmatochromis sp mbenji	3
Copadichromis sp marginatus	2
Hemitaeniochromis sp gaisi yellow	2
Mylochromis sp laticeps	2
Mylochromis sp liemi	2
Rhamphochromis sp mchenga	2
Metriaclima sp zebra white m/cat	1
Placidochromis sp deep	1
Protomelas sp black dorsal	1

Appendix 3.1 The major island/rocky reefs of the study of Ribbink *et al*. (1983), their current protection status and their size based on classification of the current study. Small means rocky island/reefs smaller than 40 metres in the longest dimension; large means rocky island/reefs larger than 500 metres in the longest dimension.

Major rocky areas of Lake Malawi that were studied by Ribbink *et al*. (1983)	Current protection status	Size of rocky areas
Maleri Islands	protected	large
Mumbo Island	protected	large
Thumbi West Island	protected	large
Domwe Island	protected	large
Monkey Bay	protected	small
Boadzulu	protected	large
Chinymwezi Island	protected	small
Chinyankhwazi Island	protected	small
Chilumba	unprotected	large
Ruarwe	unprotected	small
Usisya	unprotected	small
Nkhata Bay /Chirombo Point	unprotected	small
Chizumulu Island	unprotected	large
Likoma Island	unprotected	large
Mbenji Island	unprotected	large
Makanjila	unprotected	small

Appendix 3.2. Functions used in R package for estimation of overdispersion factor of fish abundance data and quasi likelihood analysis of the generalized linear mixed effects model of factors that affected fish abundance.

a) R script used for approximate estimation of overdispersion by comparing glmer sum squares Pearson residual and residuals degree of freedom (adapted from Bolker *et al.,* 2018).

```
overdisp_fun <- function(glmer0) {
rdf <- df.residual(glmer0)
rp <- residuals(glmer0,type="pearson")
Pearson.chisq <- sum(rp^2)
prat <- Pearson.chisq/rdf
pval <- pchisq(Pearson.chisq, df=rdf, lower.tail=FALSE)
c(chisq=Pearson.chisq,ratio=prat,rdf=rdf,p=pval)
}
overdisp_fun(glmer0)
```

b) R Script used for quasi-likelihood analysis for glmer (adapted from Bolker *et al.,* 2018)

```
cc <- coef(summary(glmer0))
phi <- overdisp_fun(glmer0)["ratio"]
cc <- within(as.data.frame(cc),
{   `Std. Error` <- `Std. Error`*sqrt(phi)
    `z value` <- Estimate/`Std. Error`
    `Pr(>|z|)` <- 2*pnorm(abs(`z value`), lower.tail=FALSE)
})
printCoefmat(cc,digits=3)
```

Appendix 3.3 Fish species identified from video footages for the point transects at different sampled sites. CHD = Chindozwa, CMW = Chinyamwezi, CNK = Chinyankhwazi, CHR = Chirundu, MBJ = Mbenji Island, MWF = Mwafufu, TW = Thumbi West Island. (+) shows species was recorded while (-) shows species was not recorded at the site.

Species name	**Name of sampling site**								
	CHD	**CMW**	**CNK**	**CHR**	**MBJ1**	**MBJ2**	**MWF**	**TW1**	**TW2**
Aulonocara koningsi, Tawil 2003	-	-	-	-	+	+	-	-	-
Bagrus meridionalis Gunther, 1894	-	-	+	-	-	+	-	-	-
Pseudotropheus sp elongatus Nkhata blue	+	-	-	-	-	-	+	-	-
Pseudotropheus sp elongatus aggressive brown	-	-	-	-	-	-	-	-	+
Pseudotropheus sp elongatus slab	-	-	-	-	-	-	-	+	-
Pseudotropheus ater (Stauffer, 1988)	-	+	+	-	-	-	-	-	-
Pseudotropheus sp elongatus mbenji brown	-	-	-	-	+	+	-	-	-
Chindongo flavus (Stauffer, 1988)	-	+	-	-	-	-	-	-	-
Chindongo sp	-	-	-	-	+	+	+	-	-
Clarias gariepinus (Burchell, 1822)	-	-	-	-	+	-	-	-	-
Copadichromis atripinnis Stauffer & Sato, 2002	-	-	-	-	-	-	-	+	-
Copadichromis borleyi (Iles, 1960)	+	-	+	-	-	-	-	-	-
Copadichromis chrysonotus (Boulenger, 1908)	-	-	-	-	-	-	+	+	+
Copadichromis insularis Stauffer & Konings, 2006	-	+	-	-	-	-	-	-	-
Copadichromis mbenji Konings, 1990	-	-	-	-	+	+	-	-	-
Copadichromis sp	+	-	+	-	+	+	+	+	-
Ctenopharynx pictus (Trewavas, 1935)	+	+	+	+	+	-	+	+	+
Ctenopharynx sp	+	-	-	-	-	-	-	-	-
Cynotilapia sp	+	+	+	+	+	-	+	+	+
Cynotilapia afra (Gunther, 1894)	-	+	-	-	+	-	+	-	+
Cynotilapia sp elongatus	-	-	-	-	-	-	+	-	-
Dimidiochromis kiwinge (Ahl, 1926)	+	-	-	-	+	-	+	+	+
Genyochromis mento Trewavas, 1935	-	+	-	+	-	-	-	+	+
Labeo cylindricus Peters, 1852	+	+	+	-	+	-	+	+	+
Labeotropheus fuelleborni Ahl, 1926	-	+	+	+	+	+	-	+	+
Labeotropheus sp	-	+	-	-	+	-	-	-	-
Labeotropheus trewavasae Fryer, 1956	+	+	-	-	+	+	-	+	-
Labidochromis sp	-	+	+	+	-	+	+	-	-

Appendix 3.3 (continued)

Species name	**Name of sampling site**								
	CHD	**CMW**	**CNK**	**CHR**	**MBJ1**	**MBJ2**	**MWF**	**TW1**	**TW2**
Labidochromis vellicans Trewavas, 1935	-	-	-	-	-	-	-	+	-
Labidochromis mbenjii Lewis, 1982	-	-	-	-	+	-	-	-	-
Protomelas kirkii (Gunther, 1894)	+	-	-	-	-	-	-	-	-
Lethrinops sp	-	-	-	-	+	+	-	+	+
Pseudotropheus livingstonii (Boulenger, 1899)	-	-	-	-	-	+	-	+	+
Mchenga eucinostomus (Regan, 1922)	-	-	-	-	-	-	-	+	+
Mchenga sp	-	-	-	-	-	+	-	-	-
Melanochromis auratus (Boulenger, 1897)	-	+	+	+	+	-	-	-	-
Melanochromis heterochromis Bowers & Stauffer, 1993	-	+	+	-	-	-	-	-	-
Melanochromis melanopterus Trewavas, 1935	-	-	+		-	-	-	-	-
Melanochromis sp	-	+	+	+	+	+	-	+	-
Metriaclima callainos (Stauffer & Hert, 1992)	+	-	-	-	-	-	+	-	+
Metriaclima mbenjii Stauffer, Bowers, Kellogg & McKaye, 1997	-	-	-	-	+	+	-	-	-
Metriaclima sp	+	+	+	+	+	+	+	+	+
Metriaclima sp OB	-	-	-	-	+	-	-	-	-
Metriaclima sp zebra red top	+	+	-	+	-	-	-	-	-
Metriaclima zebra (Boulnger, 1899)	+	+	+	+	+	+	+	+	+
Mylochromis anaphyrmus (Burgess & Axelrod, 1973)	-	-	-	-	-	-	-	+	-
*Mylochromis epichorialis (*Trewavas, 1935)	-	-	-	+	-	-	-	-	-
Mylochromis ericotaenia (Regan, 1922)	-	-	-	-	-	-	+	-	-
Mylochromis sp	-	+	+	+	+	+	+	+	+
Mylochromis sphaerodon (Regan, 1922)	+	-	-	-	-	+	+	-	-
Nimbochromis linni (Burgess & Axelrod, 1975)	-	-	+	-	+	+	-	-	+
Nyassachromis sp	+	-	-	+	-	+	+	+	-
Oreochromis sp	+	-	+	+	-	+	+	+	+
Otopharynx argyrosoma (Regan, 1922)	-	-	-	-	-	+	-	-	-
Otopharynx heterodon (Trewavas, 1935)	-	+	-	+	+	-	+	+	-
Otopharynx lithobates Oliver, 1989	-	-	-	-	-	-	-	+	-
Otopharynx sp	+	+	+	-	-	+	-	+	-
Petrotilapia genalutea Marsh, 1983	-	-	-	+	-	-	-	-	-

Appendix 3.3 (continued)

Species name	Name of sampling site								
	CHD	CMW	CNK	CHR	MBJ1	MBJ2	MWF	TW1	TW2
Petrotilapia sp	+	+	+	+	+	+	+	+	+
Petrotilapia sp fuscous	-	-	-	-	+	-	-	-	-
Petrotilapia chrysos Stauffer & van Snik, 1996	-	+	-	-	-	-	-	-	-
Petrotilapia sp yellow chin	-	-	-	-	+	-	-	-	-
Placidochromis milomo Oliver, 1989	-	-	+	-	-	-	-	-	-
Protomelas fenestratus (Trewavas, 1935)	-	-	-	+	+	-	-	+	+
Protomelas sp	+	+	+	+	+	+	+	-	-
Protomelas spilonotus (Trewavas, 1935)	-	+	+	-	+	+	+	-	+
Protomelas taeniolatus (Trewavas, 1935)	-	+	+	+	+	+	+	+	+
Protomelas triaenodon (Trewavas, 1935)	-	-	-	+	-	-	-	-	-
Pseudotropheus sp	-	+	-	-	-	-	-	-	-
Petrotilapia tridentiger (Trewavas, 1935)	-	-	-	-	-	-	-	+	+
Pseudotropheus sp williamsi north	-	-	-	+	-	-	-	-	-
Pseudotropheus sp williamsi mbenji	-	-	-	-	+	-	-	-	-
Rhamphochromis sp	+	-	-	-	+	-	+	+	-
Sciaenochromis ahli (Trewavas, 1935)	-	-	-	-	+	-	+	-	-
Sciaenochromis sp	-	-	-	-	-	+	-	-	-
Stigmatochromis sp	-	-	-	-	+	-	-	-	-
Stigmatochrromis pholidophorus (Trewavas, 1935)	-	-	+	-	-	-	-	-	-
Synodontis njassae Keilhack, 1908	-	+	-	-	-	-	+	-	-
Tramitichromis brevis (Boulenger, 1908)	+	-	-	-	-	+	-	+	+
Tramitichromis sp.	+	-	-	-	-	+	+	-	-
Trematocranus placodon (Regan, 1922)	+	-	-	-	-	+	+	+	-
Tropheops sp	+	+	+	+	+	+	+	+	+
Tropheops sp elongatus	-	-	-	-	+	-	-	+	-
Tropheops sp mbenji blue	-	-	-	-	+	-	-	-	-
Tropheops sp yellow	+	+	-	-	+	+	-	-	-
Tropheops tropheops (Regan, 1922)	-	-	-	-	-	-	-	+	-
Tyrannochromis macrostoma (Regan, 1922)	+	+	+	-	-	-	-	+	+
Tyrannochromis nigriventer Eccles, 1989	-	+	-	+	+	-	-	-	-
Unidentified *mbuna*	+	+	+	+	+	+	+	+	+
Unidentified non *mbuna*	+	+	+	+	+	+	+	+	+

Appendix 4.1. Summary of reported absolute fecundity values for cichlid fish species of Lake Malawi. SWA = South West Arm. Different values of absolute fecundity have been reported by different researchers including range, mean ± standard deviation, and mean or single value without any measure of dispersion.

Species name	Sampling locality	Absolute fecundity	Source of information
Alticorpus macrocleithrum		152	Duponchelle *et al*. (2008)
Alticorpus mentale		229	Duponchelle *et al*. (2008)
Alticorpus pectinatum		112	Duponchelle *et al*. (2008)
Alticorpus geoffreyi	SWA	86-231	Duponchelle *et al*. (2000a)
Alticorpus geoffreyi		146	Duponchelle *et al*. (2008)
Alticorpus macrocleithrum	SWA	96-304	Duponchelle *et al*. (2000a)
Alticorpus mentale	SWA	92 – 356	Duponchelle *et al*. (2000a)
Alticorpus pectinatum	SWA	38-181	Duponchelle *et al*. (2000a)
Aulonocara cf microchir		80	Duponchelle *et al*. (2008)
Aulonocara minutus		16	Duponchelle *et al*. (2008)
Aulonocara sp blue orange	SWA	9 – 41	Duponchelle *et al*. (2000a)
Aulonocara sp blue orange		28	Duponchelle *et al*. (2008)
Aulonocara sp cf macrochir	SWA	50-134	Duponchelle *et al*. (2000a)
Aulonocara sp rostratum deep	SWA	41-167	Duponchelle *et al*. (2000a)
Aulonocara sp rostratum deep		81	Duponchelle *et al*. (2008)
Buccochromis lepturus	SWA	267-627	Duponchelle *et al*. (2000a)
Buccochromis lepturus		486	Duponchelle *et al*. (2008)
Buccochromis nototaenia	SWA	100 – 315	Duponchelle *et al*. (2000a)
Buccochromis nototaenia		179	Duponchelle *et al*. (2008)
C. quadrimaculatus	Lake samples	50	Thompson *et al*. (1996)
C. quadrimaculatus		40	Duponchelle *et al*. (2008)
Chindongo heteropictus		29	Duponchelle *et al*. (2008)
Copadichromis chrysonotus	Southern Lake Malawi	48.9± 3.5	Smith (2000)
Copadichromis quadrimaculatus	SWA	15 – 62	Duponchelle *et al*. (2000a)
Copadichromis virginalis	SWA	9 – 59	Duponchelle *et al*. (2000a)
Copadichromis virginalis		28	Duponchelle *et al*. (2008)
Cynotilapia afra	Thumbi West Island	11.04 ± 8.0	Munthali & Ribbink (1998)
Cynotilapia afra	Likoma Island	9.75 ± 4.45	Munthali & Ribbink (1998)
Cynotilapia afra		21	Duponchelle *et al*. (2008)
Diplotaxodon limnothrissa	Lakewide	15	Thompson *et al. (1996)*
Diplotaxodon apogon	SWA	9 -34	Duponchelle *et al*. (2000a)
Diplotaxodon apogon		16	Duponchelle *et al* 2008
Diplotaxodon argenteus	Lakewide	15-75	Thompson *et al*. (1996)
Diplotaxodon argentius	SWA	25-53	Duponchelle *et al*. (2000a)
Diplotaxodon argentius		40	Duponchelle *et al*. (2008)
Diplotaxodon limnothrissa	SWA	10-30	Duponchelle *et al*. (2000a)
Diplotaxodon limnothrissa		17	Duponchelle *et al*. (2008)
Diplotaxodon macrops	SWA	10-37	Duponchelle *et al*. (2000a)
Diplotaxodon macrops		18	Duponchelle *et al*. (2008)
Diplotaxodon sp big eye	Lakewide	24	Thompson *et al*. (1996)
Diplotaxodon sp big eye		42	Duponchelle *et al*. (2008)

Appendix 4.1 (continued)

Species name	Sampling locality	Absolute fecundity	Source of information
Genyochromis mento		30	Duponchelle *et al*. (2008)
Labeotropheus fuelleborni	Likoma Island	26.9 ± 8.2	Marsh *et al*. (1986)
Labeotropheus fuelleborni		27	Duponchelle *et al*. (2008)
Labeotropheus fuelleborni	Monkey bay	22.5 ± 5.6	Marsh *et al*. (1986)
Labeotropheus trewavasae		27	Duponchelle *et al*. (2008)
Lethrinops argentius	SWA	43-218	Duponchelle *et al*. (2000a)
Lethrinops argentius		119	Duponchelle *et al*. (2008)
Lethrinops gossei	SWA	23 – 234	Duponchelle *et al*. (2000a)
Lethrinops gossei	SWA	108	Duponchelle *et al*. (2008)
Lethrinops longimanus	SWA	57-99	Duponchelle *et al*. (2000a)
Lethrinops longimanus	SWA	73	Duponchelle *et al*. (2008)
Lethrinops polli	SWA	11-89	Duponchelle *et al*. (2000a)
Lethrinops polli	SWA	37	Duponchelle *et al*. (2008)
Lethrinops sp deep water albus	SWA	65-151	Duponchelle *et al*. (2000a)
Lethrinops sp deep water albus	SWA	107	Duponchelle *et al*. (2008)
Lethrinops sp deep water altus	SWA	10-84	Duponchelle *et al*. (2000a)
Lethrinops sp deep water altus	SWA	37	Duponchelle *et al*. (2008)
Lethrinops sp minutus	SWA	19	Duponchelle *et al*. (2008)
Lethrinos sp oliveri	SWA	19-81	Duponchelle *et al*. (2000a)
Lethrinos sp oliveri	SWA	46	Duponchelle *et al*. (2008)
Letrinops macrochir	SWA	107	Duponchelle *et al*. (2008)
Mchenga eucinostomus	-	35	Elgar (1990)
Melanochromis auratus	Thumbi West Island	20.8 ± 5.8	Marsh *et al*. (1986)
Melanochromis auratus		24	Duponchelle *et al*. (2008)
Melanochromis joanjohnsonae	Likoma Island	15.3 ± 4.8	Marsh *et al*. (1986)
Melanochromis joanjohnsonae	Thumbi West Island	14.0 ± 3.8	Marsh *et al*. (1986)
Melanochromis vermivorous		19	Duponchelle *et al*. (2008)
Metriaclima callainos	Nkhata Bay	2.79 ± 2.93	Munthali & Ribbink (1998)
Metriaclima callainos		17	Duponchelle *et al*. (2008)
Metriaclima callainos	Thumbi West Island	5.18 ± 2.47	Munthali & Ribbink (1998)
Metriaclima zebra		27	Duponchelle *et al*. (2008)
Mylochromis anaphyrmus	SWA	58-236	Duponchelle *et al*. (2000a)
Mylochromis anaphyrmus	SWA	150	Duponchelle *et al*. (2008)
Nyassachromis sp argyrosoma	SWA	16-56	Duponchelle *et al*. (2000a)
Nyassachromis sp argyrosoma	SWA	33	Duponchelle *et al*. (2008)
Otopharynx sp productus	SWA	22-61	Duponchelle *et al*. (2000a)
Otopharynx sp productus	SWA	34	Duponchelle *et al*. (2008)
Otopharynx speciosus	SWA	51-322	Duponchelle *et al*. (2000a)
Otopharynx speciosus	SWA	162	Duponchelle *et al*. (2008)
Pallidochromis tokoloshi	SWA	40	Duponchelle *et al*. (2008)
Pallidochromis tokoloshi	SWA	13-87	Duponchelle *et al*. (2000a)
Petrotilapia nigra		45	Duponchelle *et al*. (2008)
Petrotilapia sp fuscous		46	Duponchelle *et al*. (2008)
Petrotilapia spp.	Monkey Bay	77.6 ± 21.1	Marsh *et al*. (1986)

Appendix 4.1 (continued)

Species name	Sampling locality	Absolute fecundity	Source of information
Placidochromis sp platyrhynchos	SWA	53.5	Duponchelle *et al*. (2008)
Placidochromis sp long	SWA	17-38	Duponchelle *et al*. (2000a)
Placidochromis sp long	SWA	26	Duponchelle *et al*. (2008)
Placidochromis sp platyrhynchos	SWA	23-93	Duponchelle *et al*. (2000a)
Protomelas taeniolatus	Monkey Bay	29.0 ± 7.3	Marsh *et al*. (1986)
Pseudotropheus aurora		30	Duponchelle *et al*. (2008)
Pseudotropheus barlowi		34	Duponchelle *et al*. (2008)
Pseudotropheus livingstonii	SWA	15-33	Duponchelle *et al*. (2000a)
Pseudotropheus livingstonii		26	Duponchelle *et al*. (2008)
Pseudotropheus sp aggressive blue		29	Duponchelle *et al*. (2008)
P. sp aggressive grey head		23	Duponchelle *et al*. (2008)
P. sp elongatus aggressive	Monkey Bay	22.0 ± 5.8	Marsh *et al*. (1986)
P. zebra black dorsal		33	Duponchelle *et al*. (2008)
P. sp zebra red dorsal		27	Duponchelle *et al*. (2008)
P. sp zebra yellow throat		29	Duponchelle *et al*. (2008)
Pseudotropheus williamsi		40	Duponchelle *et al*. (2008)
Metriaclima zebra	Monkey Bay	26.0 ± 6.7	Marsh *et al*. (1986)
Rhamphochromis esox		348	Duponchelle *et al*. (2008)
Rhamphochromis longiceps		50	Duponchelle *et al*. (2008)
Rhamphochromis macrophthalmus		522	Duponchelle *et al*. (2008)
Rhamphochromis longiceps	Lakewide	30-75	Thompson *et al*. (1996)
Rhamphochromis spp[29]	Lakewide	130 – 550	Thompson *et al*. (1996)
Rhamphochromis woodi		241	Duponchelle *et al*. (2008)
Sciaenochromis ahli	SWA	35-90	Duponchelle *et al*. (2000a)
Sciaenochromis ahli	SWA	48	Duponchelle *et al*. (2008)
Sciaenochromis benthicola	SWA	32-99	Duponchelle *et al*. (2000a)
Sciaenochromis benthicola	SWA	56	Duponchelle *et al*. (2008)
Stigmatochromis sp guttatus	SWA	21-64	Duponchelle *et al*. (2000a)
Stigmatochromis sp guttatus	SWA	41	Duponchelle *et al*. (2008)
Taeniolethrinops furcicauda	SWA	138-219	Duponchelle *et al*. (2000a)
Taeniolethrinops furcicauda		180	Duponchelle *et al*. (2008)
Taeniolethrinops praeorbitalis	SWA	193-250	Duponchelle *et al*. (2000a)
Taeniolethrinops praeorbitalis		226	Duponchelle *et al*. (2008)
Trematocranus brevirostris	SWA	13-47	Duponchelle *et al*. (2000a)
Trematocranus brevirostris		32	Duponchelle *et al*. (2008)
Trematocranus placodon	SWA	76-178	Duponchelle *et al*. (2000a)
Trematocranus placodon		135	Duponchelle *et al*. (2008)
Tropheops sp blue		32	Duponchelle *et al*. (2008)

[29] Species were not identified but grouped together as “larger *Rhamphochromis*” with a total length range of 90 to 500 mm.

Appendix 4.1 (continued)

Species name	**Sampling locality**	**Absolute fecundity**	**Source of information**
Tropheops sp lilac		31	Duponchelle *et al*. (2008)
Tropheops sp orange chest		31	Duponchelle *et al*. (2008)
Tropheops sp orange chest	Monkey Bay	33.8 ± 8.7	Marsh *et al*. (1986)
Tropheops sp red cheek		22	Duponchelle *et al*. (2008)
Tropheops sp red cheek	Thumbi West Island	9.21 ± 4.54	Munthali & Ribbink (1998)
Tropheops sp red cheek	Likoma Island	8.68 ± 3.85	Munthali & Ribbink (1998)