Cage aquaculture and environment in Lake Malawi: an assessment of water quality, food web shifts, and development of a decision support tool for sustainable aquaculture

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Dedication

To my wife Rosita, my daughter Claire Cátia Macuiane and son Messias Alfredo Macuiane Junior, my nephews, my mother Catarina Gilberto Macuiane, my brothers and sisters, thank you for your endless support.

Abstract

The impact of cage aquaculture on the water quality and native fish community was studied between November 2011 and September 2012 in the South East Arm of Lake Malawi. This ancient African Great Lake has the greatest number of fish species of any lake in the world, and the fishery is a major source of animal protein in Malawi. However, the decline of the capture fishery stocks has forced the Government of Malawi to promote cage aquaculture. The Maldeco Aquaculture Limited is the first cage aquaculture operation initiated in 2004 to farm endemic and native fish species in Lake Malawi at commercial scale. Unfortunately there is no legal framework for sustainable cage aquaculture development. The study found that cage aquaculture attracts wild fish populations and also changes their community structure. However, the diversity was not significantly affected by the cage farm despite the increased abundance of fish, especially smaller fish. Water temperature and dissolved oxygen were minimal between April and June, a period that cage aquaculture farms should consider as critical in their operation. Chlorophyll *a* had a single seasonal peak in April concurrent with the minimum in transparency. There was no significant difference in water quality parameters between the aquaculture site and sites 5 km away. Stable isotope signatures of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) of the wild fish revealed shifts in small particle feeding planktivorous fish and possibly in zooplanktivorous fish, but not in benthivorous, molluscivorous, and zoobenthivorous fishes which maintained their natural diets even at the farm site. A dissolved oxygen model indicated that the average carrying capacity of the farm is 1,870,000±96, kg. A mean stocking density of 23,000 ±440kg per cage is recommended to allow adequate fish growth rates and attainment of desirable marketable size within a

short cycle without significant impact on oxygen concentration. Un-regulated expansion of cage aquaculture activities at Maldeco Aquaculture farm or increase in the number of cage farms has the potential of increasing changes in wild fish community structure, modifying food webs, and causing conflicts with local fishermen.

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Chapter 1

Overview of the fisheries sector in Malawi

1.1 Introduction

Lake Malawi is shared among the three riparian countries: Malawi, Mozambique, and Tanzania and is the southernmost African Great Lake. Different names such as Niassa in Mozambique, Nyasa in Tanzania and Malawi in Malawi are used. However, the lake will be treated as Lake Malawi throughout the study as the study was entirely conducted in the Malawian portion of the lake. Lake Malawi (28,000 km^2, 700 m deep) is famous for its spectacular high fish diversity with between 500 and 1,000 fish species (Ribbink, 1994; Snoeks, 2000), with the vast majority of these species being endemic (Fryer and Iles 1972, Ribbink et al., 1983).

More than 52 percent of the population in Malawi live below the national poverty line, and about 22 percent are extremely poor (World Bank 2007). Many Malawians are at risk of multiple nutrient deficiencies due to inequality in consumption of essential nutrients (Ecker and Qaim, 2008) which especially affects children, and thereby, they are known to be undernourished (GOM NSO 2012). Fresh, dried, powder, or smoked fish is an important source of dietary essential amino acids for many people living in remote villages; it may also be the main source in urban and peri-urban areas (Béné and Heck, 2005) being carried there by fish traders. The importance of the fisheries sector is attested by its contribution in the supply of fish as an essential protein and macronutrients to Malawian people. It also creates direct and indirect employment to about 1.6 million people. The fishery formerly contributed more than 70% of animal protein prior to the long term decline of the fishery beginning in early 1970's (Banda et al., 2005). Its decline

resulted in increasing malnutrition across Malawi (Mumba and Jose 2005) which is still widely prevalent (World Bank, 2007), and based on projected population growth of about 3.3 percent per year, more people will be food insecure in the coming years (USDA, 2012).

The biomass and abundance of many fish species have been affected by illegal fishing, habitat destruction, violation of closed seasons, catchment damage, violation of protected areas, and overfishing in the past decades, but the most visible effects have been on the lucrative *chambo* fishery (*Oreochromis lidole, O. squamipinnis,* and *O. karongae*) (Banda et al., 2005) which fetch the highest market prices. These are shallow water species and are accessible to artisanal fishermen using inexpensive gears. To counteract the declining trends in the capture fisheries sector various governmental and donor funded aquaculture initiatives were implemented in Malawi to support local farmers to adopt pond aquaculture. Integration of fish farming with traditional crops increased consumption of protein and helped generate household income for poor farmers (Dey et al., 2007) and reduced vulnerability to drought while increasing production and profit at household level (WorldFish Center, 2007). Important initiatives such as the Presidential Initiative for Aquaculture Development, the National Aquaculture Strategic Plan, and the Chambo Restoration Strategic Plan support the restoration of the *chambo* fisheries and introduction of cage aquaculture farming in Lake Malawi to reduce pressure on this fishery.

The use of Lake Malawi for farming fish in cages is the central focus of the current study. The impacts of cage aquaculture in marine and freshwater systems due to use of excess fish feed that enriches the water column and benthic environments have

been studied worldwide (Aure and Stigebrandt, 1990; Brown et al., 1987; Islam, 2005; Gondwe et al., 2011b). Gradual increase in nutrient loadings and metabolic wastes as the number of cages increases can lead to events such as excessive algal growth that can affect the quality of the host water body. Phosphorous is the limiting nutrient for algal growth in freshwater systems (Wetzel, 2000). The growth of algae in freshwater systems is a concern especially in areas where cage culture is being developed because high amounts of phosphorous and nitrogen are contained in commercial feeds because fish meal and soybean meal are added to achieve high growth rates. Therefore, all efforts that minimize release of phosphorous by fish farms should be taken into consideration for the sustainability of freshwater cage culture (Hua et al., 2008). An earlier study by Gondwe et al. (2011) investigated phosphorous and nitrogen losses to Lake Malawi from the Maldeco Aquaculture Farm and found that release of these nutrients are comparable with commercial cage aquaculture farms in temperate regions, but they found minimal impact to the surrounding environment probably due to advective transport that minimizes waste sedimentation at the site. They warned that intensification of farming activities has the potential to increase the nutrients and occurrence of eutrophication in Lake Malawi.

1.2 Thesis objectives and hypothesis

The current study was conducted eight years after the introduction of a commercial tilapia cage aquaculture farm in Lake Malawi. Four main objectives were established for the study to address the following questions: (1) how is cage aquaculture farming affecting the fish community structure in Lake Malawi (2) what is the effect of cage farm aquaculture on the water quality in Lake Malawi (3) what is the impact of cage aquaculture on the food web structure that supports the wild fish communities in the vicinity of the aquaculture cages (4) what is the carrying capacity of the farm in order to guide the private sector to stock adequate amounts of fish in the cages and to guide regulatory authorities to monitor cage aquaculture activities in the lake.

Objective 1- Chapter 2 investigates the fish community structure at three fishing sites, one at the farm and two located 5 km from it using similarities and dis-similarities analysis with Bray-Curtis index to find out whether changes in the community were associated with the cage aquaculture farm. The null hypothesis tested is that the cage farm has no impact on fish community structure.

Objective 2- Chapter 3 reports water temperature, dissolved oxygen, chlorophyll *a*, Secchi depth, total phosphorous, and total nitrogen at the three established sampling sites to understand their dynamics to determine what water quality recommendations may be necessary for sustainable farming in Lake Malawi. Again the null hypothesis for the study was that the farm site has no impact on water quality.

Objective 3- Chapter 4 determines whether uneaten commercial feeds and feces emanating from the cage farm are consumed in significant amounts by wild fish communities occupying five trophic levels in Lake Malawi through application of stable

isotopes of carbon $\delta^{13}C$ and nitrogen $\delta^{15}N$ in commercial feeds and muscles tissue of farmed and wild fish populations found at the three fishing sites. The basic hypothesis tested was that isotopic signatures of trophic groups of fishes at the farm would not be different from the same groups at sites remote from the farm.

Objective 4- Chapter 6 examines the suitability of a sub-model of water quality based on oxygen concentrations and currents at the farm and cages (developed for use in the North Sea) to be used as a decision support tool in Lake Malawi cage aquaculture farms. Measurements of oxygen concentrations and currents flowing in and out of the farm and cages were done to estimate the carrying capacity of cages and the farm. The hypothesis for this objective was that the sub-model is suitable for Lake Malawi environment which is much warmer and has lower oxygen than the North Sea locations for where the model was developed. In order to apply the model, in Chapter 5 the specific oxygen consumption rates of the farmed fish, *Oreochromis karongae* (Trewavas, 1941) and *Oreochromis shiranus* (Boulanger, 1896), were measured under experimental condition using water from the lake and fish supplied by Maldceo Aquaculture Limited.

Chapter 2

Changes in fish community structure associated with cage aquaculture in Lake Malawi

Abstract

Local fishermen claim that introduction of a commercial cage aquaculture farm in Lake Malawi resulted in low fish catches as fish take refuge within the farm. This study was conducted in three fishing sites, one at the farm and two 5 km southeast and northwest of the farm. The fish community structure was sampled in February, April, June and August 2012. The cage aquaculture farm contributes to changes in wild fish community structure in Lake Malawi. Multivariate analyses confirm significant differences in spatial (Global R = 0.472, p=0.005) and temporal (R=0.472, p=0.004) distribution of wild fish community. Overall, the two sites away from the farm had similar fish community structure (R=0.250, p=0.225) and both had different community structure compared to the site at the farm (R=0.563, p=0.037). Seasonally, different fish communities were observed between (February and April, R=0.917, p=0.037), (February and June, R=0.667, p=0.037), and (June and August, R=0.583, p=0.037). Fishing site 1, located on the northwest side 5 km away from the farm was classed as undisturbed while fishing site 2 located at the farm and fishing site 3 southeast the side of the farm, 5 km away from it, were classed as moderately and grossly disturbed, respectively. Site 2 is affected by the farm itself and site 3 is affected by high fishing pressure. However, fish diversity was not affected by cage farming and fishing pressure. The major differences arise because of the increased occurrence of small bodied fish species which are a

characteristic of disturbed fishing areas. A revision of the Malawi Fisheries and Aquaculture policy is suggested to solve the conflicts between cage aquaculture operators and local fishermen; lastly, the enforcement of fishing zones to reduce pressure to maintain the sustainability of wild fish populations is encouraged.

2.1 Introduction

Lake Malawi as it is known internationally and in Malawi, Lago Niassa and Lake Nyasa in Mozambique and Tanzania respectively, lies in south/central Africa (Fig. 2.1). The lake is referred to as Lake Malawi throughout the study. This ancient lake is famous for its spectacular diversity of fish species, which is greater than in any other lake in the world. More than 90% of the fish species are endemic cichlids (Fryer and Iles, 1972; Ribbink et al., 1983; Snoeks, 2000) with most of these being the haplochromine cichlids (Eccles and Trewavas, 1989). Lake Malawi accounts for about 500 to 1,000 fish species (Fryer and Iles, 1972; Konings, 1995), and there are still more fish species being identified (Snoeks, 2000). The highest diversity of cichlid species is in the near the shore and the rocks. These species are referred to as *mbuna* (Konings, 1990; Bootsma and Hecky, 1993). The fish inhabiting the offshore pelagic waters of Lake Malawi belong to four families: the Cichlidae, the Cyprinidae, the Clariidae, and the Mochokidae (Thompson et al., 1995). Clupeidae and Centropomidae which are found in Lake Tanganyika are not found in Lake Malawi (Coulter, 1991), although the families found in Lake Malawi are also found in other African Great Lakes (Thompson et al., 1995).

The riparian countries (Malawi, Mozambique and Tanzania) benefit from Lake Malawi as it provides potable drinking water, water for domestic use, irrigation, fish for domestic consumption and income, transportation, tourism, scientific research, electricity (Bootsma and Hecky, 1993), and export of the colorful ornamental fish. Fishing is one of the most important activities in Malawi (Jamu et al., 2011) where it is especially practiced by poor people using low cost fishing gears. It is estimated that among other sources of protein in Malawi, fish provide 70% of animal protein supply and 40% of total

protein intake (Banda et al., 2005) and the sector directly employs about 60, 000 people and over 450, 000 people indirectly (GOM, 2009). This contribution is especially valuable in Malawi which is constrained by increased food and nutritional insecurity due to low land productivity, low rural income and poverty (Jamu and Chimatiro, 2005). Unfortunately, the combined effects of illegal fishing, habitat destruction, violation of closed seasons, catchment damage, violation of protected areas, and overfishing have reduced the contribution of Malawi fishery particularly the more lucrative *chambo* fishery (*Oreochromis lidole, O. squamipinnis,* and *O. karongae*) as a source of protein (Banda et al., 2005), and increased the price of fish, making it unaffordable to low income people in Malawi.

The *Chambo* Restoration Strategic Plan proposes several management interventions to restore Lake Malawi fishery with special attention to the *chambo* fishery. The plan includes restriction of fishing gears (mesh size and head line length), introduction of cage culture farming in existing water bodies, establishment of fish sanctuaries, artificial reefs, community property rights to fishing areas, and restocking of the fishery (Banda et al., 2005) to reduce pressure for sustainable fisheries exploitation. The plan has met resistance and had limited success because some of the strategies are constantly being ignored by local artisanal fishermen who are challenged by lack of alternative livelihood strategies as such and do not accept the government's authority to manage the lake.

The current study focused on one of the strategies of the restoration plan, the cage culture of the *chambo* fishery. *Chambo* has been farmed on land in small fish ponds since the 1960's to improve the living standards of poor families, but unfortunately small scale

farming has not been able to supply adequate amounts of fish for the growing population of Malawi (2.8% per annum; NSO, 2008) due to use of poor quality feed and poor quality fingerlings leading to early reproduction and stunting. Lack of operational capital to purchase fertilizers and other farm inputs contribute to poor harvests. There has been an increase in the number of fish ponds from 300 to 7 000 over the past 25 years (Allison, 2011), however, the only visible benefits include somewhat improved total farm productivity, income, and consumption of fresh fish at the household level (Dey et al., 2007). The current fish production is far too low to meet the country's demand for fish in Malawi. The focus now is to venture into cage culture in Lake Malawi (Windmar et al., 2008) and support this promising industry which was introduced into Lake Malawi in 2004. The advantages of cage culture farming include farming high fish biomass in existing water bodies, reduced pressure on land that is already under pressure from urbanization and agriculture production as well as being challenged by persistent drought which makes some places unsuitable for pond based aquaculture farming.

At a global scale, the contribution of aquaculture was about 46 percent of total food fish supply in 2008 when both capture fisheries and aquaculture produced 142 million tons (FAO, 2010). In Malawi, the cage aquaculture industry stimulated an increased farmed fish production from 666 tonnes in 2003 to 3,433 tonnes in 2011 (FAO, 2005-2013) and it is predicted to increase with increased number of farms coupled with improved farming strategies. However, regardless of this contribution, there have been local and worldwide environmental concerns about the impacts on water quality and on local fish community structure that support local traditional capture fisheries. The impacts of cage aquaculture wastes on water quality in Lake Malawi were investigated by

(Gondwe et al., 2011a) and were reported minimal at the scale of the initial operating site but may increase with increase in the number of cages within a farm as well as potentially having lake wide affects as the industry expands.

While the impacts of cage aquaculture may vary from one country to another, in Malawi the major concern has been expressed by local fishermen who claim that the introduction of Maldeco Aquaculture Farm resulted in reduced fish catches because fish take refuge in the farm. Previous fish community studies in the south east arm of Lake Malawi (SEA) (Banda et al., 1996; Duponchelle et al., 2003; Weyl et al., 2005) were conducted before the introduction of commercial cage aquaculture, consequently nothing is known about the structure and composition of fish communities in relation to cage culture farming although this knowledge is important for lake wide aquaculture expansion and management of the lake fishery. The current study was conducted in 2012, eight years after the introduction of cage aquaculture in Lake Malawi to investigate the spatial and temporal changes in fish community structure in the SEA to understand the current fish community composition in relation to cage aquaculture farming in the south east arm of Lake Malawi.

2.2 Materials and methods

2.2.1 *Lake Malawi*

The physical and chemical properties of the surface mixed layer of Lake Malawi are characterized by warm surface water temperatures ranging between 28-30^{o}C. There is seasonal stratification of the surface waters with mixing depths that range from 30 to 200 m. The surface mixed layer is deepest during the cool windy season (Eccles, 1974; Halfman, 1993). The deep waters are permanently stratified at 230-250 m (Eccles, 1974). The hypolimnion is persistently anoxic probably because convective vertical mixing does not extend into deep hypolimnetic waters (Wüest et al., 1996). The position of the oxic-anoxic boundary is a product of physical mixing and the oxygen demand created by organic matter produced in surface waters. The possible impact of the cumulative effect of nutrient enrichment and resulting higher primary productivity of surface waters, on the depth of anoxia remains a concern in the longer term as a reduction in the depth of the oxic layer would represent a loss of fish habitat for the lake.

Lack of complete mixing of the lake throughout its depth annually results in the deep waters being rich in nutrient while the surface waters (Bootsma et al. 2003) have quite low nutrients concentration, almost undetectable concentrations of nitrate nitrogen (NO_3-N), ammonia nitrogen (NH_3-N) and soluble reactive phosphorous (SRP); the nutrient concentrations increase with depth with highest concentrations in the hypolimnion (Peterson and Kachinjika, 1995). Riverine inputs, atmospheric deposition and nitrogen fixation are the main mechanisms by which nutrients are added in lakes (Bootsma et al., 1996). Rivers and precipitation add phosphorous to the lake (Hecky, 2000), but the external input of nutrients in Lake Malawi is less than 15% of the average

demand (Guildford et al., 2000) which is why the lake is still considered oligotrophic (Guildford et al., 2003). Under low external input of nutrients, water column regeneration processes (grazing, excretion, and mineralization) and the supply of nutrients from the metalimnion to epilimnion are suggested to play an important role in maintaining current phytoplankton growth rates in Lake Malawi (Guilford et al., 2000). Biological fixation of atmospheric nitrogen also contributes a significant amount of fixed nitrogen to Lakes Malawi, Tanganyika and Victoria (Hecky et al., 1996). Loss of nutrients to the outflow is very minimal for Lake Malawi which retains most of the plant nutrients coming to the lake e.g. S (90%), N (99%), P (97%), and Si (96%) which are stored in the sediments or lost in gaseous form to the atmosphere (Hecky et al., 1996).

Warm waters and dissolved oxygen which is generally above 3 mg/l (Halfman, 1993) and between 4.4-7.7 $mg.L^{-1}$ in the South East Arm (Gondwe, 2009) and low pressure from industrial and urban pollution, position Lake Malawi as a suitable site for cage farming of local cichlid and non-cichlid species. The shallowness of the South East and South West Arms of the lake where the wind action is strong enough to replenish the oxygen by preventing persistent the thermal stratification (Eccles, 1974) is advantageous for cage farming

2.2.2 *Study area*

Lake Malawi (Figure 2-1) is the third largest African Great Lake by area after Lakes Victoria and Tanganyika. The catchment area of Lake Malawi is 97, 740 km^2, of which 64, 373 km^2 lies in Malawi, 26, 600 km^2 lies in Tanzania, and only 6, 768 km^2 in Mozambique (Department of Water/UNDP, 1986). The lake is 550 km long with a mean width of 48-60 km (Patterson and Kachinjika, 1995; Kanyika, 2000). The maximum

depth of 700 m is found in the northern region from which the basin continuously shoals to the south and into the South East Arm from which the Shire River exits. The lake surface area is 29, 743 km^2, a mean depth of 474 m and an estimated volume of 7,723 km^3 (Department of Water/UNDP, 1986). Lake Malawi is connected to downstream Lake Malombe through Shire River which is the only outlet of Lake Malawi. The Shire River runs through the southern region of Malawi and connects to the Zambezi River in Mozambique.

Maldeco Aquaculture Limited is the only cage aquaculture operation allowed by the Government of Malawi to operate at a commercial scale in Lake Malawi. The farm is dedicated to the monoculture of *chambo* and polyculture with *O. shiranus*, another mouth brooding tilapia species which is commercially sold as *chambo*. The parent fish are kept in earthen ponds at Maldeco Aquaculture farm for production of fingerlings. The fingerlings are kept in nursery ponds prior to stocking into circular cages (16 m diameter and 6 m deep) moored in the lake where water depths range between 12.0±0.1 and 22.1±0.2 m (Figure 6-1) in the South East Arm. As of July-August 2010, each active cage was stocked with an average of 130,000 fish or 108 fish/m^3 and the operational cages were fed with approximately a ton a day of nutritionally complete feed during two daily feeding periods, between 9 and 11 am in the morning and between 1 to 3 pm in the afternoon. The feed is locally manufactured by Maldeco Aquaculture Limited using local ingredients such as maize meal, soybean, wheat flour and imported supplements such as fish meal, vitamins and minerals. The fish are fed at a nominal daily rate of 5% body weight; feeding rates are adjusted during production cycle. Fish are harvested after a year and locally sold. No antibiotics are used in the current operation. The various ingredients

are combined in three diets: the starter feed for fry and fingerlings, the grower feed for juveniles, and the finisher for mature fish. The study was conducted when the farm was under-stocked with most of the cages empty during the sampling.

2.2.3 *Sample collection*

Fishing was done at three fishing sites (Figure 2-1) during the day time in February (F), April (A), June (J), and August (AU) 2012 using four experimental gillnets with similar dimensions to catch different fish species and sizes in order to determine changes of fish community composition in time and space, abundance, biomass, and diversity indices. The fishing sites were replicated twice and named as F11 for samples collected in February at site 1 replicate 1, (F12) February site 1 replicate 2, (F21) February site 2 replicate 1, (F22) February site 2 replicate 2, (F31) February site 3 replicate 1, (F32) February site 3 replicate 2, (A11) April site 1 replicate 1, (A12) April site 1 replicate 2, (A21) April site 2 replicate 1, (A22) April site 2 replicate 2, (A31) April site 3 replicate 1, (A32) April site 3 replicate 2 (J11) June site 1 replicate 1, (J12) June site 1 replicate 2, (J21) June site 2 replicate 1, (J22) June site 2 replicate 2, (J31) June site 3 replicate 1, (J32) June site 3 replicate 2, (AU11) August site 1 replicate 1, (AU12) August site 1 replicate 2, (AU21) August site 2 replicate 1, (AU22) August site 2 replicate 2, (AU31) August site 3 replicate 1, (AU32) August site 3 replicate 2. Fishing site 1 was located to the northwest of the farm 5 km away from it. Site 2 was located at the farm while fishing site 3 was located 5 km to the southeast of the farm. Sites 1 and 3 were therefore located 10 km apart. Fishing sites 1 and 3 were chosen based on their similar distance offshore and similar depth as site 2. The gillnets are 250 feet long, 6 feet

deep, constructed of mono-filament nylon, with nylon float lines. Each net consists of five randomly placed panels each with 50 feet and ¾", 1", 1 ¼", 1 ½", and 2" webbing. After harvesting the catch, fish were identified and sorted to species level using published keys and descriptions. The bulk and individual fish were counted and the total weighed and measured to the nearest 0.01g.

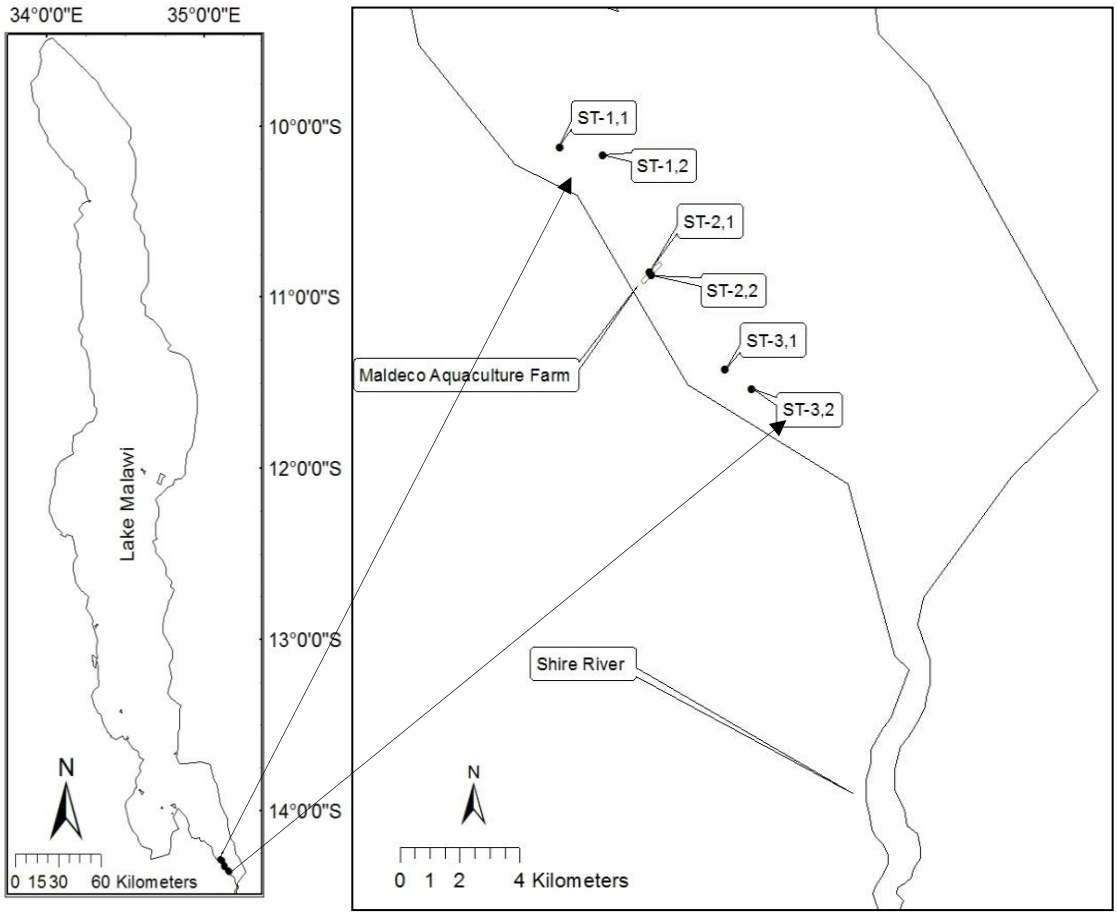

Figure 2-1 Lake Malawi (left) and fishing sites (ST-1,1 is fishing site 1 replicate 1, ST-1,2 is fishing site 1 replicate 2, ST-2,1 is fishing site 2 replicate 1, ST-2,2 is fishing site 2 replicate 2, ST-3,1 is fishing site 3 replicate 1, and ST-3,2 is fishing site 3 replicate 2) including Maldeco Aquaculture farm (right).

2.2.4 *Data analysis*

Multivariate analysis using PRIMER (Plymouth Routines in Marine Ecological Research) program (version.6.1.8) (Clarke and Warwick, 2001; Clarke and Gorley, 2006) was employed to investigate the spatial and temporal changes of fish community structure. Raw abundance data (number of individuals per site per net) were square root transformed to reduce the variance. The Bray-Curtis similarity index, which is widely used in similarity analysis of species composition in community ecology (Bloom, 1981) was employed to test the hypothesis of no spatial and temporal difference in fish community composition at fishing sites (Bray and Curtis, 1957). Cluster analysis and Multidimensional scaling (MDS) were used for graphical visualization of fish community structure onto two dimensional plots. While MDS analysis has been used in community studies at stress levels close to zero, complex data rarely give a zero stress (Clarke and Ainsworth, 1993). A higher stress level is not known to give a perfect representation of the whole story of abiotic patterns at specific dimensional scales (Clarke at al., 1993). The current study reveals a complex fish community as shown by relatively high stress levels (0.21). However, MDS provided enough of a visual difference of fish community in south east arm of Lake Malawi which is later detected by two-way crossed (with replicates) Analysis of Similarity (ANOSIM) (Clarke and Warwick, 2001; Clarke and Gorley, 2006) by significant differences in average rank dissimilarity of fish community composition among different sites and months.

Similarity of Percentage Analysis (SIMPER) (Clarke and Warwick, 2001; Clarke and Gorley, 2006) was used to determine which species, if any, contributed to spatial and temporal dissimilarities. SIMPER analysis reports the ranked contribution of each species

to overall average dissimilarity, contribution to dissimilarity (δ), and cumulative percentage contribution ($\sum\delta_i$ %). The cut-off dissimilarity was set at 50% cumulative contribution. Only sites and months with significant dissimilarity are reported (see Tables 2-5 to 2-9). The Abundance Biomass Comparison (ABC) method (Warwick, 1986) was used determine undisturbed and disturbed fishing sites based on biomass and abundance curves. The ABC routine generated cumulative abundance/biomass curves with either positive or negative *W* (Warwick) statistic values. Positive values classed the fishing sites as undisturbed/unpolluted when biomass curves were above the abundance curves and negative *W* values classed fishing sites as disturbed/polluted when abundance curve were above the biomass curve (Clarke and Warwick, 2001).

Total number of fish species (*S*) and total individuals (*N*) in a fishing site were recorded and the abundance of the *i*th species P_i (i=1,2,3,..,S) was estimated by *i*th individuals *Ni* (*i*=1,2,3,..,*S*) and, divided by their sum (*N*) (Clarke and Gorley, 2006). Shannon's diversity index ($H'=\sum P_i \log (P_i)$) (Shannon and Weaver, 1963), Species richness (Margalef) Diversity Index (d=(S-1)/ *log N*) (Margalef, 1958), Pielou's Evenness Index ($j'=H'/\log_e S$) (Pielou, 1975) characterized the species assemblages, and finally, the Simpson diversity index ($\lambda= P_i^2$) (Heip et al., 1998) measured fish diversity.

2.3 Results

A total of 51 fish species making up to 628 individuals were identified from all catches respectively. Table 2-1 shows the fish community composition and individuals sampled in February 2012. *C. chrysonotus* and *Lethrinops lethrinus* were found in all fishing sites. *C. virginalis* and *Stigmatochromis guttatus* were only found in fishing sites 1 and 3 while *Trematocranus placodon* was found in fishing sites 1 and 2. About 50 percent of fish species found in fishing site 1 were not found in fishing sites 2 and 3. About 73 percent of fish species found in fishing site 2 were not found in either fishing site 1 or 3. Fishing site 3 had the lowest number of fish species, and only two species found at fishing site 3, *Nyasachromis argyrosoma* and *Placidochromis suboccularis* were not found in sites 1 and 2 (Table 2-1). The number of fish species increased in all fishing sites and reached its maxima in April (Table 2-2). Fishing sites 1 and 2 had 23 different fish species each. However, regardless of increased number of fish species only 4 fish species: *L. parvidens, O. karongae, O. squamipinis, Taeniolethrinops praeorbitalis* were found in sites 1 and 2. Site 2 consisted of 11 fish species absent in sites 1 and 3. Likewise 9 fish species found in site 1 were not recorded in sites 2 and 3. Species recorded in all fishing sites include: *L. lethrinus, Otopharynx argyrosoma, Pseodotropheus livingstonii, P. suboccularis,* and *Trematocranus placodon* (Table 2-2). Site 3 had fewer species than sites 1 and 2. All fish species found in site 3 were either found in sites 1 or 2. Five fish species: *C. gariepinus, C. virginalis, Ctenopharynx intermedius, Mylochromis melanotaenia,* and *Synodontis njassae* were found in fishing sites 1 and 3 while only 3 fish species: *Buccochromis rhoadesii, Protomelas similis,* and *Stigmatochromis woodi* were only found in fishing sites 2 and 3 (Table 2-2).

Fish species composition declined in June (Table 2-3). Fishing sites 1, 2, and 3 recorded only 11, 13, and 7 fish species respectively (Table 2-3). *Hemitilapia oxyrhynchus* and *P. suboccularis* were the only two species found in all three fishing sites. *Buccochromis lepturus, C. virginalis, M. melanotaenia, P. triaenodon, P. kirkii,* and *T. placodon* which accounted for over 50 percent of fish species found in fishing site 1 were not found in sites 2 and 3. Similarly, *B. nototaenia, C. chrysonotus, Dimidiochromis kiwinge, Fossorochromis rostratus, Hemitaeniochromis spilopterus, O. auromarginatus,* and *P. elegans* which accounted for over 50 percent of species found in fishing site 2 were found in sites 1 and 3 (Table 2-3). *L. parvidens and Pseudotropheus livingstonii* were the only two fish species found in sites 1 and 2 and not in site 3, while *S. woodi* was only found in fishing sites 1 and 3. *O. argyrosoma,* and *Rhamphochromis* (*long fin yellow*) were the two fish species only found in site 3 and absent in sites 1 and 3 in June (Table 2-3). Fish species declined to the lowest numbers in August (Table 2-4). The composition at fishing sites 1, 2, and 3 was comprised of 7, 12, and 8 fish species respectively. *C. crysonotus, C. virginalis, Ctenopharynx intermedius, L. lethrinus, O. auromarginatus,* and *T placodon* were common in all fishing sites (1, 2, and 3) whilst *H. urotaenia, L. parvidens, O. argyrosoma, R. ferox,* and *S. woodi* were only found in site 2 and absent in fishing sites 1 and 3. On the other hand *Bathyclarias species* found at fishing site 1 was not found in sites 2 and 3, likewise *B. nototaenia* and *P. suboccularis* found in site 3 were not found in sites 1 and 2 (Table 2-4).

Overall, fish community composition (Tables 2-1 to 2-4) fluctuated over the sampling period. Some fish species were represented by few individuals whilst others had ≥ 5 individuals per site or month. The highest number of individual fish was recorded in

fishing site 2 throughout the study and the lowest individual numbers in site 1 (see Tables 2-1 to 24). On the other hand fishing site 3 had relatively higher fish numbers than fishing site 1, except in April when both sites had 42 fish each (Table 2-3). The total number of fish species in site 2 in February was mostly contributed by *C. chrysonotus, C. intermedius, L. lethrinus, O. argyrosoma, P. elegans,* and *T. placodon* represented by ≥5 individuals. *C. chrysonotus* was the only species amounting to ≥5 individuals in site 1 and 3 (Table 2-1, February 2012). In April (Table 2-2), the number individuals contributing with ≥5 fish was higher in site 2 than sites 1 with similar number of species but different in composition. Only *P. suboccularis* and *T. placodon* contributed with ≥5 individuals in site 1 while there were 9 species contributing with ≥5 species in site 2 on which *C. chrysonotus, O. auromarginatus,* and *O. argyrosoma* contributed with over 10 individuals in fishing site 2 (Table 2-2). It is important to mention that the number of species doesn't necessarily mean more individuals per species, e.g. site 3 had almost half of fish species found in site 1 (Table 2-2), but each had 42 individuals. Table 2-3 shows 11 and 7 fish species in sites 1 and 3 respectively indicating relatively more species in site 1, but the individuals found in site 3 outnumbers those in site 1.

June and August recorded low individual numbers (Tables 2-3 and 2-4). *C. chrysonotus, C. pleurostigma, L. lethrinus, O. auromarginatus, P. livingstonii* were represented with ≥5 individuals in site 2 (Table 2-3) while site 3 was only represented by *C. chrysonotus* and *O. argyrosoma* with ≥5 individuals. None of the 11 fish species found in site 1 accounted to ≥5 individuals (Table 2-3). Similarly, none of the 7 fish species found in site 1 in August had ≥5 individuals (Table 2-4). The presence of ≥5 individuals

reduced in sites 2 and 3, *C. chrysonotus* and *O. argyrosoma* are the only species with ≥5 individuals in site 2 while only *C. chrysonotus* had ≥5 individuals in site 3 (Table 2-4).

Table 2- 1 Fish species and numbers in parentheses caught in February 2012.

Site 1	Site 2	Site 3
Bagrus meridionalis(1)	*Copadichromis chrysonotus*(52)[+]	*Copadichromis chrysonotus*(16)[+]
Copadichromis chrysonotus(5)[+]	*Caprichromis orthognathus*(2)	*Copadichromis virginalis*(1)[*]
Copadichromis quadrimaculatus(2)	*Corematodus taeniatus*(1)	*Ctenopharynx intermedius*(7)[#]
Copadichromis virginalis(2)[*]	*Ctenopharynx intermedius*(16)[#]	*Lethrinops lethrinus*(1)[+]
Lethrinops lethrinus(1)[+]	*Lethrinops lethrinus*(10)[+]	*Nyasachromis argyrosoma*(2)
Mylochromis anaphyrmus(2)	*Otopharynx auromarginatus*(6)	*Placidochromis subocculari*s(1)
Oreochromis karongae (1)	*Otopharynx sp*(1)	*Stigmatochromis guttatus*(1)[*]
Placidochromis platyrhynchos(2)	*Pseudotropheus elegans*(7)	
Stigmatochromis guttatus(1)[*]	*Protomelas similis*(2)	
Trematocranus placodon(1)[x]	*Trematocranus microstoma*(1)	
	Trematocranus placodon(6)[x]	
No. of species 10(18)	No. of species 11(104)	No. of species 7(29)

[+]Fish species found in fishing sites 1, 2, and 3; *Fish species found only in fishing sites 1 and 3
[x]Fish species found only in fishing sites 1 and 2; [#]Fish species found only in sites 2 and 3.

Table 2- 2 Fish species and numbers in parentheses caught in April 2012.

Site 1	Site 2	Sites 3
Bathyclarias species(1)	*Buccochromis rhoadesii*(1)[#]	*Buccochromis rhoadesii*(1)[#]
Chilotilapia rhoadesii(1)	*Caprichromis liemi*(1)	*Clarias gariepinus*(1)*
Clarias gariepinus(1)*	*Copadichromis chrysonotus*(27)	*Copadichromis virginalis*(6)*
Copadichromis pleurostigma(2)	*Copadichromis quadrimaculatus*(4)	*Ctenopharynx intermedius*(5)*
Copadichromis virginalis(1)*	*Dimidiochromis kiwinge*(5)	*Lethrinops lethrinus*(10)[+]
Ctenopharynx intermedius(4)*	*Fossorochromis rostratus*(6)	*Mylochromis melanotaenia*(2)*
Lethrinops parvidens(2)[x]	*Hemitaeniochromis spilopterus*(4)	*Otopharynx argyrosoma*(10)[+]
Labeo mesops(1)	*Hemitilapia oxyrhynchus*(6)	*Pseodotropheus livingstonii*(1)[+]
Lethrinops lethrinus(4)[+]	*L. cf. parvidens*(6)	*Protomelas similis*(1)[#]
Lethrinops oliveri(1)	*Lethrinops parvidens*(1)[x]	*Placidochromis suboccularis*(1)[+]
Mylochromis anaphyrmus(1)	*Lethrinops lethrinus*(3)[+]	*Stigmatochromis woodi*(1)[#]
Mylochromis melanotaenia(1)*	*Oreochromis karongae*(1)[x]	*Synodontis njassae*(1)[*]
Oreochromis karongae(1)[x]	*Oreochromis squamipinnis*(1)[x]	*Trematocranus placodon*(2)[+]
Oreochromis squamipinnis(1)[x]	*Otopharynx auromarginatus*(14)	
Otopharynx argyrosoma(2)[+]	*Otopharynx argyrosoma*(14)[+]	
Otopharynx speciosus(1)	*Pseodotropheus livingstonii*(3)[+]	
Pseodotropheus livingstonii(1)[+]	*Protomelas similis*(7)[#]	
Placidochromis suboccularis(6)[+]	*Placidochromis suboccularis*(4)[+]	
Protomelas kirkii(1)	*Stigmatochromis woodi*(4)[#]	
Rhamphochromis esox(1)	*Tramitichromis lituris*(1)	
Synodontis njassae(1)[*]	*Taeniolethrinops praeorbitalis*(1)[x]	
Taeniolethrinops praeorbitalis(2)[x]	*Trematocranus microstoma*(4)	
Trematocranus placodon(5)[+]	*Trematocranus placodon*(5)[+]	
No. of species 23(42)	No. of species 23 (123)	No. of species 13(42)

[+]Fish species found in fishing sites 1, 2, and 3; *Fish species found only in fishing sites 1 and 3
[x]Fish species found only in fishing sites 1 and 2; [#]Fish species found only in sites 2 and 3.

Table 2- 3 Fish species and numbers in parentheses caught in June 2012.

Site 1	Site 2	Site 3
Buccochromis lepturus(2)	*Buccochromis nototaenia*(4)	*Copadichromis chrysonotus*(15)[#]
Copadichromis virginalis(1)	*Copadichromis chrysonotus*(17)[#]	*Hemitilapia oxyrhynchus*(1)[+]
Hemitilapia oxyrhynchus(2)[+]	*Copadichromis pleurostigma*(5)	*Lethrinops lethrinus*(3)[#]
Lethrinops parvidens(3)[x]	*Dimidiochromis kiwinge*(2)	*Otopharynx argyrosoma*(14)
Mylochromis melanotaenia(2)	*Fossorochromis rostratus*(3)	*Placidochromis suboccularis*(3)[+]
Pseodotropheus livingstonii(2)[x]	*Hemitaeniochromis spilopterus*(2)	*Rhamphochromis(long fin yellow)* (1)
Protomelas triaenodon(1)	*Hemitilapia oxyrhynchus*(4)[+]	*Stigmatochromis woodi*(2)[*]
Placidochromis suboccularis(4)[+]	*Lethrinops parvidens*(2)[x]	
Protomelas kirkii(1)	*Lethrinops lethrinus*(8)[#]	
Stigmatochromis woodi(1)[*]	*Otopharynx auromarginatus*(5)	
Trematocranus placodon(2)	*Pseudotropheus elegans*(1)	
	Pseodotropheus livingstonii(5)[x]	
	Placidochromis suboccularis(2)[+]	
No. of species 11(21)	No. of species 13(60)	No. of species 7(39)

[+]Fish species found in fishing sites 1, 2, and 3; *Fish species found only in fishing sites 1 and 3
[x]Fish species found only in fishing sites 1 and 2; [#]Fish species found only in sites 2 and 3

Table 2- 4 Fish species and numbers caught in parentheses in August 2012.

Site 1	**Site 2**	**Site 3**
Bathyclarias species(1)	*Copadichromis chrysonotus*(65)$^{+}$	*Buccochromis nototaenia*(1)
Copadichromis chrysonotus(2)$^{+}$	*Copadichromis virginalis*(1)$^{+}$	*Copadichromis chrysonotus*(35)$^{+}$
Copadichromis virginalis(2)$^{+}$	*Ctenopharynx intermedius*(1)$^{+}$	*Copadichromis virginalis*(1)$^{+}$
Ctenopharynx intermedius(1)$^{+}$	*Hemitaeniochromis Urotaenia*(2)	*Ctenopharynx intermedius*(2)$^{+}$
Lethrinops lethrinus(3)$^{+}$	*Lethrinops parvidens*(1)	*Lethrinops lethrinus*(2)$^{+}$
Otopharynx auromarginatus(2)$^{+}$	*Lethrinops lethrinus*(4)$^{+}$	*Otopharynx auromarginatus*(2)$^{+}$
Trematocranus placodon(2)$^{+}$	*Otopharynx auromarginatus*(3)$^{+}$	*Placidochromis subocculari*s(2)
	Otopharynx argyrosoma(8)	*Trematocranus placodon*(1)$^{+}$
	*Placidochromis subocculari*s(2)	
	Rhamphochromis ferox(1)	
	Stigmatochromis woodi(1)	
	Trematocranus placodon(2)$^{+}$	
No. of species 7(13)	No. of species 12(91)	No. of species 8(46)

$^{+}$Fish species found in fishing sites 1, 2, and 3; *Fish species found only in fishing sites 1 and 3
^{x}Fish species found only in fishing sites 1 and 2; $^{\#}$Fish species found only in sites 2 and 3

2.3.1 *Changes in fish community structure*

Visual inspection of the dendrogram plot (Figure 2-2) for the whole fish community composition (fish abundance) shows scattering of fish species from sites 1 and 3 to margins of the dendrogram with a tendency for fish communities from site 2 to occur near the center of the dendrogram. The MDS plot (Figure 2-3) shows a clear visualization of grouping near the center of fish species from site 2 and scattering of species from sites 1 and 3 in the upper and lower left and right sides in the two dimensional presentation. Scattering and grouping indicate a degree of difference in fish community at the fishing sites.

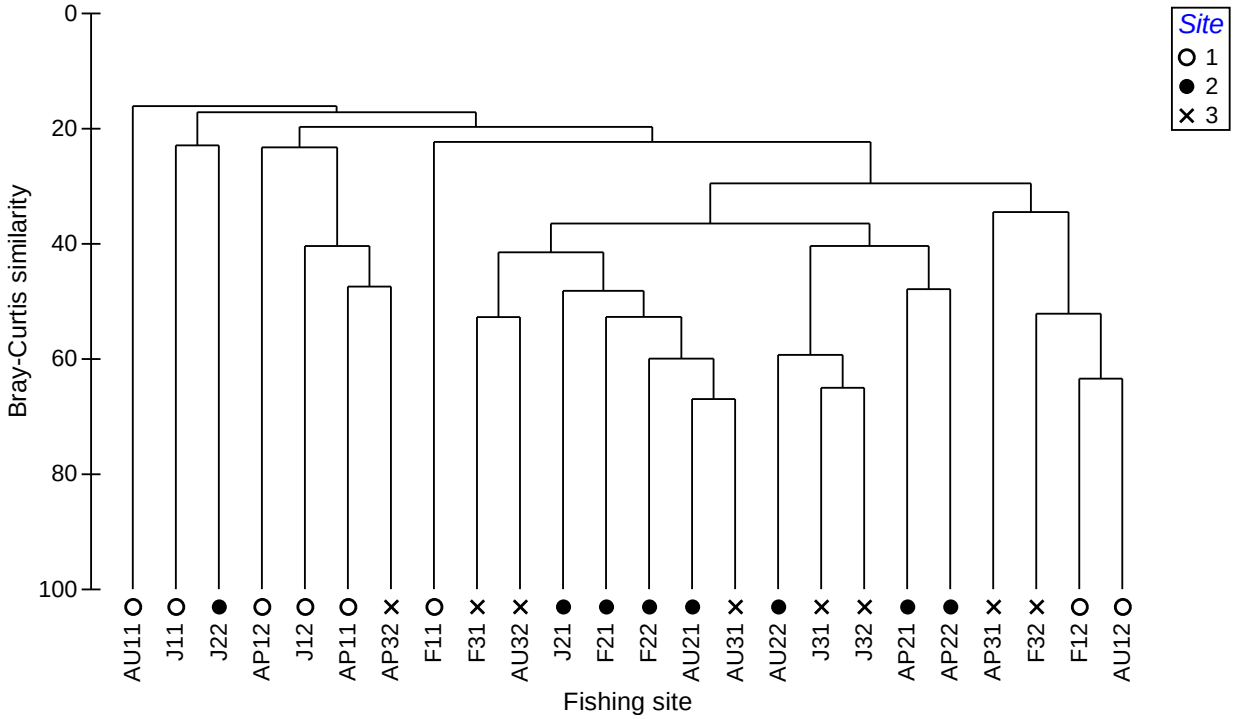

Figure 2-2 Dendrogram of similarity of sampling site replicates based on square root transformation of abundance of fish species using Bray-Curtis similarity index.

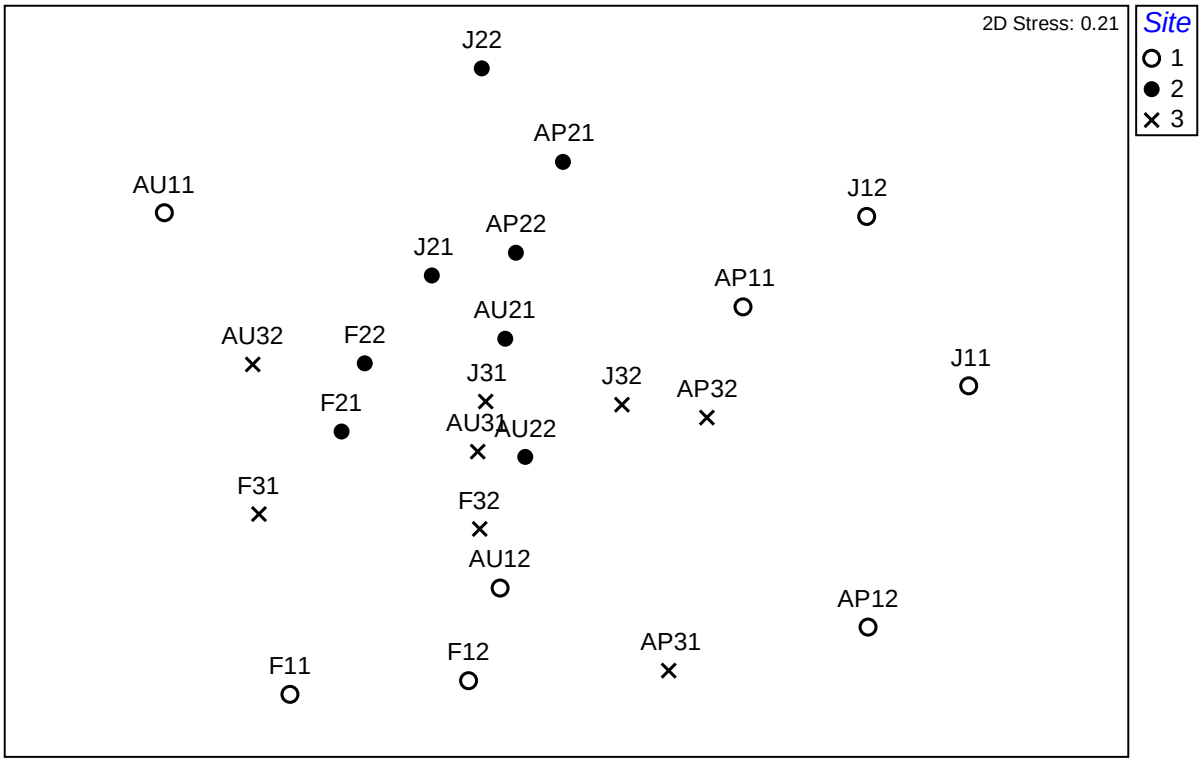

Figure 2-3 Non-metric multi-dimensional scaling (NMDS) plot of spatial and temporal and distribution of fish community structure. Symbols represent sites, open circles represent site 1, black circles represent site 2, and the x represent site 3.

The ANOSIM test confirms the graphical results of the dendrogram (Figure 2-2) and MDS plot (Figure 2-3). There was a significant spatial difference in fish community composition (Global R = 0.472, p=0.005). Pairwise test detected significant differences between fishing sites 1 and 2 (R=0.563, p=0.03) and between fishing sites 2 and 3 (R=0.563, p=0.04). No significant difference was observed between sites fishing 1 and 3 (R=0.250, p=0.22). Significant temporal differences in fish community structure were also detected (Global test R=0.472, p=0.004). Pairwise tests reveals significant temporal

difference of fish community structure between (February and April, R=0.917, *p*=0.037), (February and June, R=0.667, *p*=0.037), and between (June and August, R=0.583, *p*=0.037). There was no temporal significant difference of fish community structure between (February and August, R=-0.167, *p*=0.667), and (April and June, R=167, *p*=0.37), and between (April and August, R=0.417, *p*=0.148). The list of fish species responsible for both spatial and temporal dissimilarity is presented in Tables 2-5 to 2-9. Table 2-5 shows eight fish species (*C. chrysonotus, O. auromarginatus, C. intermedius, L. lethrinus, O. argyrosoma, T. placodon, P. suboccularis,* and *C. virginalis*) representing 50% of commutative contribution of species dissimilarity between sites 1 and 2. The dissimilarity between sites 2 and 3 is made of seven fish species, the same species that contributed to dissimilarity between sites 1 and 2 with exception of *C. virginalis.*

The cumulative contribution species dissimilarity between February and April was made by nine species (see Table 2-7). While *S. njassae* added the number of already known species contributing to dissimilarity (Table 2-7), *H. oxyrhynchus* and *L. parvidens* also added the number of species contributing to community dissimilarity between February and June (Table 2-8) to already known species. Table 2-9 shows seven fish species contributing to species dissimilarity between June and August. These species are similar to those contributing to species dissimilarity in other months; however, *S. woodi* is contributing to community dissimilarity for the first time. Overall, many species contributed to a certain degree for spatial and temporal dissimilarity. *C. chrysonotus, C. intermedius, L. lethrinus, O. argyrosoma, T. placodon,* and *P. suboccularis* are the six fish species that contributed to both spatial and temporal dissimilarity. *C. chrysonotus* accounted for the highest number of individuals whilst the numbers of other species

fluctuated in space and time, though it was generally relatively higher than the species that didn't contribute to dissimilarly.

Table 2-5 SIMPER analysis for fish community structure between fishing sites 1 and 2, with dissimilarity cut-off set at 50% cumulative contribution. Mean abundance (square rooted data) expressed as individuals per site.

Species	**Mean abundance**		**Contribution[a]**	**Cumulative %**
	Site 1	**Site 2**	**δ_i**	**contribution $\sum\delta_i$ %**
Copadichromis chrysonotus	0.57	4.29	1.82	19.16
Otopharynx auromarginatus	0.18	1.57	1.52	26.41
Ctenopharynx intermedius	0.48	0.83	0.92	31.90
Lethrinops lethrinus	0.68	1.53	0.98	37.22
Otopharynx argyrosoma	0.18	1.14	0.75	41.88
Trematocranus placodon	0.76	0.88	1.11	46.39
Placidochromis suboccularis	0.75	0.73	0.96	49.64
Copadichromis virginalis	0.60	0.13	0.94	52.85

[a]Ranked contribution of each species to overall average dissimilarity (δ= 78.40) between sites 1 and 2.

Table 2- 6 SIMPER analysis for fish community structure between fishing sites 2 and 3, with dissimilarity cut-off set at 50% cumulative contribution. Abundance (square rooted data) expressed as individuals per site.

Species	**Mean abundance**		**Contribution[a]**	**Cumulative %**
	Site 2	**Site 3**	**δ_i**	**contribution**
				$\sum\delta_i$ %
Copadichromis chrysonotus	4.29	2.38	1.63	11.33
Otopharynx auromarginatus	1.57	0.18	1.53	20.21
Otopharynx argyrosoma	1.14	1.14	0.98	28.30
Lethrinops lethrinus	1.53	1.15	1.61	35.64
Trematocranus placodon	0.88	0.30	1.02	40.61
Placidochromis suboccularis	0.73	0.73	0.99	45.43
Ctenopharynx intermedius	0.83	0.79	0.75	50.12

[a]Ranked contribution of each species to overall average dissimilarity (δ= 63.53) between sites 2 and 3.

Table 2- 7 SIMPER analysis for fish community structure between February and April, with dissimilarity cut-off set at 50% cumulative contribution. Abundance (square rooted data) expressed as individuals per site.

Species	**Mean abundance**		**Contribution[a]**	**Cumulative %**
	February	**April**	**δ_i**	**contribution**
				$\sum\delta_i$ %
Copadichromis chrysonotus	3.12	1.21	1.34	11.13
Ctenopharynx intermedius	1.38	0.84	1.40	19.62
Otopharynx argyrosoma	0.00	1.82	1.64	27.94
Lethrinops lethrinus	1.04	1.47	1.24	34.33
Placidochromis suboccularis	0.17	1.21	1.13	40.30
Trematocranus placodon	0.74	0.98	1.12	44.66
Copadichromis virginalis	0.00	0.74	0.86	49.00
Synodontis njassae	0.00	0.33	0.66	51.57

[a]Ranked contribution of each species to overall average dissimilarity (δ= 78.52) between February and April 2012.

Table 2- 8 SIMPER analysis for fish community structure between February and June, with dissimilarity cut-off set at 50% cumulative contribution. Abundance (square rooted data) expressed as individuals per site.

Species	**Mean abundance**		**Contribution[a]**	**Cumulative %**
	February	**June**	**δ_i**	**contribution $\sum\delta_i$ %**
Copadichromis chrysonotus	3.12	1.82	2.31	9.74
Ctenopharynx intermedius	1.38	0.00	0.87	17.35
Placidochromis suboccularis	0.17	1.09	1.26	24.33
Otopharynx argyrosoma	0.00	0.81	0.61	30.99
Lethrinops lethrinus	1.04	0.87	1.20	36.52
Hemitilapia oxyrhynchus	0.00	0.74	0.91	41.26
Lethrinops parvidens	0.00	0.64	0.87	45.74
Trematocranus placodon	0.74	0.24	0.97	50.18

[a]Ranked contribution of each species to overall average dissimilarity (δ= 73.95) between February and June 2012.

Table 2- 9 SIMPER analysis for fish community structure between June and August, with dissimilarity cut-off set at 50% cumulative contribution. Abundance (square rooted data) expressed as individuals per site.

Species	**Mean abundance**		**Contribution[a]**	**Cumulative %**
	June	**August**	**δ_i**	**contribution $\sum\delta_i$ %**
Copadichromis chrysonotus	1.82	3.50	1.52	10.42
Otopharynx argyrosoma	0.81	0.64	0.95	19.90
Lethrinops lethrinus	0.87	1.09	1.70	28.58
Placidochromis suboccularis	1.09	0.47	1.20	36.67
Otopharynx auromarginatus	0.52	0.76	0.91	43.10
Lethrinops parvidens	0.64	0.17	0.88	48.42
Stigmatochromis woodi	0.50	0.17	1.20	53.67

[a]Ranked contribution of each species to overall average dissimilarity (δ= 72.55) between June and August 2012.

2.3.2 *Fish abundance, biomass, and diversity indices*

The average number of fish species and the biomass was not significantly different at three sampling sites (Table 2-10) (Figures 2-4a and 2-4b), but the average abundance (number of fish per site) was significantly different at fishing sites (Table 2-10). Site 2 had had significantly higher abundance than site 1 and 3 (p=<0.05) (Figure 2-4c). There was no significant differences in the number of fish between sites 1 and 3 (p>0.05).

Table 2-10 One-Way ANOVA of fish abundance, biomass, number of fish species, diversity indices, and W-statistic bvalues at fishing sites.

Parameter	**F value**	***p-value***	**Pairwise test**
Abundance	18.701	0.001	1x2, 1x3
Biomass	2.106	0.147	Not significant
Number of fish species	3.037	0.069	Not significant
Margalef diversity index	2.802	0.083	Not significant
Evenness diversity index	7.080	0.004	1x2, 1x3
Shannon diversity index	3.424	0.052	Not significant
Simpson diversity index	6.459	0.007	1x3
W-statistics	8.427	0.002	1x2, 1x3

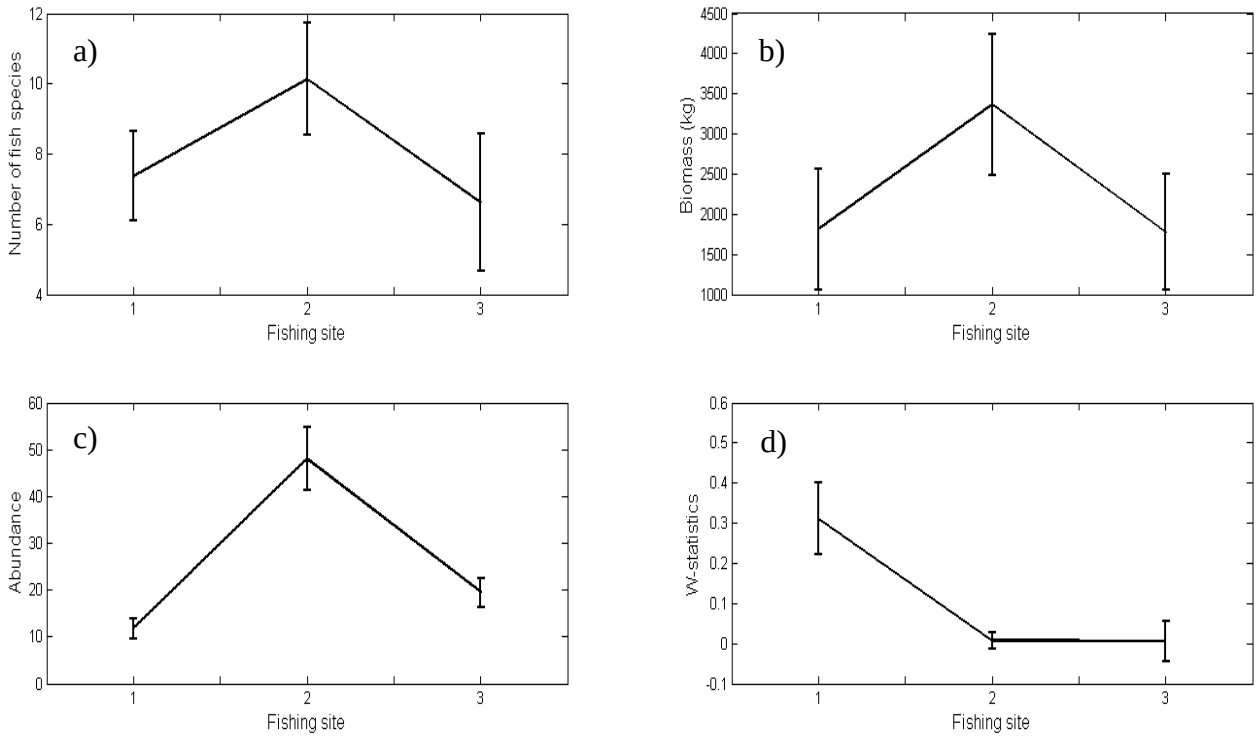

Figure 2-4 a) Average number of fish species, b) average fish biomass, c) average fish abundance, d) and average W-statistics value recorded at fishing sites 1, 2, and 3 in February, April, June, and August 2012.

2.3.3 *Health status of fishing sites*

The health status of fishing sites attested by abundance/biomass comparison generated average positive and negative W-statistic values used to classify whether a site is undisturbed or disturbed. The fishing sites had significantly different W-statistic values (Table 2-10) (Figure 2-4c). Fishing site 1 had significantly higher W-statistic value than fishing sites 2 and 3 ($p<0.05$) and was classed as undisturbed as revealed by dominance of biomass curves over abundance curves over the sampling period (Figure 2-5, F1, AP1, J1, and AU1). Fishing sites 2 and 3 had similar low W-statistic values of 0.007±0.070 and 0.006±0.129 respectively and were classed as moderately to grossly disturbed sites.

The biomass and abundance curves in sites 2 and 3 were closely coincident and crossed each other, at least once when the sites were moderately disturbed and when the sites were grossly disturbed the abundance dominated over biomass curve and sometimes overlapped (Figure 2-5). Fishing site 2 exhibited moderate disturbance in February (Figure 2-5, F2), April (Figure 2-5, AP2), and June (Figure 2-5, J2) and gross disturbance in August (Figure 2-5, AU2). Fishing site 3 exhibited moderate disturbance in February (Figure 2-5, F3) and April (Figure 2-5, AP3) and gross disturbance in June (Figure 2-5, J3) and August (Figure 2-5, AU3).

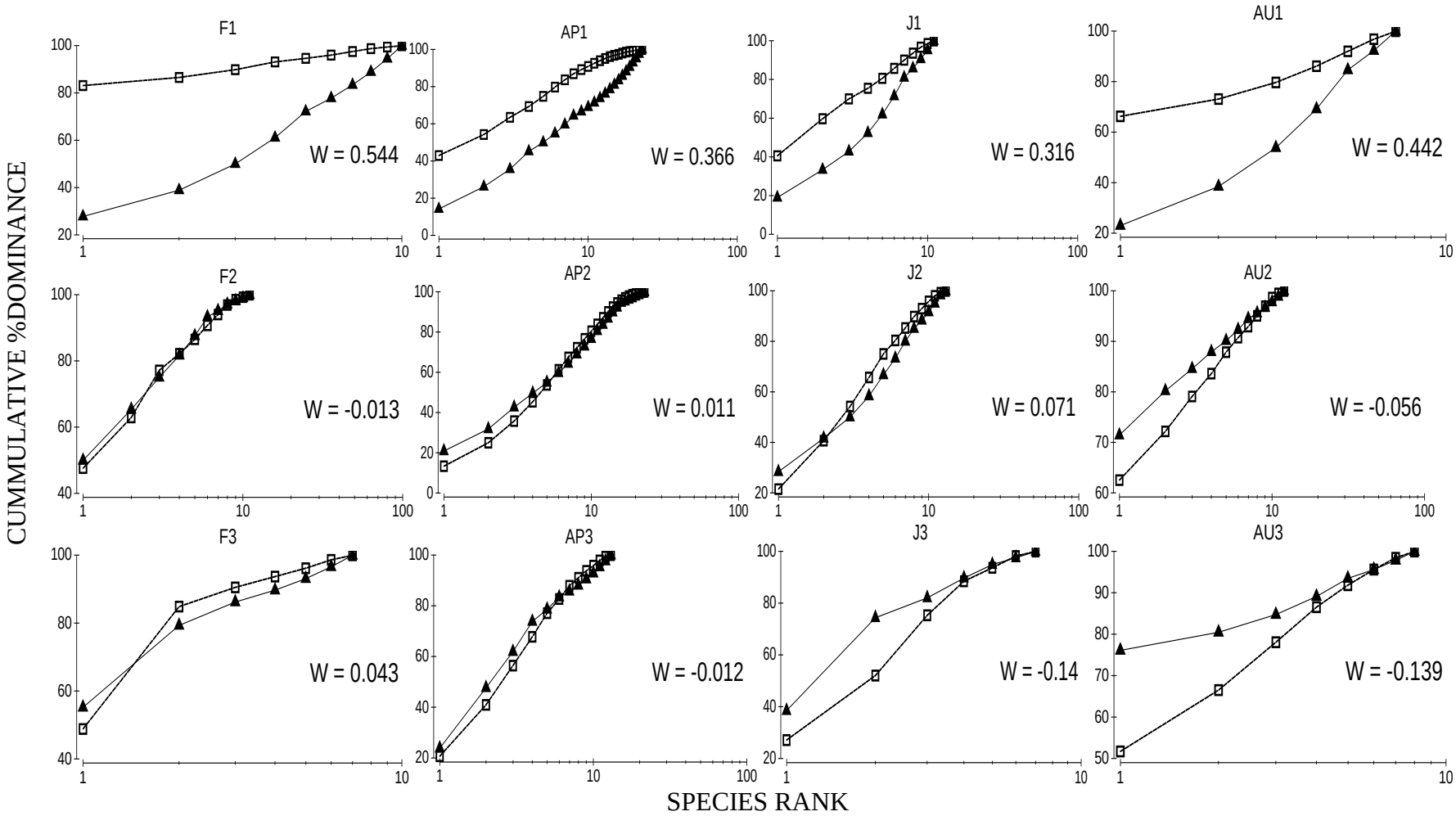

Figure 2- 5 Abundance Biomass Curves (ABC) curves for fish community in Lake Malawi. Abundance (▲) and biomass (□).

2.3.4 *Diversity indices*

The three fishing sites had significantly different Pielou's Evenness and Simpson diversity indices (Table 2-10). Fishing site 1 had significant higher Pielou's Evenness diversity index than sites 2 and 3 ($p<0.05$) (Figure 2-6a), but the difference was not significant between fishing sites 2 and 3 ($p>0.05$). Fishing site 1 had higher Simpson diversity index than site 3 ($p<0.05$) (Figure 2-6b). There was no significant difference in Simpson diversity indices between fishing sites 1 and 2 ($p>0.05$) and between fishing sites 2 and 3 ($p>0.05$) (Figure 2-7). No significant difference was noted in Shannon and Margalef diversity indices among the fishing sites (Table 2-10) (Figure 2-6c and 2-6d).

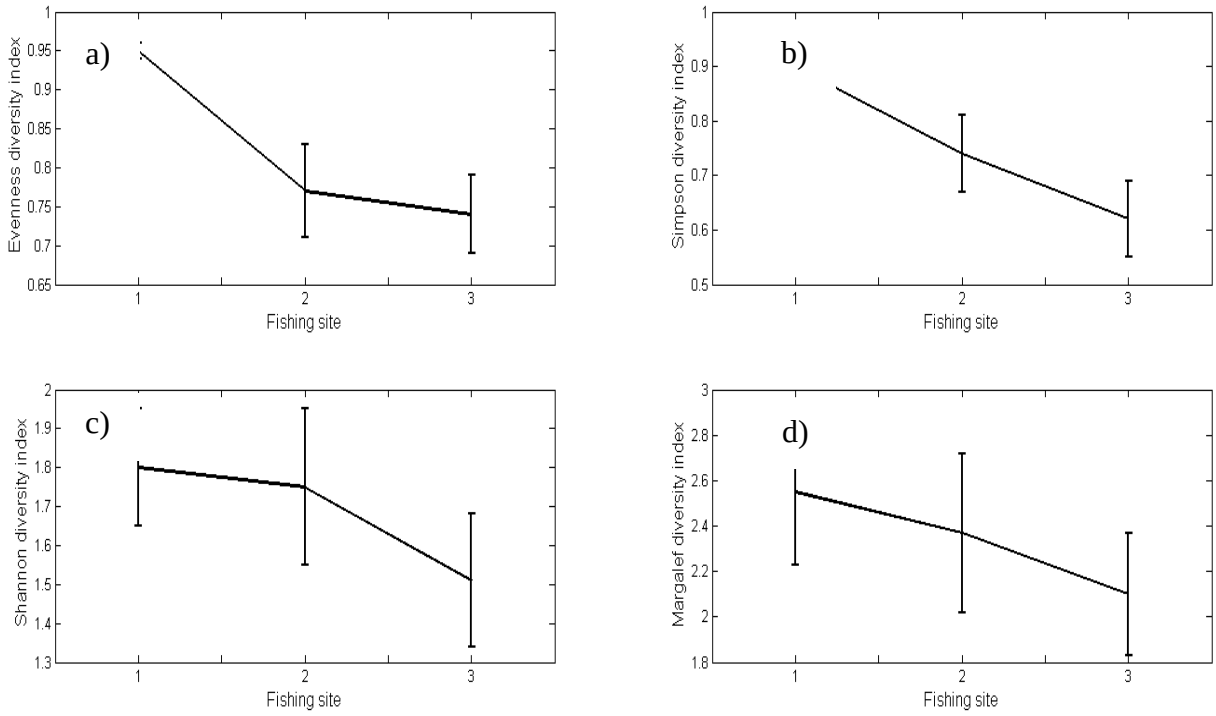

Figure 2-6 a) Average Pielou's Evenness diversity index, b) average Simpson diversity index, c) average Shannon diversity index, and d) average Margalef diversity index from fish samplings at fishing sites 1, 2, and 3 in February, April, June, and August 2012.

2.5 Discussion

The total number of fish species reported in the current study (51) is the aggregate number of all species caught in sites 1, 2, and 3 and sampled more than once, e.g. in February, April, June, and August 2012; such sampling strategy provides valuable data to be used for better recommendations towards sustainable use of the lake for cage farming and conservation of local fishery (Winston and Angermeier, 1995). The numbers of fish species were variable at the site level. Fish species were either found in all sites in a specific month or just found in one site and not in other sites. In some cases, species found in one replicate were not found in another replicate in the same site. The fact that there was no significant differences in the number of fish species in fishing sites 1, 2, and 3 (p=0.069), does not necessarily suggest similar fish communities in these sites, or even similar abundance. Fishing site 2 had significantly higher fish abundance compared to fishing sites 1 and 3 (p<0.05) suggesting that wild fish communities have an advantage by staying at the cage farm. Although it is not fully understood what attracts them to site 2 (located at the cage farm), the attraction of wild fish communities to the cage farm causes significant differences in fish abundance (see Figure 2-4c) which is the major concern for artisanal fishermen at SEA since their sales are made by the number of fish.

The remote fishing sites had lower fish abundance compared to fishing site 2 at the cage farm (Figure 2-4c). This effect seems responsible for significantly different fish communities between fishing sites 2 and 1 (R=0.563, p=0.025) and between fishing sites 2 and 3 (R=0.563, p=0.037). The fish community structure at fishing sites 1 and 3 located 10 km apart was not significantly different (R=0.250, p=0.222) suggesting that the cage aquaculture farm has a strong effect on fish communities in nearby areas and less or no

effect on ones far from it. Although the study didn't find any statistical evidence of biomass differences among the three sites probably due to high variability of fish weight and number of species (Figure 2-4b) characterized by few numbers of large bodied species such as *B. meridionalis* and *B. species* found at site 1but never seen in sites 2 and 3 where of small bodied species such as *C. chrysonotus, L. lethrinus,* and *O. auromarginatus* (Tables 2-1 to 2-4) predominated. The results support the complaints from local fishermen that wild fish community take refuge at the farm, leading to significantly higher numbers of fish beneath and around the farm than in remote fishing sites 1 and 3. It is then likely true those wild fish communities close to the cage farm gain benefits that are not available to those ones far away from it. It is easy to see different fish species with the unaided eye at the farm, especially during the period when the caged fish are being fed. The excess food and fish wastes emanating from cage farms are known to attract wild fish populations (Beveridge, 1984) allowing easy access to food resources and possibly protection from predators (Dempster et al., 2002; Sudirman et al., 2009).

The number of wild fish populations have been reported to increase in cage aquaculture farms as the number of cages increase (Dempster et al., 2002; Dempster, 2004; Tuya et al., 2006), especially during the feeding time of captive fish (Tuya et al., 2006), which confirms our field observations. There were more wild fish around the farm in 2010 when the farm had more cages stocked than in 2012 when the farm had few stocked fish. Elsewhere, wild fish populations have been reported to consume 27% of the lost pallets (Sudirman et al., 2009). The percentage of consumed pellets may even be higher at Maldeco Aquaculture Limited farm since the farm uses sinking pellets but the impact of feed pellets depends on currents which may sweep them away from the feeding

site. Dependence on artificial feeds emanating from the cages instead of consumption of natural diets may change the feeding behavior of wild fish populations and may lead to a change in the body composition and condition of fish (Skog et al., 2003; Fernandez-Jover et al., 2007). While our field study cannot provide conclusive results about the behavior of wild fish populations in regard to changes in feeding behavior, it suggests that wild fish populations stay long enough at the farm to the extent of following the boat during the feeding period, a behavior expressed by captive fish when they hear the noise of engine boats when the feeding crew staff approach the farm during feeding period.

While fish species and the of individuals provide the species richness, evenness and diversity indices used by ecologists to describe or characterize sites, the health status of such sites whether disturbed or not cannot be fully described by these parameters. The abundance-biomass comparison method can indicate the level of pollution or disturbance of a particular site (Clarke and Warwick, 2001). The result obtained in the current study is consistent with the expected results, from what is known of the sites, which indicate a moderate disturbance of fishing site 2 and no disturbance in fishing site 1. Fishing site 1 was comprised of large bodied species and fishing site 2 was comprised by high numbers of small bodied fish species (Tables 2-1 to 2-4). The high levels of disturbance detected in site 3 classed as grossly disturbed is the result of excessive overfishing in this site. Illegal (non-selective) seine nets, locally known as “kandwindwe” prohibited by the Government of Malawi are actively used in this area by local fishermen who do not obey fisheries laws. The disturbance detected at fishing site 2 is mainly attributed to attraction of small bodied fish species by the cages/farm resources (uneaten feeds, feces, shelter).

The patterns of variations in number of fish species (richness) and their even or equal distribution (evenness) at fishing sites 1, 2, and 3 showed significant difference in average Pielou's Evenness and Simpson diversity indices which classed fishing site 1 as more species diverse than fishing sites 2 and 3. These results are supported by abundance rank (Figure 2-7) observations which show the high degree of evenness at fishing site 1 compared with fishing sites 2 and 3 which had high incidence of *C. chrysonotus* (Table 2-10); therefore, fishing site 1 had higher Pielou's evenness diversity index and fishing sites 2 and 3 have low evenness; consequently high Simpson diversity index which accounts for both richness and evenness classed fishing site 1 as more diverse than fishing sites 2 and 3. On the other hand, Shannon and Margalef diversity indices which is less affected by a single species dominance showed no significant difference in species diversity among the fishing sites (Figures 2-6c and 2-6d), suggesting that the cage aquaculture farm and high fishing pressure have not yet affected fish diversity. Previous studies in south east arm (SEA) of Lake Malawi (Tweddle and Turner, 1977; Banda et al., 1996; Weyl et al., 2010) observed that overexploitation and increasing fishing pressure have depleted the larger commercial fish species, changed species composition of catches, and caused local extirpations, consequently, the contribution of fish declined to less than 30% of the total animal protein supply, and per capita fish consumption dropped from 14 kg in mid-1970 to below 3 kg in 2003 (Banda et al., 2005). Wely et al., further recommended no addition of pair-trawl effort in SEA, effort elimination in Area "A" in the SEA, and artisanal and pair-trawl fisheries should be managed similarly. Fish diversity of SEA is already affected, but comparisons made on the three fishing sites suggests no effect on

fish diversity at these inshore locations, however, the major concern is the incidence of small bodied fish populations which are unevenly distributed among these fishing sites.

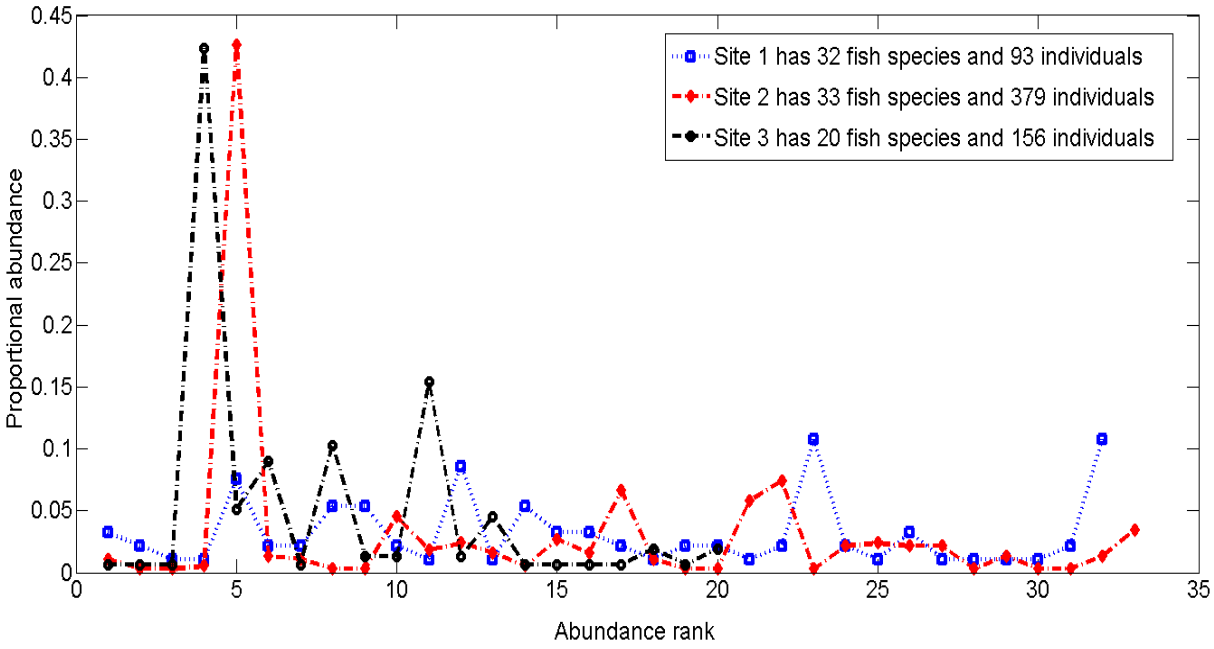

Figure 2-7 Abundance-rank of fish communities recorded at fishing sites 1, 2, and 3 in February, April, June, and August 2012.

2.4.1 *Implications to fisheries and aquaculture policy*

The abundance of wild fish populations beneath/around the farm not only inspires visitors who see fish swimming as they tour the farm, but it also attracts different species of birds and more importantly attracts local fishermen with little or no alternative livelihood strategies apart from fishing to support their families. Maldeco Aquaculture Limited has been allowing local fishermen to catch fish outside the farm perimeter delineated by large red/orange buoys for many years starting from 2004. However, the

farm has been experiencing fish theft. Cages have been harvested by unknown people thereby affecting the company's operations since the expected harvest tonnage is no longer met. While it is not yet known who steals the fish, local fishermen using canoes and non-motorized plank boats have been seen fishing inside the farm. This brings the suspicion that has resulted in local fishermen being arrested and taken to the police station where they pay arbitrary fees which are not known by the Fisheries Department. Local fishermen on one hand claim that they are harvesting the "Government fish" that are resident or transient at Maldeco farm while Maldeco, on the other hand, claim the ownership of lake space and protects it by not allowing local fishermen to invade their space. Cage farming is relatively new in Malawi and the National Fisheries and Aquaculture Policy (GOM, 2001) does not address in detail the legal framework for cage aquaculture development on Malawi water bodies. The current study provides necessary basic information for the Fisheries Department, private aquaculture industry, and existing agencies to formulate the legal framework for sustainable cage aquaculture farming taking into consideration potential conflicts between local fishermen and the private sector and the impact that cages pose on wild fish populations.

2.5 Conclusion

1. The current study has established that Maldeco Aquaculture farm has a strong near field impact on fish community structure in the SEA of Lake Malawi. The difference at fishing site 2 was primarily due to higher numbers of smaller-bodied species and individuals.
2. The diversity indices evaluated in the current study based on species richness and species abundances from sampled fishing sites provide no evidence of different species diversity in the established fishing sites. The Pielou's Evenness diversity index informs us that fish species composition from fishing site 1 is more evenly distributed than fishing sites 2 and 3 as the Simpson diversity index does. On the other hand, Margalef and Shannon diversity indices give no evidence of differences in fish species diversity. No effect of the cage aquaculture farm or high fishing pressure was detected on fish diversity in the locations studied in the southeast of Lake Malawi.
3. Comparison of the biomass and abundance curves based on species rank indicated that Site 2 was moderately disturbed compared to site 1 which was classed as undisturbed. The undisturbed nature of fishing site 1 to the northwest of site 2 and downstream of the dominant currents from the southeast suggest that the farm has less or no impact on fish communities beyond the immediate farm itself. The moderate disturbance on fishing site 2 may be due to the fact that the farm had few cages stocked during the sampling period suggesting there may be an increased impact in nearby locations when the farm becomes fully stocked with fish.

4. The grossly disturbed status of fishing site 3 is attributed to high fishing activity due to persistent use of illegal, active seine nets locally known as kandwindwe and other gears. These results provide an opportunity to Fisheries Department of Malawi to enforce the fisheries laws that prohibit the use of illegal fish gears in the southeast arm of Lake Malawi.

2.7 Recommendations

At the country scale, cage aquaculture in Malawi is still at its infant stage and the production is very low relative to the demand for fish. While Maladeco Aquaculture Limited is making efforts to increase fish production, there is also an increase in conflict between the fisherman and the farm.

Located in Mangochi, in one of the most densely populated areas of Malawi, Maldeco Aquaculture Limited is subject to local conflicts with local fishermen. A short term plan should include a discussion between local fishermen and cage aquaculture operators to be aware of the different views and interests of the two groups that may lead to conflicts. The importance of the cage aquaculture industry to the overall economy and food security of Malawi should be made clear and supported by everyone including the fishermen, likewise, the fishermen's contribution to the national fish supply should be acknowledged and their protection should be encouraged. The social set up of local fishermen is unique especially in Malawi where livelihood strategies are limited. Complaints from both sites in addition to the results of the current study will form the basis of long term plans for a sustainable aquaculture industry in Malawi.

Long term plans should address proper zoning of cage farms with clear boundaries that prevent fishermen from entering the farms. This decision doesn't help the fishermen, who claim to be following local fish populations, but it is a fair decision that will ensure that the aquaculture industry feels safe in investing in Lake Malawi. However, the sustainability of the cage aquaculture should be achieved through an inclusionary process that involve a diverse range of stakeholders including the fishermen who have been fishing before the establishment of the farm, otherwise conflicts may

persist not only in south east of Lake Malawi but in other potential within Malawi where cage farming promises to be suitable when key stakeholders are disenfranchised from social or economic decision making.

While the previous recommendations are specifically made to ensure sustainability in cage farming which is believed to reduce the pressure on already dwindling capture fisheries stocks and increase fish consumption in Malawi, it should not be forgotten that the wild fish stocks are still under pressure in the south arm of Lake Malawi. The evidence is expressed on site 3 classed as grossly disturbed as a result of overfishing with use of active illegal seine nets suggesting that the attention for fisheries management should be devoted for both sustainable cage farming and exploitation of wild fish populations.

Figure 2-8 Local fishermen fishing inside Maldeco Aquaculture Limited Farm in 2012.

Chapter 3

Temporal and spatial changes in water quality parameters in Lake Malawi/Niassa, Africa: implications for cage aquaculture management

Abstract

Temporal and spatial measurements of water quality: water temperature (WT), Secchi depth (SD), percent dissolved oxygen (%DO), as well as concentrations of dissolved oxygen (DO), total nitrogen (TN), total phosphorous (TP), and chlorophyll *a* (Chl *a*) were made in February, April, June, and August 2012 at three sampling sites distributed along a 10 km south-north transect including a tilapia cage aquaculture farm in the south east arm (SEA) of Lake Malawi. Sites 1 and 3 were located 5 km away from the cage farm at north and south side of the farm respectively. Site 2 was located close to the farm. % DO, DO, Chl *a,* and SD exhibited clear seasonal changes at all three sites. As the WT decreased, % DO and DO decreased as well reaching their minimum values in June. Chl *a* and SD were inversely correlated, with the highest Chl *a* concentrations and lowest Secchi depths occurring in April. WT, %DO, and DO at the northern site were consistently greater than those at the farm and southern site. Secchi depth readings indicated low water clarity at the farm relative to the non-farm sites. Interestingly this pattern was not seen in the Chl *a* suggesting decreased transparency at the farm site was caused by some factor in addition to Chl *a*. TN and TP were high at the farm relative to the non-farm sites during the sampling in February, the stratified season, however during the other times sampled there was no consistent pattern or statistically significant difference between TN and TP at farm and non-farm sites. Dissolved oxygen, Chl *a,* and

TP concentrations are water quality parameters frequently used to assess aquaculture impacts. In this study, none of these water quality indicators were consistently different at the farm compared to non-farm sites suggesting that at the stocking densities present from February 2012 until the end of the study August 2012 the cage activity did not impact these water quality parameters. The minimum DO of 6.0 mg/l observed in June 2012 (the cool, upwelling season) was above the minimum (3.0 mg/l) level for tilapia farms, however, the statistically significant decrease in DO and %DO at all three sites from April to June indicates that it is during this upwelling period that water quality problems could be exacerbated by farm impacts. Therefore, water quality monitoring programs at the cage aquaculture farm should carefully monitor the upwelling period between April and July to avoid potential stress or fish kills induced by sub-optimum WT (less than 24^{o}C), decreased %DO, DO, and reduced water transparency.

3.1 Introduction

Aquaculture continues to be the world's fastest growing animal-food industry and on a global scale contributed about 46 percent of total food fish supplied in 2008 when both capture fisheries and aquaculture produced 142 million tons (FAO, 2010). In 2011, the industry achieved a remarkable milestone when fish production overtook beef; this gap further increased in 2012 when the aquaculture industry produced about 66 million tons compared to 63 million tons from the beef production industry (Larsen and Roney, 2013). Aquaculture is a promising industry which is increasingly developing mass production technologies that are being adopted in many developing countries through donor, government, and private initiatives and therefore, promises to further increase fish production in the future. The cage aquaculture industry is still in its infant stage in Lake Malawi with only one commercial farm, Maldeco Aquaculture Limited leading with tilapia production. Community based cage aquaculture initiatives are being supported by international organizations to empower local communities to produce fish in small cages made locally with netted materials to keep fish during the production cycle.

While aquaculture in general increases fish production, creates employment opportunities, and boosts local economies, concerns are often expressed about possible negative impacts on receiving waters due to accumulation of nutrients linked to primary production of aquatic ecosystems. Håkanson et al. (1988) estimated that about 80% of phosphorous (P) provided in fish feed is lost to the environment in particulate (70%) and dissolved (10%) form, and only 20% of P is used for fish growth and eventual harvest. Similarly for nitrogen (N), only 25% of N in feed is used for fish growth with 75% lost to the environment (Håkanson et al., 1988). Islam (2005) estimated that in one ton (wet

weight) of fish produced about 132.5 kg of nitrogen and 25 kg of phosphorous are released into the environment. Bristow et al. (2008) investigated the effect of a rainbow trout (*Oncorhynchus mykiss*) cage farm in the Experimental Lakes Area in Canada during the first three years of its operation and concluded that the annual input of phosphorous from waste (67-100 kg) exceeded the natural budget inputs (4-18 kg) from atmospheric deposition and inflows to the small study lake. Gondwe et al. (2011a) in an earlier study of the impact of aquaculture in Lake Malawi estimated that carbon losses to the environment range between 81-90% of feed carbon, nitrogen losses between 59-80% and phosphorous losses between 85-92%. Gondwe estimated that the average discharge of 12, 341; 1,303; and 534 kg/year of C, N, and P, from the scale of farm operation at the time (~200 tones fish/year in 2007) had minimal impact to the surrounding environment of this large lake probably due to the advective transport effect that minimized waste sedimentation locally. However, despite minimal detectable impacts in his period of study, Gondwe et al. (2011a) warned that nutrient additions into the lake by the cage industry have the potential to stimulate eutrophication. Strong tidal flows and currents are known to prevent detection of environmental impacts of cage farms by scouring the settled organic materials and nutrients (Alongi et al., 2009). Gondwe et al. (2011b) noted strong bottom water currents that may prevent accumulation or cage effluents at the site.

In poorly flushed areas, the increase in suspended solids derived from fish farms in the form of uneaten feeds and feces, organic and inorganic nutrients mainly nitrogen, phosphorous, and carbon in the water column and sediments (Håkanson et al., 1988) is accompanied by increased lake productivity, a process called cultural eutrophication (Laws, 2000) characterized by overall degradation of water quality status. The effects of

eutrophication include oxygen depletion in the water column (Aure and Stigebrandt, 1990), increased phytoplankton production and blooms (Dillion and Rigler, 1974), the presence of cyanobacteria associated with organic enriched nutrients (Laws, 2000), the presence of sulphur bacteria *Beggiatoa* spp. beneath the cages (Brown et al., 1987), impacts on benthic diversity and communities (Alongi et al., 2009) and dominance of opportunistic polychaetes *Capitella capitata* and *Scolelepis fuliginosa* (Brown et al., 1987) known to be associated with organically polluted areas (Tsutsumi, 1987; Reish, 1972; Bellan, 1979). Impacts from increased nutrients may be severe in oligotrophic lakes such as Lake Malawi where nitrogen, phosphorous, and iron are the main limiting nutrients in Lake Malawi (Guildford et al., 2003). Thus, any addition of these nutrients, especially phosphorous whether from aquaculture operations, agricultural runoffs, or other point or non-point sources will not only increase phytoplankton biomass, but will favor nitrogen fixing bacteria and the presence of potentially toxic phytoplankton species to fish and humans (Guildford et al., 1999).

The impact of aquaculture not only affects the surrounding environment, but its impact is potentially on the farm itself. Many farms do not have water quality monitoring strategic plans. Monitoring of water quality is important not only for the sake of complying with regulations and providing data to regulatory authorities to show that the farm is not having negative impacts in a specific water bodies, but because it is important to the fish being cultured. Fish and other aquatic organisms are dependent on water for all their bodily requirements and functions; therefore, it becomes important to monitor water quality for the success of the farm. A slight change in water quality may affect the fish thereby, creating unnecessary monetary losses to the farm. The current study investigated

possible impacts of aquaculture activities on water quality in Lake Malawi by measuring water quality parameters at the farm and at sites 5 km south and north of the farm. The water quality parameters most associated with poor water quality are dissolved oxygen and chlorophyll *a* and these were the main focus of this study. Other parameters measured that are highly relevant to chlorophyll concentration are algal nutrients nitrogen and phosphorus and Secchi depth, a measure of water transparency which can inform about the amount of light available for algal growth and that can also be highly correlated to chlorophyll concentration. In addition, temperature was measured as it can impact metabolism of all organisms from bacteria to fish and it can determine the strength and duration of stratification in the water column. Any stratification of the water could influence the circulation of oxygen and nutrients. While it is recognized that many aquaculture farms cannot maintain large, expensive water quality monitoring programs, a useful outcome of this study would be to identify a suite of simple inexpensive measurements that could be collected on a regular basis by aquaculture farmers to help prevent deterioration of water quality and importantly to improve farm productivity.

3.2 Materials and methods

3.2.1 *Data collection*

The study was conducted in Lake Malawi, the third largest African Great Lake after lakes Tanganyika and Victoria. The lake is a valuable resource to the people of Malawi, Mozambique and Tanzania. The data set in the current study was collected in the south east arm of Lake Malawi along a 10 km south-north transect at three sites (Figure 3-1) which include the Maldeco cage aquaculture farm. The Maldeco cage aquaculture facility is the focal study area while the southern and northern sites are used as controls. Maldeco Aquaculture, established in 2004 is the only commercial cage operation in Lake Malawi. The Company farms *chambo* species, an aggregate of three endemic cichlids to Lake Malawi (*Oreochromis karongae, O. lidole,* and *O. squamipinnis*). In addition to *chambo*, the Company farms *O. shiranus*, a native cichlid species similar to *chambo*, hence it is sold as *chambo*. Figure 3-1 shows the location of the three sites sampled in this study. The geographical position of the sampling sites including replicates, depth of the water column at each site, distance to the farm, and distance to shore line are shown in Table 3-1. The distance was measured with a line measurement (planar) on ArcMap-version 10.1. Sampling was done in February, April, June, and August 2012 during the day. The three sites were located at approximately 16 m water depth. At each of the three widely separated sites which were also used to study the fish community structure (Chapter Two), *in situ* profiles were made at two closely spaced locations to provide replication of the measurements for each site (Figure 3-1). Water temperature (^{o}C), percent dissolved oxygen (% DO), dissolved oxygen (DO mg/l) and Chl *a* fluorescence were measured using a Conductivity Temperature and Depth (CTD) (Branckner, XR-

620). Inspection of the profiles revealed that there was no persistent thermal stratification at any of the sites. However diel heating and cooling of the surface 3 m was observed occasionally. In order to eliminate these diel variations which could depend strongly on time of sampling and to examine the portion of the water column that is within the same depth range as the aquaculture cages (6 m) only the data from 4.5 to 5.5 m in the profiles was used. This depth range was chosen after examining all the profiles and determining this depth was the most representative depth. Secchi depth (SD) was determined by manual deployment of the Secchi disk, a white and black disk with 20 cm diameter Wildco Secchi disk attached to measuring line. The depth at which the disk was no longer visible was the measured depth.

Water was collected at each sampling location by dipping a clean Nalgene bottle just under the water surface. Water was used for extraction of Chl *a* which was used as an estimate of phytoplankton biomass in this study. The water samples were first pre-screened with a Nytex netting material (210 µm nominal pore size) to remove large organisms such as zooplankton or suspended organic and inorganic particles and then passed onto 47-mm Whatman GF/F filters (0.7-µm nominal pore size). The filters were then wrapped in aluminum foil and kept frozen for subsequent analysis. Chl *a* was extracted from filters in 90% acetone for approximately 24 hours and fluorescence readings were made using a Turner 10AU fluorometer calibrated with a pure Chl *a* standard. Surface samples (0-0.1m) for TP and TN were collected directly into clean Nalgene sample bottles and preserved by storing them frozen. Before proceeding with preservation, the samples were pre-screened bypassing through a netting material (210 µm nominal pore size). Total phosphorous (µg/l) was analyzed following a protocol

adapted from Stainton et al. (1977), Murphy and Riley (1962), and by Wetzel and Likens (2000). The water samples were digested by adding freshly made saturated potassium persulphate ($K_2S_2O_8$) and processing in a Harvey sterileMax sterilizer for an hour. TP was quantified spectrophotometrically after the addition of the reagents and development of color (Stainton et al 1977) by reading the absorbance at 885 nm in a UV spectrophotometer (UV-1800). Digestion with potassium persulphate was also applied in total nitrogen analysis. The Total nitrogen (mg/l) samples were analyzed by the Flow Injection method in a Lachat (QuikChem, series 8000).

Table 3- 1 Geographical location of sampling sites and their replicates (ST-1,1 is site 1 replicate 1, ST-1,2 is site 1 replicate 2, ST-2,1 is site 2 replicate 1, ST-2,2 is site 2 replicate 2, ST-3,1 is site 3 replicate 1, and ST-3,2 is site 3 replicate 2), depth of the water at the site, distance to the farm, and distance to shore line. The coordinated (longitude and latitude) are presented in Universal Transverse Mercator (UTM) system.

Site	**Longitude (UTM)**	**Latitude (UTM)**	**Depth (m)**	**Distance to the farm (m)**	**Distance to the shore (m)**
ST-1,1	730370	8419210	~16	5,145	1, 559
ST-1,2	731795	8418950	~16	4,019	1, 557
ST-2,1	733367	8415186	~16	10	1, 278
ST-2,2	733431	8415075	~16	10	1, 228
ST-3,1	736762	8411400	~16	4, 040	1, 627
ST-3,2	735882	8412024	~16	5, 085	1, 498

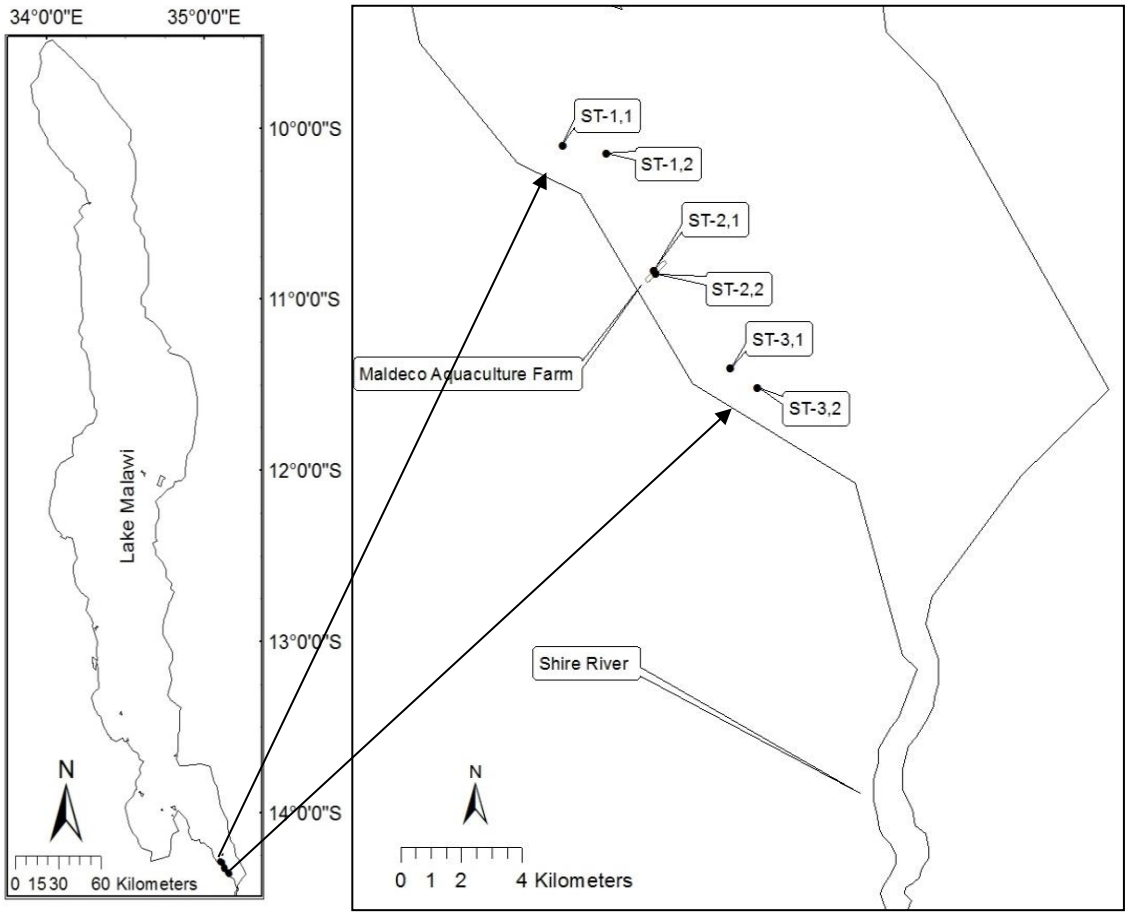

Figure 3- 1 Lake Malawi (left) and sampling sites (ST-1,1 is site 1 replicate 1, ST-1,2 is site 1 replicate 2, ST-2,1 is site 2 replicate 1, ST-2,2 is site 2 replicate 2, ST-3,1 is site 3 replicate 1, and ST-3,2 is site 3 replicate 2) including Maldeco Aquaculture farm (right)

3.2.2 *Statistical methods*

Two-way Analyze of Variance (ANOVA) using SPSS Statistics v-20 was applied to identify significant differences within and between months and sampling sites. Bi-monthly and site mean values were plotted to visualize and describe seasonal and spatial trends in water quality parameters. In addition to general *p*-values provided by ANOVA;

Post Hoc multiple comparison used Least Significant Difference (LSD) to discriminate months and sites that were significantly different from each other and those that were not, at a significance level of p=0.05.

3.3 Results

The surface Chl *a* concentrations were low in February (site 1=0.57±0.01 µg/l, site 2=0.63±0.06 µg/l, and site 3=0.65±0.05 µg/l) (Figure 3-2a) but increased in April when all sampling sites had significantly higher concentrations (site 1=3.95±0.19 µg/l, site 2=4.79±0.65 µg/l, and site 3=5.54±0.29 µg/l) than those recorded in February ($p<0.05$). The April surface Chl *a* concentrations were also significantly higher than the concentrations measured in June and August ($p<0.05$) (Figure 3-2a). Since changes in surface Chl *a* concentrations were similar at all three sampling sites no significant differences were detectable among the sites in February, June, and August ($p>0.05$). A significant difference was detected in April between site 3 (5.54±0.29 µg/l) and site 1 (3.95± 0.19 µg/l) ($p<0.05$) (Figure 3-2a), but was not significantly different from site2 ($p>0.05$).

Water temperature exhibited a clear seasonal pattern characterized by coolest temperatures in June (site 1=22.73±0.05^{o}C, site 2=22.40±0.04^{o}C, site 3=22.49±0.00^{o}C) and warmest in February (site 1=28.15±0.04^{o}C, site 2=27.95±0.09^{o}C, site 3=27.77 ±0.01^{o}C) (Figure 3-2b). Overall, the lake WT dropped by 5.42^{o}C, 5.56^{o}C, and 5.28^{o}C in sites 1, 2, and 3 respectively between the warmer (February) and cooler (June) month. Significant differences in February were observed between sites 1 and 3 ($p<0.05$), but not between sites 1 and 2, nor between sites 2 and 3 ($p>0.05$). The first drop in WT was observed in April and the WT measured in this month was significantly lower than that recorded in February ($p<0.05$); the loss of heat in the lake in April was strong and similar at all sites, therefore, no significant difference were detected among the sites ($p>0.05$, Figure 3-2b). Water temperature was cooler in June than any other month, as such the

water temperatures measured in June were significantly lower than the rest of the months (February, April, and August) ($p<0.05$) in all sites (Figure 3-2b). Although June was the coolest month, site 1 had significantly warmer waters than sites 2 and 3 ($p<0.05$). No significant difference were detected between sites 2 and 3 in June ($p>0.05$). The lake began to warm in August and the water temperature become significantly higher than those measured in June in all sites ($p<0.04$) (Figure 3-2b). In August the sites were not significantly different from each other with respect to WT ($p>0.05$) (Figure 3-2b).

Low Secchi depth, which indicates reduced water clarity or increased turbidity was recorded in April in all sites (Figure 3-2c), resulting in April being significantly different from February, June, and August ($p<0.05$, Figure 3-2c). Sites 1 (6.00± 0.00 m) and 3 (6.25± 0.35 m) had similar Secchi depth values ($p>0.05$) in February, and both had significantly different values with those measured in site 2 ($p<0.05$). Site 1 maintained higher water clarity than other sites even when all the sites had increased turbidity in April; as such site 1 (4.00±0.00 m) clarity was significantly higher than those recorded in sites 2 (1.9±0.10 m) and 3 (2.00±0.00 m) ($p<0.001$, Figure 3-2c), but sites 2 and 3 were not significantly different from each other ($p>0.001$).Although there was no significant difference in Secchi depth values among the sampling sites in June and August ($p>0.05$, Figure 3-2c), the values recorded in these month were significantly different from those recorded in April ($p<0.05$, Figure 3-2c).

There was a strong seasonal effect on dissolved oxygen concentrations (Figure 3-2e). Site 1, the site north of the farm, had significantly higher DO concentrations than sites 2 and 3 in February, April, and August ($p<0.05$) but not in June. In June DO was similar in sites 1 and 2, but were both significantly higher than DO recorded in site 3

(p<0.05) (Figure 3-2e). Sites 3 had higher DO than site 2 in February (p<0.05), but the concentrations were similar in April and August. Oxygen concentrations were significantly different between February and April (p<0.05) (Figure 3-2e) when the lake was cooling; the significance difference was even higher between February and June, the beginning of the windy, upwelling season (p<0.05) when the lake recorded the minimum DO (site 1=6.53±0.01 mg/l, site 2=6.39±0.02 mg/l, and site 3 = 6.13±0.07 mg/l). Oxygen concentrations increased in all sampling sites in August. Although the August concentrations were significantly different with those measured in June and February (p<0.05), there was no significant difference with those recorded in April (p>0.05). Dissolved oxygen concentrations remained significantly higher in August in site 1 compared to sites 2 and 3 (p<0.05) (Figure 3-2e).

Percent dissolved oxygen exhibited significant temporal changes over the sampling period (p=<0.05) (Figure 3-2d). The lowest values (site 1=76.06±0.07%, site 2=74.07±0.14%, and site 3=71.06±0.77%) and the highest (site 1=98.31±0.39%, site 2=91.94%, and site 3=93.61±0.24%) were recorded in June and February respectively (Figure 3-2d). The waters from site 1 were significantly closer to saturation than sites 2 and 3 in February (p<0.001), April (p<0.05), and in August (p<0.001) (Figure 3-2d), but not in June. Sites 1 and 2 were similar in June and both had significantly higher percent DO than site 3 (p<0.05). Sites 3 had higher percent DO than site 2 in February (p<0.001). Percent DO was similar between sites 2 and 3 in April and August. As the lake was becoming cooler (Figure 3-2b), the percent dissolved oxygen also followed suit; the lake gradually becomes less oxygen saturated towards June, but in August the oxygen saturation returns to previous saturated values seen in April (Figure 3-2d), therefore, there

was no significant difference in percent dissolved oxygen recorded between April and August in sites 1 and 3 ($p>0.05$). Other significant differences were observed between February and April ($p<0.05$), February and June ($p<0.05$), and between June to August ($p<0.05$, Figure 3-2d).

Relative temporal changes in TN over the sampling period (Figure 3-2f) were similar at sites 2 (the farm site) and 3 (south of the farm). Both sites started with relatively higher concentrations in February (site 2=148.45±1.67 mg/l, site 3=93.85±0.64 mg/l) but with TN at site 2, the farm site being significantly higher ($p<0.05$, Figure 3-2f). TN concentrations declined at sites 2 and 3 in April and June and stayed relatively low in August. The TN concentration at site 1, the northern site closest to the open lake was initially similar to site 3 but then increased at each sampling time and exhibited the highest TN of all sites in August. Although there were significant differences between sites at times and between dates for some sites, there was no consistent pattern that would support the hypothesis that the farm had higher TN than the remote sites.

Total phosphorous concentration was significantly different in all sites in February, April, June, and August ($p<0.05$, Figure 3-2g). Similar to the temporal pattern in TN concentrations, the TP pattern was similar in sites 2 (the farm) and 3 (south of the farm) (Figure 3-2g). Both sites started with relatively high TP concentrations in February though they were significantly different from each other ($p<0.05$, site 2=23.64±2.01, site 3=17.36±0.65 µg/l). Site 2 lagged behind in reduction of its TP compared to site 3. While the concentrations dropped immediately in site 3 in April (Figure 3-2g) and were then stable in April, June and August (non-significant different, $p>0.05$), the concentrations in site 2 (the farm) dropped to a minima in June and this concentration was significantly

lower than those recorded in February and April ($p<0.05$) at the same site, but higher than those recorded in sites 1 and 3 ($p<0.05$) in the same month (Figure 3-2g). The TP concentration at site 1 (north or the farm) was significantly lower that the farm or site 3 in February and April but was significantly higher in August at the end of the upwelling season.

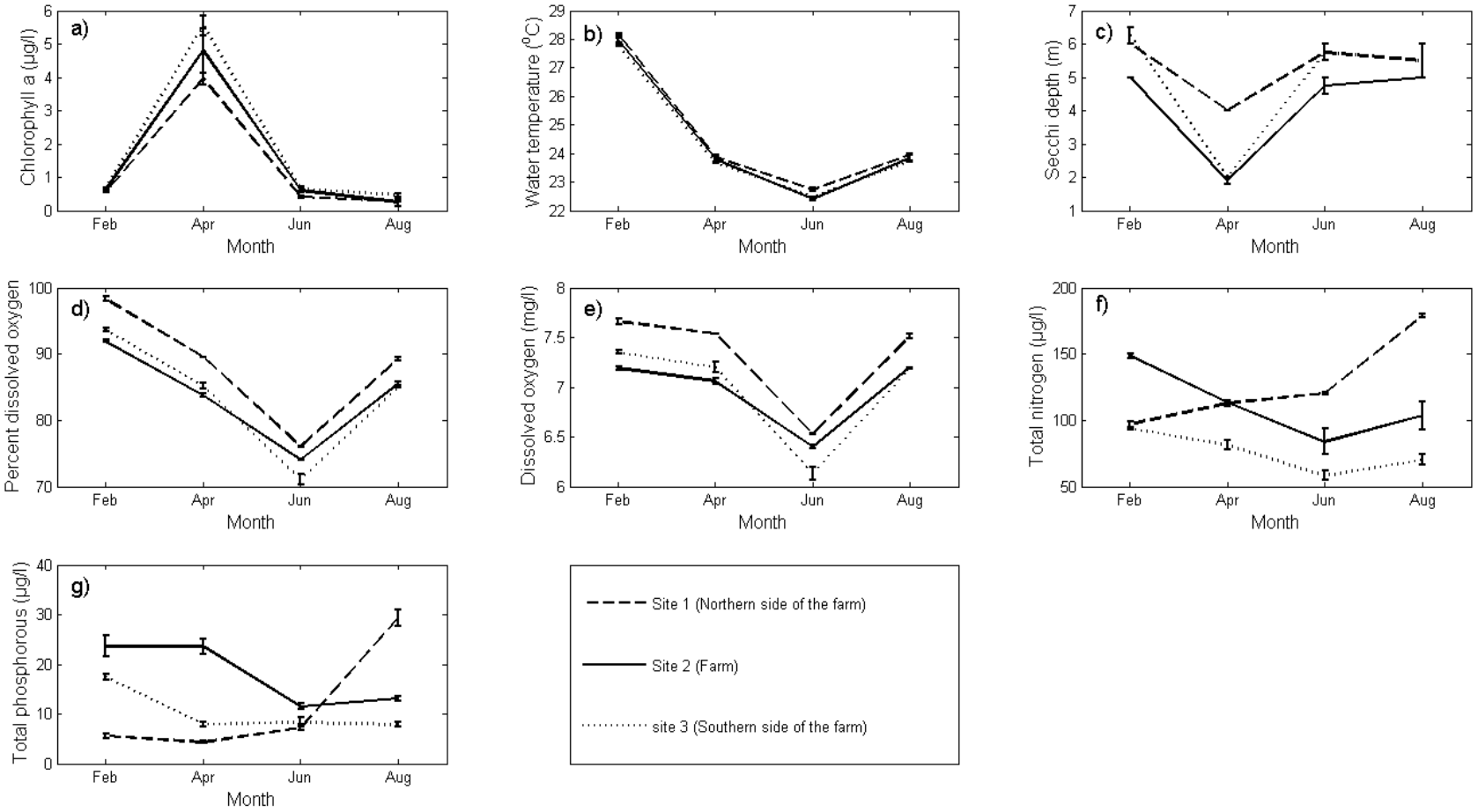

Figure 3- 2 Temporal (month) and spatial (site) changes in surface water quality parameters in Lake Malawi along a north-south 10 km transect including the tilapia cage aquaculture farm.

3.4 Discussion

High percent dissolved oxygen, dissolved oxygen, and Secchi depth readings were first observed in February when the highest water temperatures were reported for all sampling sites. The lake became less oxygen saturated with relatively low oxygen concentrations starting in April and reached minimum concentrations in June, but in August it recovered to previous saturated values seen in April (Figure 3-2d) at all sampling sites. Minor lags in cooling and warming of water temperature, decrease and increase in percent and dissolved oxygen were observed among the sampling sites. For instance, April and August marks the months on which the water temperature was statistically similar in the three sites. Site 1 was warmer in June, while in February the temperature was only higher compared to that recorded in site 3. The slightly warmer site 1 (Figure 3-2b) had significantly higher %DO than sites 2 and 3 (the significantly cooler sites) (Figure 3-2d). Percent oxygen concentration was always higher in site 1, as was the dissolved oxygen concentrations regardless of changing water temperatures. These results are an important component for both farm and lake wide management. When water is equilibrated with the atmosphere warmer waters hold less oxygen than colder water. The fact that %DO was higher at site 1 compared to site 2 and 3 suggests that whatever phenomenon was causing oxygen to be depleted at sites 2 and 3 was stronger than at site 1.

Dissolved oxygen plays an important role in fish production as it directly effects feed consumption, energy expenditure, and the rate of metabolism in farmed fish (Elliott, 1982; Van Dam and Pauly, 1995). Thus the DO concentrations have the potential of affecting farm's operational costs if they fall below optimum recommended levels for a

particular organism. Although oxygen concentration varies inversely with water temperature, water temperature is a difficult physical parameter to control in cage aquaculture systems. Therefore, farms should try to control DO required by the fish to aerobically generate required energy for growth (Van Dam and Pauly, 1995). Some active management strategies to prevent oxygen stress would include avoiding overcrowding of fish in cages, frequent sampling for DO, and partial harvests in the farm to prevent low DO if the problem is thought to be due to high stocking biomass.

The climate in Malawi is characterized by warm and dry (October–November), warm and wet (December–April), and cool and dry (May - September) periods (Eccles, 1974; Spigel and Coulter, 1996). For instance, Macuiane et al. (2011) observed a drop in water temperature in Lake Chilwa from 28^{o}C in February to 21.6^{o}C between May and July, the low water temperatures in Lake Chilwa had. Low water temperatures during this period were also noted in southern Lake Malawi in MonkeyBay station in in 1967 and 1968 (Eccles, 1974). Although site 1 has statistically significant higher temperature than site 2 and 3 the absolute difference in temperature is very small. What is most interesting is that the DO which was corrected from %DO and WT is much higher at site 1 than at site 2 the farm site and site 3. Site 1 closer to the deep open lake, and it appears that oxygen is well supplied to this site however site 2 and to some extent site 3 have lower oxygen suggesting that there is some source of lower oxygen water at these sites. Low DO concentrations at site 2 could be influenced by the farm itself due to oxygen consumption by farmed fish and wild fish populations thereby reducing the concentration at the farm perimeter. Site 3 is located at the same depth with sites 1 and 2 and all sites are located at similar distance to the shore. However, the bathymetry surrounding site 3,

nearer the southern end of the basins is overall shallower than that of sites 1 and 2, therefore, low oxygen concentrations at site might be related to the surrounding shallow areas.

Upwelling is important in Lake Malawi. As noted earlier by Bootsma et al. (2003), the nutrients at the surface waters are low and increase with depth. Lack of thermal mixing prevents the nutrients from reaching the upper photic zone, especially in deep areas of the lake. Hamblin et al. (2003) noted on four occasions from May to August 1997 upwelling driven by offshore SE winds which resulted in longitudinal temperature gradients in the southern part of Lake Malawi. Although the sampling sites in this study had high WT and DO concentrations most of the time, minimum WT and DO were recorded in June. Gondwe et al. (2011b) observed a similar trend; they also found bottom DO of 3.0 mg/l in May at 23^{o}C. Cooler waters equilibrated with the atmosphere would be expected to have higher DO than warmer waters, but the opposite trend was seen in these sites in the SE arm suggesting that the upwelling during May through June creates upward transport of low oxygen waters to the surface in the SE arm. It is therefore, important for aquaculture operations in Lake Malawi to appreciate that there will be periods of low oxygen in this area created by lake wide processes.

The minimum oxygen concentrations observed (above 6.0 mg/l) was still higher than critical levels (1.2 mg/l) estimated for Nile tilapia (Yi, 1999), a popularly cultured fish worldwide in the same genus as the fish cultured at Maldeco cichlid species, and higher than minimum DO of 3.0 mg/l recommended in catfish raceways (Brown et al., 2011) and tilapia farming (Ross, 2000). Consequently, the farm and remote sites from it at the time of data collection were well ventilated and the fish were provided with

optimum oxygen concentrations. In addition, %DO was above 70%, a level below which is known to affect feed consumption of channel catfish (Buentello et al., 2000). However, even if the surrounding environment has high DO concentrations, e.g. above 6.0 mg/l, it should be noted that oxygen demand by captive fish depends on the standing biomass in the cages plus the wild fish populations at the farm which can further reduce DO locally in and around the cages. Tilapias are known to exhibit optimum growth rates above 3.0 mg/l (Ross, 2000). Sub-optimum oxygen concentrations, less than recommended may cause stress and affect optimum fish growth rates. Based on minimum DO of 3.0 mg/l, Brown et al. (2011) estimated that only 3.38 mg/l DO is available to fish if the inflowing DO waters are 6.38 mg/l. suggesting that if the inflowing DO is 6.0 mg/l, only 3.0 mg/l will be available to fish. Therefore, farm operators should carefully monitor farm water quality for low DO and % DO, especially between April and July. April, on the other hand exhibited the highest phytoplankton biomass estimated by Chl *a* concentrations and the lowest water clarity which may have resulted from increased dissolved nutrient concentrations advected from deeper waters early in the upwelling period.

Commercial cage culture systems use large amounts of feed containing high nitrogen and phosphorous concentrations required to promote the growth of captive fish that no longer depend entirely on lake productivity. Dissolved inorganic nutrients can affect the pelagic ecosystems most since they are quickly absorbed and assimilated by phytoplankton and bacteria (Olsen and Olsen, 2008) and may consequently increase lake's primary productivity and cause algal blooms and eutrophication when the system is unable to handle increased loading rates of nutrients. Depending on the system, nutrients levels released in one system with no signs of negative effects may have

deleterious effects in another system which may be more poorly ventilated by current. Thus, it becomes important to investigate the capacity of a particular lake location to process nutrient loadings that are projected for cage culture or expansion of cages while maintaining healthy ecosystem for potential and alternative use of the water resource.

Mass balance analyses have been worldwide used to quantify the amount of nutrients released by cage farms into the environment. Unfortunately, association of cage aquaculture effluents to nutrients concentrations in Lake Malawi environment and probably in other lakes seem to be difficult to trace owing to energetic lake dynamics and potential imports of nutrients advected from other areas e.g. during upwelling; the calm and stratified period prior to upwelling of higher nutrient concentrations in the water. Site 2 at the farm, had significantly higher TN and TP in February compared to other sites, suggesting that this nutrient concentration may derives from the farm during this period. A decrease in TN and TP was noted in April in sites 2 and 3 with an opposite trend in site 1 which reached its higher TN and TP concentrations than sites 2 and 3 in August.

In addition to maximum upwelling in June, Eccles (1974) noted that during April and May the southern winds become predominant in Lake Malawi. It is suggested that is within this period that locally accumulated nutrients are dispersed to the north, hence, site 1 located to the north had high TN and TP concentrations. This result is supported by a significant decrease in TN and TP in site 3 between February and August.

The minimum and maximum TP of 4.34±0.27 µg/l and 29.19±1.64 µg/l recorded in April and August in site 1 respectively and those recorded in other sites (Figure 3-2g) are comparable to values recorded by Nordvarg and Johansson (2002) in fish farms areas of Järsö, Nyhamn, Flisö, and Björkö in the Åland archipelago Baltic coastal areas

between 1997 and 1999 on where they investigated six farms producing between 4637 and 5274 tons of fish. TN values recorded by Nordvarg and Johansson (2002) relatively higher compared to those recorded in the current study (Figure 3-2f). No significant effects of the farms in surface water quality were detected (Nordvarg and Johansson, 2002). Similarly, earlier study by Gondwe et al. (2011) found slightly or no spatial and temporal changes in ammonium (NH_4^+), nitrate (NO_3^-), soluble reactive phosphorous (SRP), particulate phosphorous (PP), particulate carbon (PC), and particulate nitrogen (PN) in the water column, despite high fish biomass at the farm (Table 3-2). While Gondwe et al. (2011) attributed the contribution of strong bottom currents and wild fish populations on dispersion of nutrients and consumption of cage effluents respectively, the current study suggests that more frequent sampling during the stratification and mixing periods is likely required to detect sources or changes in nutrients at sites where cage aquaculture operations are active and currents can be strong.

Table 3-1 Mean Secchi depth (SD), total suspended solids (TSS), extracted chlorophyll (Chla), ammonium (NH_4^+), nitrate (NO_3^-), soluble reactive phosphorous (SRP), particulate phosphorous (PP), particulate carbon (PC), and particulate nitrogen (PN) sampled along four station transects at one km intervals to the south (including near site 3) and north (including near site 1) and at the farm. Source: Gondwe et al. (2011).

Location	**SD (m)**	**TSS (mg/l)**	**Chl*a*** (µg/l)	**NH_4^+** (µg/l)	**NO_3^-** (µg/l)	**SRP** (µg/l)	**PP** (µg/l)	**PC** (µg/l)	**PN** (µg/l)
Southern	6.1±1.9	1.22±0.53	0.81±0.49	8.4±3.2	7.1±4.9	4.2±2.4	3.6±1.5	291±77	38±10
Farm	5.7±1.8	1.45±0.89	0.91±0.54	7.9±2.6	8.1±5.9	4.3±2.2	3.8±1.7	284±53	38±6
Northern	5.9±1.8	1.38±0.86	0.83±0.52	8.2±4.2	6.4±4.4	4.7±3.0	3.4±1.3	294±92	40±12

While cage aquaculture contributes to nutrient additions in Lake Malawi, other sources, including land clearing and erosion contribute to the nutrient pool in Lake Malawi (Bootsma and Hecky, 1993). Hecky et al. (2003) also suggest that agricultural development may have already increased nutrient loading to Lake Malawi by 50% owing to clearing of the forest. These early observations were made before the recent introduction of fertilizer subsidy program that promotes crop production by poor farmers and before the introduction of cage farming in Lake Malawi. Based on the previous observations and finding from the current study, the question is how increased nutrient loading from cage culture and other sources will affect the primary productivity, phytoplankton and phytoplankton communities, wild fish populations in Lake Malawi? Skewed fish abundances towards site 2 and high fishing pressure at site 3 have been noted, however, without any impact of fish diversity (Chapter one).

Temporal differences in Chl *a* concentrations were driven by the peak in April at all sites. The concentrations were lower but again similar among sites in February (site 1=0.57±0.01 µg/l, site 2=0.63±0.06 µg/l, site 3=0.65±0.05 µg/l) and increased to a single peak in April (site 1=3.95±0.19µg/l, site 2=4.79±0.65 µg/l, site 3=5.54±0.29 µg/l) on which Chl *a* concentrations were significantly higher than others months (February, June, and August) (p<0.05) which were not difference among themselves (Figure 3-2a). Site 2 which was expected to have high Chl *a* due to its proximity to the farm did not. The results revealed otherwise, the concentrations were significantly higher at site 3 than other sites during the peak, in June, and in August. February is the only month on which Chl *a* concentrations were similar is all sampling sites (Figure 3-2a). It is interesting to note that Chl *a* concentrations increased towards north-south direction (from site 1 to 3)

as revealed by higher Chl *a* concentrations at 3, but also by significantly higher concentrations at site 2 than site 1 in April, June, and August ($p<0.05$). The pattern in extracted surface Chl *a* concentrations found in the current study is similar to that observed extracted Chl *a* by Gondwe (2009). He found low Chl *a*, less than 1.0 µg/l most of his sampling period and a single peak in May (~2.4 µg/l) in all sampling sites, however, with lower Chl *a* concentration than those recorded in the current study. As noted earlier by Gondwe (2009), these peaks, although occurring at different months (May and April), but same meteorological period, suggest dominance of diatoms which benefit from suspension of nutrients during short mixing period characterized by single peak. In both studies, the peaks seem not having direct effect from the cage aquaculture farm, but from lake wide seasonality. However, increased chlorophyll concentrations in this study were higher than historical values reported for the main lake, less than 1.0 µg/l (Guildford et al., 2007) and recorded before the establishment of cage aquaculture in Lake Malawi. The results shown in Figure 3-3 reveal underestimation of Chl *a* concentrations from surface samples (Figure 3-2a) since they are not representative of whole water column and the concentrations are not uniform throughout the depth (Figure 3-3) and are higher than those recorded by Gondwe (2009), thereby, suggesting an increased lake productivity. However, while the surface Chl *a* did not represent whole water column, the minimum and peak concentrations (Figure 3-2a) observed in the current study seem to be responsible to high and low water clarity through accumulated phytoplankton cells (Figure 3-2c). Secchi depths recorded in February, June, and August are relatively similar to those recorded by Gondwe et al. (2011b), but significantly different to those recorded in April. The importance of water transparency in African

cichlids is well explained by Seehausen et al., (1997). While working in Lake Victoria, they found a relationship between species diversity and color diversity and distinction of male coloration with high water transparency. Finally, reduction of water transparency in Lake Malawi has the potential to affect haplochromine cichlids and therefore, reduce their potential as food source or ornamental fish that fetch high export values, as low fish species diversity are found in turbid areas due to cultural eutrophication (Seehausen et al., 1997).

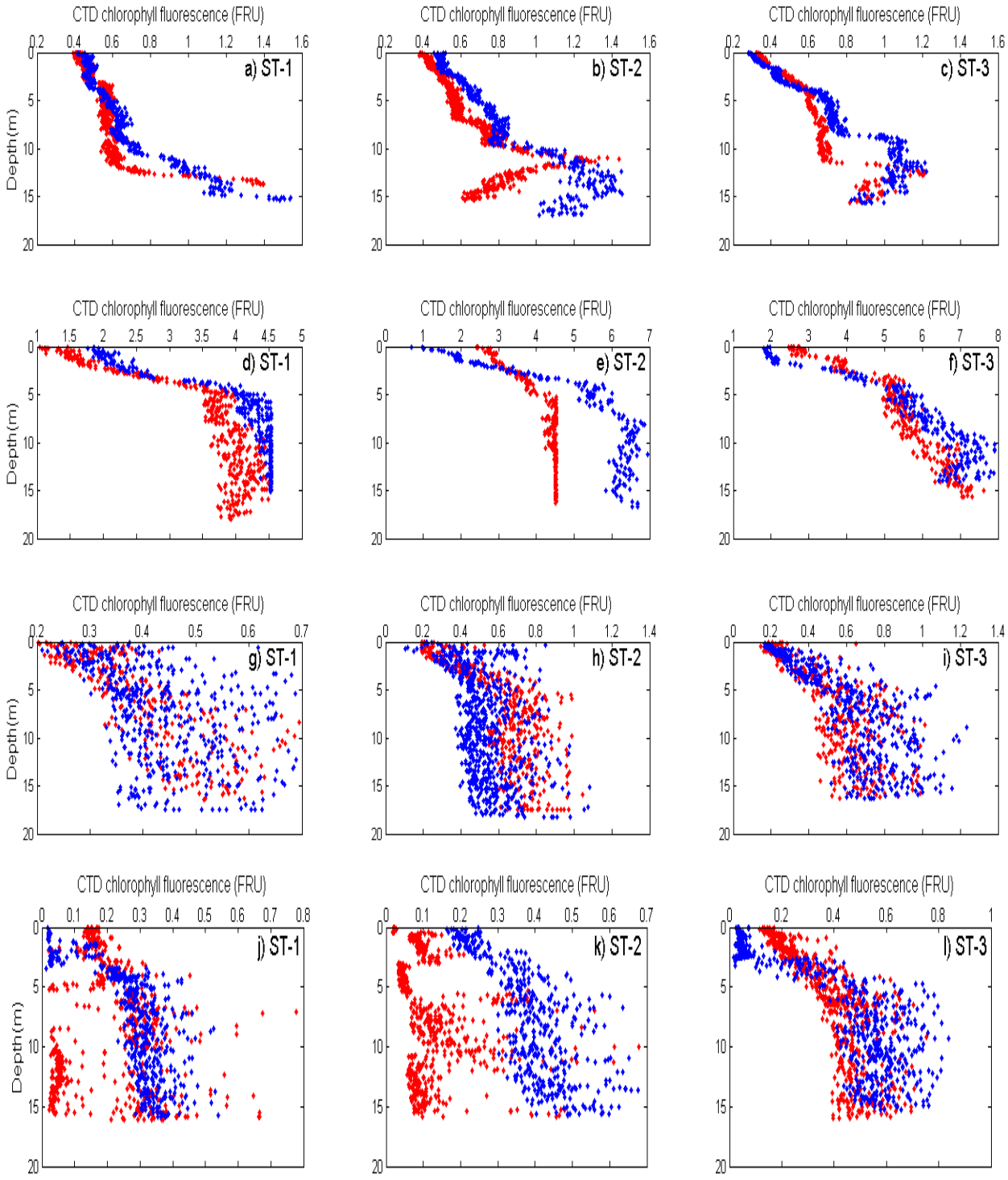

Figure 3-3 CTD chlorophyll *a* profiles at sampling sites in February: a), b), and c); April: d), e); f); June: g), h), and i); August: j), k), and l). Red dot is replicate 1 and blue dot is replicate 2.

3.5 Conclusions

- Dissolved oxygen and Chl *a* frequently used as indicator parameters of healthy or impacted aquatic ecosystems did not show any significant association to cage aquaculture farm. Both followed a clear seasonal pattern mediated by seasonal changes in water temperature related thermal mixing in the lake and do not indicate being affected by the farm operation or any other site.
- Peak Chl *a* concentrations above 5.0 µg/l reported here are much higher than previous observations in the SE Arm of Lake Malawi and suggest increased phytoplankton biomass in the lake. Surface Chl *a* may underestimate whole water column concentrations as Chl *a* increased with depth.
- Surface nutrient concentrations (TN and TP) were higher in south and at the farm during the warm stratified period but may have been advected to the north by strong south eastern winds starting from April and seem not to be directly responsible for changes in Chl *a* concentrations.
- The farm did not cause any measurable significant effect on WT and SD.
- Given the strong and seasonally variable currents in the SE Arm, much more frequent or even continuous monitoring of temperature and oxygen will likely be necessary to separate farm related impacts from wider scale seasonal ecosystem changes.
- Monitoring programs for cage aquaculture in Malawi should consider the period between April and July as potentially stressful because of sub-

optimum WT (less than 24^{o}C), decreased %DO, DO, and reduced water transparency.

Chapter 4

Application of $\delta^{13}C$ and $\delta^{15}N$ isotopes to trace the use of cage aquaculture wastes by wild fish populations in Lake Malawi, Africa

Abstract

This study examined whether uneaten commercial feed emanating from a cage aquaculture farm was utilized as a food source for wild fish populations in Lake Malawi. Stable isotope signatures of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) were measured on wild fish populations collected from three fishing sites, one located at the farm (Site 2) and two others (Sites 1 and 3) along the coast but 5 km away from the farm in opposite directions. Fishing was done during the day in February, April, June, and August 2012 with a multi-mesh gillnet. Commercial feed was donated by Maldeco Aquaculture farm and farmed fish were bought from the same Company. The isotopic fractionation between feed and farmed fish was similar to that reported in an earlier study being <1 ‰ in $\delta^{13}C$ and approximately 3.1‰ in $\delta^{15}N$ as expected for an organism feeding on a uniform food source. Wild caught *Oreochromis karongae*, a fine particle planktivore and also one of the farmed species, caught at site 2, the farm, was more similar in its isotopic composition to farmed fish than the same species caught at sites away from the farm. However, the other four trophic groups (zooplanktivores, benthivores, molluscivores, zoobenthivores) of wild fish were heavier in $\delta^{15}N$ and $\delta^{13}C$ than farmed fish, and there was no significant difference among fish caught at sites 1, 2 and 3. Although fish abundance was higher at the farm and the community structure was significantly different (Chapter 2), this study found little evidence that the fish of various trophic groups in the

vicinity of the farm benefit from commercial feed or waste as their isotopic composition differed significantly from that of farmed fish. The attraction of wild fish to the vicinity of the farm does not result in any demonstrable impact on the trophic behavior of the fish nor do they gain any significant trophic benefit at the farm site.

4.1 Introduction

Malawi, a landlocked country in Southern Africa, is blessed to have 20% of its area covered by water resources which include Lake Malawi, Lake Malombe, Lake Chilwa, and Lake Chiuta as well as Shire River and other rivers and streams. These water resources collectively provide potable drinking water for local communities and support a strong inland fishery that contributes to the nutritional and economic needs of Malawian people and other beneficiaries in remote areas of Mozambique and Tanzania. Fishing is an important economic activity in Malawi (Jamu et al., 2011), it directly employs about 60, 000 people and over 450, 000 people indirectly (GOM, 2009). Fish provides over 60% of dietary animal protein intake and 40% of the total protein supply (Russell et al., 2008) which helps meet human nutritional needs in a country where the diets are dominated by maize and cassava (Jamu et al., 2011). However, growing human population, increased overfishing and habitat degradation have led to the decline of local fish populations and overfishing of some fish stocks in the past two decades (Banda et al., 2005) and effectively reduced the per capita fish consumption from 13-14 kg/year in the 1970s to 4-7 kg/year (Jamu and Chimatiro, 2005; FAO, 2005). Poor households who cannot compensate their protein intake with other more expensive sources of protein are the people most affected with decline of fish stocks (Russell et al., 2008).

Small-scale-earthen pond based aquaculture systems integrating fish and crop production has been encouraged by the Malawi Government to offset the deficit in fish supply in rural areas. Unfortunately, despite the potential that pond-based systems have to produce fish locally and be integrated with crop production, it has not succeeded as expected, and the focus now is to venture into cage culture in Lake Malawi (Windmar et

al., 2008). Therefore, in 2004, the first commercial cage aquaculture farm was launched in Lake Malawi to farm "*chambo*" a collective local name for three endemic tilapiine cichlids (O*reochromis karongae, O. squamipinnis,* and *O. lidole*). Since 2004, there has been expansion of cages and fish production which is being stimulated by the increasing demand for fish that is no longer sustained by the dwindling capture fisheries industry. The aquaculture sector provides protein (farmed fish), reduces fishing pressure on wild stocks, creates direct and indirect employment opportunities for many people through the traditional long value chain of fish, and generates economic benefits to the people of Malawi. However, cage culture is often associated with deleterious environmental changes (Azevedo et al., 2011; Beveridge, 2004) caused by release of solid organic-rich debris and dissolved nutrients such as phosphorous (P) and nitrogen (N) (Azevedo et al., 2011) which increase bacteria and phytoplankton biomass and increase the potential for eutrophication as well as increasing local oxygen demand.

The question of how cage effluent affects the food web of the wild fish community remains unanswered in Lake Malawi. Haplochromine cichlids in Lake Malawi and in other African Great Lakes have undergone extensive adaptive radiation (Fryer and Iles, 1972) that has resulted in modifications of body morphology, especially in the skull, the feeding apparatus (oral jaws, pharyngeal jaws, dentition, guts), the eyes, the colour, orientation and musculature, size, and the gills (Liem, 1973; Greenwood, 1991; Goldschmidt and Witte, 1992; Galis and Metz, 1997; Albertson et al., 2005; Turner, 2007). This adaptive specialization has allowed the haplochromine cichlids to utilize almost all food resources available in the African Great Lakes. But this visible trophic specialization has been added to a basic, highly retained generalized suction

feeding mode which enables apparently highly specialized cranial morphologies to harvest a wide spectrum of foods (Liem 1984; McKaye and Marsh 1983). Food items are always taken by at least one or several cichlid species (Goldschmidt and Witte, 1992). So the availability of the "new" food source offered by cage waste may be potentially available to a wide range of "specialized" fish species. The high density of fish in the vicinity of the cages (Gondwe et al. 2011a, see Chapter two) may also not affect the cichlids because they often coexist in high densities in their natural habitat. For instance, Ribbink et al. (1983) reported high fish density in rocky nearshore habitat in Lake Malawi where more than 500 individuals and 22 species can be found in 50 m^2. Similarly, Goldschmidt and Witte (1992) working in Lake Victoria in a 45 km^2 area of Mwanza Gulf found 200 haplochromine species of which 70 + species could be found in a small Butimba Bay (0.5 km^2).

Adaptive radiation has resulted in cichlids that evolved a relatively large eye enabling them to see at long distances which also encourages trophic specialization (Seehausen et al., 2003). While some species have the lateral line expanded to detect movement of prey hidden in mud (Turner, 2007), most cichlids rely on their acute color-vision to rely on daytime feeding of a vast array of food resources, e.g. ectoparasites on other fishes, scale eaters, fin-biters, egg and larval (from mouth brooding female cichlids), and molluscivores, rock-scrapers, sediment sifters, zooplankton feeders, crab eaters, benthic invertivores, detritivores, macrophytivores and piscivores (Fryer and Iles, 1972; McKaye and March, 1983; Witte and van Oijen, 1990; Turner, 2007). Turner (2007) reports one cichlid species that feeds on flies that rest on rock surfaces near the water, and another preys on insect larvae that hide in the rocks. The mode of resources

partitioning and extreme trophic diversification may be an important factor for cichlid coexistence in Lake Malawi (Goldschmidt and Witte, 1992; Kassam et al., 2003) and such competition is reduced by the niche partitioning (Goldschmidt and Witte, 1992). Optimal food resource exploitation by cichlids using their acute vision, anatomical diversification and behaviour allows them to partition the diverse food resources more efficiently than other fish (Liem and Osse, 1975).

The high fish abundance and different trophic groups at the farm (Chapter two; Gondwe et al., 2012) does not alone provide evidence of utilization of cage wastes as a food resource. These new manmade floating structures may, as well, provide a suitable environment for cover from predation or fishing pressure and may also serve as foraging grounds of natural food resources. The increased availability of natural food resources outside the cages may make the cage environment an area of increased transfer of energy from the lower food web to higher trophic levels for the many different fish species and birds that visit the cages. However, the importance of congregating fish populations in the vicinity of the cages has been hypothesized to reduce the local impacts of cage culture through consumption and translocation of uneaten feed and waste emanating the cages in Lake Malawi (Gondwe et al., 2011a). If this waste was left unconsumed in the local environment there could be negative impacts such as toxic algal blooms, decreased oxygen concentration and general eutrophication (Beveridge et al., 1997). Consequently the fish aggregations may be serving an important ecosystem function in reducing local impacts. But the reduction of local impact by fish may also broaden the area of impact of particulate and dissolved nutrients if the fish are only transient visitors to the site. An alternative hypothesis is that the cages encourage fish aggregations for cover but retain

their dietary preferences and natural diets leading to overexploitation of local native food resources. The latter hypothesis might actually encourage local extinctions of these notoriously stenotopic haplochromines through increasing competition. Increased competition for breeding space might also result if cage wastes are heavily utilized preferentially by some haplochromine species, but not others, resulting in local community distortions and species extirpations.

While the potential contribution of wild stocks in terms of consumption of feed and waste emanating from the cages has been identified, it is not known which species benefit directly from cage feed and waste; it is also not known how effective the high fish densities are in reducing the impact of cage waste on the Lake Malawi environment. In order to promote sustainable development and management of cage culture in Lake Malawi and elsewhere we must understand how the cages are affecting the dietary food items and the partitioning of the feed among the speciose fish communities and also how the wild fish communities may be minimizing the impacts of the cages in Lake Malawi. Understanding the interaction between the wild fish community with the "new" cage environments is imperative in a lake with a high degree of endemism with most of the species dependent on littoral food resources (Bootsma et al., 1996). The creation of a new food resource in the littoral zone of Lake Malawi in turn allows testing of hypotheses about how trophically specialized Malawi cichlids may be and whether only a small number of species may benefit from the new feeding opportunity.

The present study focused on five cichlid groups with different trophic levels classified by Froese and Pauly (2011); (I) the planktivorous **(***O. squamipinnis* (tr=2.14±0.00) and *O. karongae* (tr=2.00±00), the two species are quite similar and they

are found in sandy shore and shallow areas and feed on phytoplankton, detritus, and zooplankton (Konings, 1990) and their collective trophic position is tr=2.07±0.00, **(**II) the benthivores were only represented by *Lethrinops lethrinus*, a sand dweller with a protruded mouth foraging on invertebrates buried in the bottom and phytoplankton near the bottom (Konings, 1990). *L. lethrinus* has a trophic level of tr=3.5±0.37, (III) molluscivores, was comprised by *Trematocranus placodon* (tr=3.37 ±0.58), an endemic cichlid to Lake Malawi, preying mainly on snails from sand substrates where they are crushed by its hard lower and upper pharyngeal jaws in the throat (Fryer and Iles, 1972), (IV) zoobenthivores were comprised by *Pseudotropheus livingstonii* (tr=3.13±0.33), an epipelic algae eater (Ribbink et al., 1983) and *P. elegans* (tr=3.25±0.34), which eats invertebrates buried in the sand (Konings, 1990); both sand and rock dwellers, or at rock/sand interface (Stauffer, 1991) and finally, V) the zooplanktivores represented by *Copadichromis chrysonotus* (tr=3.40±0.45), an open water zooplankton feeder.

The wild fish interaction with the cage farm and potential contribution in reducing the impact of cage culture on the immediate lake environment and in remote areas by consuming uneaten feed and waste emanating from the farm was investigated. The specific objectives included: (1) to identify fish species significantly utilizing uneaten commercial feed and feces emanating from the farm and (2) to investigate the food web dynamics of wild fish communities after the introduction of the cage culture industry to see if the cage site alters the trophic relationships of wild fish. The $\delta\ ^{13}C$ and $\delta^{15}N$ isotopic signatures of five trophic groups were investigated to test the following hypotheses: (i) the wild fish communities in the vicinity of the cages are heavily dependent on uneaten feed and waste emanating from the cages and do not consume

native food sources, (ii) only a few fish species or trophic groups consume uneaten feed and waste emanating from the cages, and (iii) the trophic interactions in the food web around the farm area are different from similar coastal habitats in the South East Arm.

Several studies have investigated fish diets through stomach contents in Lake Malawi fish communities (Jackson et al., 1963; Fryer and Iles, 1972; Allison et al., 1995) as well as in Lake Victoria (Witte and van Oijen, 1990). The studies provide valuable quantitative information about the diets of existing trophic groups. For instance, the diet studies in Lake Malawi reveal that most of cichlids have mixed diets that include algae, zooplankton, *Chaoborus edulis*, fish larvae, and larger fish >200 mm total length. The piscivores prey on the small cyprinid *Engraulicypris sardella* (Walczak, 1982) and almost all fishes (herbivorous or carnivorous) consume eggs or fry of other fishes whenever they have an opportunity (Fryer and Iles, 1955). Witte and van Oijen (1990) investigated the ecology of Lake Victoria haplochromine which are trophically similar to Lake Malawi and provide a description that includes the feeding habits of each of the fifteen sub trophic groups. Although this information is still valuable, both the Lakes Malawi and Victoria studies were conducted before relatively recent major environmental changes (the introduction of cage culture in Lake Malawi in 2004 and eutrophication and the upsurge of Nile perch, *Lates niloticus* in Lake Victoria at the beginning of the 1980s, that led to disappearance of haplochromine and other fish).

Despite the fact that stomach content analysis can provide information about the diets taken by a particular fish, it should be noted that this method is only indicative of short term dietary intake information, i.e. food items that have been recently ingested or those that undergo slow digestion and therefore may underestimate the abundance of food

items that are rapidly digested (Würzberg et al., 2011). An alternative approach is the use of stable isotope analysis (SIA) to trace the food sources and the trophic position in aquatic systems (Peterson and Haworth, 1987; Hobson and Welch, 1992; DeNiro and Epstein, 1978; Minagawa and Wada; 1984; Gu et al., 1994; Beaudoin et al., 1999). The SIA technique uses the isotopic ratios of carbon (^{13}C: ^{12}C, expressed as $\delta^{13}C$) and nitrogen (^{15}N: ^{14}N, expressed as $\delta^{15}N$) to define and map food webs. Fish reflect the stable isotopic composition of their prey as modified by metabolic isotopic discrimination that selectively reduces/eliminates the lighter isotopes in organisms (^{12}C, or ^{14}N) relative to the heavier isotopes (^{13}C, or ^{15}N) (Newman, 2010). Therefore, different isotopic compositions of two or more individuals reflect their different feeding strategies and prey selection (Bootsma et al., 1996) or consumer's relative trophic position (Peterson and Fry 1987; Hesslein et al., 1991; Post, 2000). These patterns of isotopic variation among species allow better interpretation of dietary relationships than stomach content analyses because isotope ratios record dietary material that is actually assimilated by organisms (Michener and Schell, 1994). However, it should be noted that similar isotopic composition among individuals does not necessarily imply similar feeding strategies but probably similar isotopic composition of some of their food sources (Bootsma et al., 1996). The other advantage of tracing the dispersal of aquaculture diets in freshwater ecosystems through stable isotope ^{15}N and ^{13}C is that the protein sources for aquaculture diets is marine fish meal and it can have a different signature compared to freshwater systems thereby making it more efficient to trace aquaculture food sources in freshwater than marine systems (Sutherland et al., 2001).

Bootsma et al. (1996) were the first to apply stable isotope analysis to Lake Malawi food webs and found evidence that substantiated differential use of available food resources in rocky shore communities. Similarly Kidd et al. (2001; 2003) observed a broad range of isotopic signatures in Lake Malawi littoral cichlids indicating trophic specialization. However, it should be noted that isotope signals of primary producers reliant on dissolved sources of C and N can vary considerably more than other trophic levels in the system owing to constant changing of nutrient sources and concentrations (O'Reilly et al., 2002). The expression of this variability at the base of the food web in the isotopic composition of upper food web organisms will depend on their size and growth rate (Hesslein et al., 1991) with fish integrating such seasonal variability into relatively time-stable composition. Most fish exhibit ontogenetic diet shifts as they grow and so juvenile fish can have very different diets and isotopic composition compared to adults (Genner et al., 2003). Genner found isotopic variability owing to dietary shift from planktonic to benthic food sources in *Pseudotropheus callainos,* an endemic haplochromine Lake Malawi cichlid through the life history. It therefore seems that understanding the life history stages of fish can be critical in interpreting isotopic changes (Genner et al., 2003). The current study focused on isotopic signatures of commercial feed used by Maldeco Aquaculture to raise farmed fish, farmed fish and in selected wild fish populations caught near the farm and at replicated fishing locations distant from the cages in order to determine the impact of the cage farm on trophic relationships as seen in the isotopic composition of wild fish of different trophic groups.

4.2 Materials and methods

4.2.1 *Sampling procedure*

Fish specimens were caught for $\delta^{13}C$ and $\delta^{15}N$ analyses during day time in February, April, June, and August 2012 from three fishing sites (Figure 4-1) using four experimental gillnets. Catches were sufficient at the three sites to allow statistical analysis testing for differences. Fish were caught using nets that were 250 feet long and 6 feet deep each consisting of nylon float lines and made up of five randomly spaced 50 foot panels with mesh sizes of ¾", 1", 1 ¼", 1 ½", and 2." After each catch, the fish were identified and sorted to species level and group followed by individual measurements of their total weight and length. The caged fish (*O. karongae* and *O. shiranus*) were bought from Maldeco Aquaculture Limited in February and April. No farmed fish were acquired in June and August. The samples of commercial feed were offered by the Company.

A section of white muscle tissue was collected from the fish behind the dorsal fin and dried at 50-60^{o}C and then stored wrapped in aluminum foil and placed in micro trays and kept in a dry environment. Likewise, samples of commercial feed were also dried and wrapped in aluminum foil prior to analysis at the Biogeochemistry Laboratory/Large Lakes Observatory/University of Minnesota Duluth using a Finnigan Delta Plus XP isotope ratio monitoring mass spectrometer. Subsamples were weighed to approximately a gram, wrapped in aluminum capsules, and compacted to form a round ball shape prior to $\delta^{13}C$ or $\delta^{15}N$ analyses. The subsamples were weighed along with five calibration standards (acetanilide, B-2153, B-2159, caffeine, and urea). A blank, made of wrapped aluminum capsule was run after every ten samples during an analytical run. Carbon and nitrogen stable isotope ratios are expressed in delta (δ) notation, defined as parts per

thousand (‰, or per mil) deviations from a standard material. Isotopic results reported are $\delta^{13}C_{VPDB}$ (relative to Pee Dee Belemnite) and $\delta^{15}N_{AIR}$ (relative to atmospheric N) where: $\delta^{13}C$ or $\delta^{15}N = (R\text{sample}/R\text{standard} - 1) \times 1000$, and R is the ratio of heavy: light isotope = $^{13}C/^{12}C$ or $^{15}N/^{14}N$. A more positive "δ" value is isotopically enriched, meaning that the sample contains proportionally more of the heavy stable isotope (^{13}C or ^{15}N).

Analysis of Variance (ANOVA) using SPSS version 20 discriminated samples with or without significant differences in their $\delta^{13}C$ or $\delta^{15}N$ signatures. Probability of Type 1 error <0.05 was adopted as the test for significant effects in all comparisons.

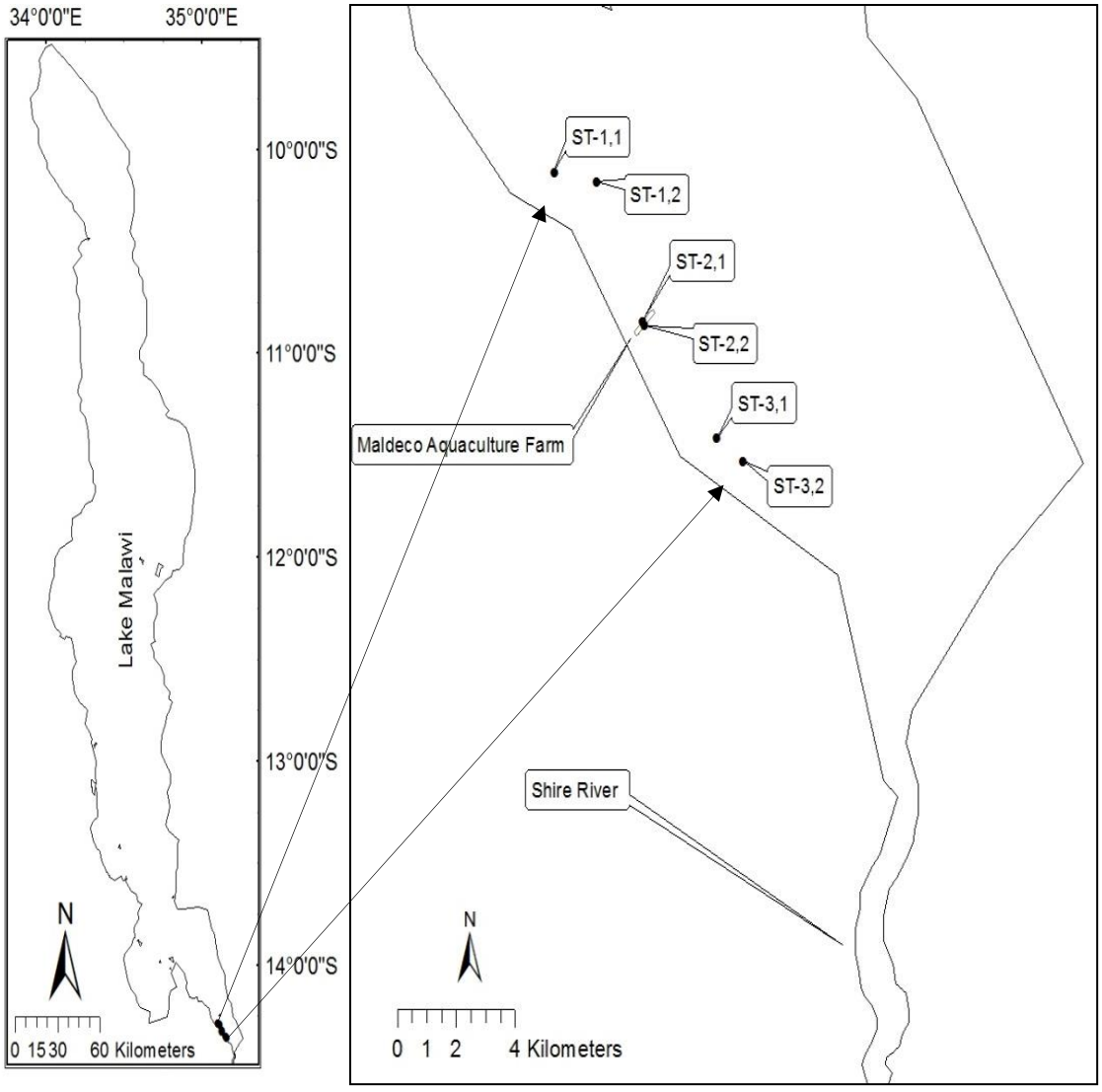

Figure 4- 1 Lake Malawi and the fishing sites in the southeast arm: site 1 replicate 1 (11), site 1 replicate 2 (12), site 2 (aquaculture farm) replicate 1 (21), site 2 replicate 2 (22), site 3 replicate 1 (31), and site 3 replicate 2 (32).

4.3 Results and discussion

4.3.1 *Commercial feed*

Mean (±SE) $\delta^{13}C$ and $\delta^{15}N$ of commercial feed (Table 4-1, Figure 4-2) sampled in February, April, June, and August exhibited some variability ranging between -22.2±0.5 and -21.4±0.2‰ for $\delta^{13}C$ and between 2.4±0.8 and 3.4±0.3 ‰ for $\delta^{15}N$. Possible causes of the variability are variation in the $\delta^{13}C$ and $\delta^{15}N$ composition of locally grown corn and soybeans used as carbohydrate and protein sources respectively and cassava as binder and most critically imported marine anchovy fish used as protein source. Isotopic variability can also be due to non-homogeneous mixing of ingredients during feed processing. Both the $\delta^{13}C$ and $\delta^{15}N$ of commercial feeds were not significantly different among dates (Table 4-1), and they are comparable to results found by Gondwe et al. (2012) at the same farm ($\delta^{13}C$=-22.4±0.4‰ and $\delta^{15}N$=3.0±0.1‰). The similarity of the current results with those of Gondwe sampled in 2009 indicates that the composition of the feed is relatively stable over time and makes it possible to compare the results reported here for fish and prey to the isotopic composition reported by Gondwe et al. 2012.

Table 4- 1 Mean (±SE) $\delta^{13}C$ and $\delta^{15}N$ of commercial feed used at the aquaculture farm during this study. SE=standard error. Results are compared with those of Gondwe et al (2012) for the same farm. The feed is milled locally from imported fish meal and local grains.

Sample	Month	n	$\delta^{13}C$±SE (‰)	$\delta^{15}N$±SE (‰)
Commercial feed	February	3	-21.4±0.2	3.3±0.2
	April	3	-21.4±0.8	2.4±0.8
	June	4	-22.2±0.5	3.1±0.5
	August	2	-21.4±0.2	3.4±0.3

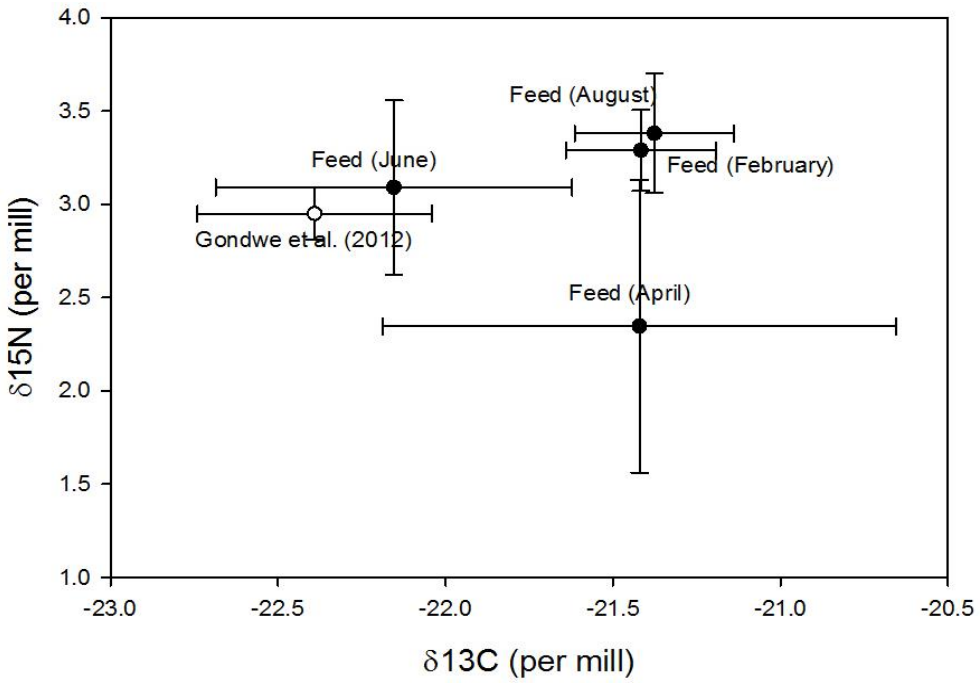

Figure 4- 2 Mean $\delta^{13}C$ (±SE) and $\delta^{15}N$ (±SE) of commercial feed fed to caged fish during production cycle. Mean $\delta^{13}C$ (±SE) and $\delta^{15}N$ (±SE) of commercial feed sampled by Gondwe et al. (2012) are included.

4.3.2 *Farmed fish*

Mean stable isotope composition of harvested caged fish in February ($\delta^{13}C$=-21.4±0.2‰, $\delta^{15}N$=6.2±0.2‰) and April ($\delta^{13}C$=-20.8±0.2‰, $\delta^{15}N$=8.7±0.1‰) (Figure 4-3) were not significantly different in $\delta^{13}C$ composition (p>0.05); however, significant differences were noted in their $\delta^{15}N$ due to enriched $\delta^{15}N$ of caged fish in April (p<0.05) (Figure 4-3, Table 4-2). The February results were nearly identical with the isotopic composition of the caged farm fish reported by Gondwe. A consumer's tissue is related to its food (DeNiro and Epstein, 1978; Minagawa and Wada, 1984), but there is a trophic fractionation between consumer and food source resulting in small changes of the carbon-isotope ratios ($\delta^{13}C$) from prey to predator. This small change in $\delta^{13}C$ can allow tracing the prey carbon sources which can vary in their $\delta^{13}C$ (Hesslein et al., 1991; Vander Zanden and Rasmussen, 2001). The mean $\delta^{13}C$ values of caged fish in February and April would be consistent with farmed fish being obligate consumers of commercial feed. First, they were significantly enriched in $\delta^{13}C$ compared to commercial feeds (p<0.05); and secondly, the average $\delta^{13}C$ fractionation between caged fish in February and April of about 0.35‰ and 0.84‰ respectively is within the 0-1‰ range of consumer-food relationship generally expected in a trophic transfer (Vander Zanden and Rasmussen, 2001; Minagawa and Wada, 1984). This is true because caged fish are fed daily and the high stocking densities and feed additions at the farm make the contribution of natural foods passing the net pens negligible.

The fraction between the mean $\delta^{15}N$ of caged fish in February and commercial feed of 3.2‰ falls within the 3.0-5.0‰ range expected for trophic enrichment for a single prey and predator transfer (Minagawa and Wada, 1984; Hesslein et al., 1991), while the

fractionation between mean caged fish in April and mean commercial feed of 5.8‰ (or 6.3‰ compared to April feed) is well outside this range. The average $\delta^{15}N$ of commercial feed in April is significantly lower than that recorded in February ($p<0.05$) and is not comparable to results found by Gondwe et al. (2012). These values represent an analysis of six fish sampled in April and the high $\delta^{15}N$ values may not be attributed to the sampling protocol, or to lab contamination, as the samples had low standard error and were treated similarly to February samples. Consequently the higher $\delta^{15}N$ for April caged fish samples is regarded as anomalous at this time. The February isotopic results for caged fish agrees well with multiple month samples of caged fish reported by Gondwe (2012) growing on feeds of similar composition to those reported here. Therefore, in this study, comparisons made with wild fish were based on the February results for caged fish.

Table 4- 2 Mean (±SE) $\delta^{13}C$ and $\delta^{15}N$ of farmed fish and their mean total weight.

Sample	**Month**	**ABW (g), TL (cm)**	**n**	**$\delta^{13}C$±SE (‰)**	**$\delta^{15}N$±SE (‰)**
Farmed fish	February	202.43, 185.00	6	-21.3±0.2	6.2±0.2
	April	207.67, 167.83	6	-20.8±0.2	8.7±0.1

SE=standard error, Average body weight (ABW) in grams, Total length (TL) in centimeters

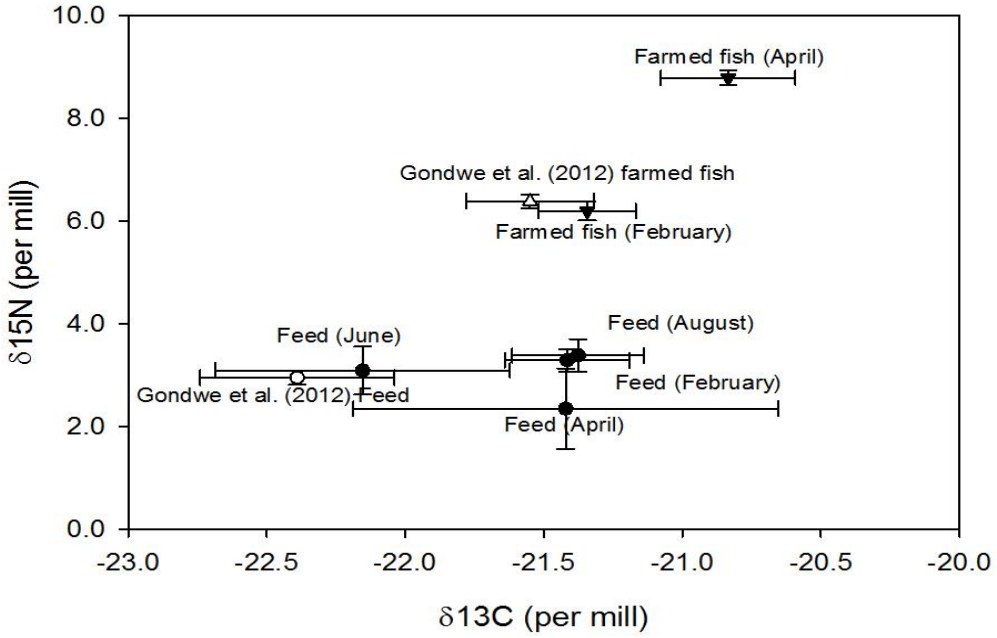

Figure 4- 3 Mean $\delta^{13}C$ (±SE) and $\delta^{15}N$ (±SE) of commercial feed and cages fish sampled in February and April. Mean $\delta^{13}C$ (±SE) and $\delta^{15}N$ (±SE) of commercial feed and caged fish measured by Gondwe et al. (2012) are included.

4.3.3 *Cage aquaculture and wild fish populations*

Habitats characteristics of two or more locations are not expected to be homogeneous, nor are the processes occurring at those habitats synchronized. Hence, resource qualities at the three investigated fishing sites separated by a distance of 5 km are expected to be different (McCann, 2012) and should provide a better understanding of spatial influence of the cage aquaculture farm uneaten commercial feed as an energy source for wild fish populations and the potential impact of the cage feed and waste on trophic shifts in such populations. The dependence of wild fish on cage aquaculture effluent is based on similarities of their isotopic composition with that of caged fish. The

catch composition at the three fishing sites included 51 fish species making up to 628 individuals (see Chapter two). However, not all fish species were present at three fishing sites or if present, their numbers were not enough to compare their $\delta^{13}C$ and $\delta^{15}N$ composition at all three sites to make a case for trophic shifts due to the caged aquaculture operation in Lake Malawi. Thus, the study combined different species into five trophic groups (planktivores (eating small particles, phytoplankton and detritus), benthivores, zoobenthivores, molluscivores, and zooplanktivores) of cichlids with broad range of isotopic composition ranging between -14.2 and -22.1‰ in $\delta^{13}C$ and between 3.3 and 11.3‰ in $\delta^{15}N$ (Table 4-3), representing different feeding strategies achieved by morphological and behavioral diversity which reduces interspecific competition in Lake Malawi (Fryer, 1957). Following the first specific objective "*to identify fish species significantly utilizing uneaten commercial feed and feces emanating from the farm*" and the first hypothesis "*the wild fish communities in the vicinity of the cages are heavily dependent on uneaten feed and waste emanating from the cages and do not consume native food sources*" and the second hypothesis "*only a few fish species consume uneaten feed and waste emanating from the cages and directly benefit thereby distorting natural community structure and habitat utilization,*" the five trophic groups were collected at each of the three sites to determine if the isotopic composition of each group differed at site 2 (the farm site) from the other two groups. If fish from site 2 were different than the other two sites, then the similarity of site 2 wild fish to the farmed fish could be examined to see if feed could explain the difference from the other two sites.

All five fish trophic groups were present at site 2. The mean $\delta^{13}C$ of planktivorous (*O. karongae* and *O. squamipinnis*) which were only found in fishing sites 1 and 2 was

significantly lighter at fishing site 2 (-21.5±0.1‰) and heavier at site 1 (-17.7±0.4‰) (p<0.05) (Figure 4-4, Table 4-3). The non-statistically significant difference in $\delta^{13}C$ between the planktivores at site 2 and caged fish (p>0.05) in addition to $\delta^{13}C$ an average fractionation of 0.2‰ in relation to artificial feed which falls within the 0-1.0‰ range, suggests that planktivorous fish at the farm site (site 2) could be taking a large portion of commercial feed. Gondwe et al. (2012) found heavier $\delta^{13}C$ in *O. karongae* in the vicinity of the cage farm of -18.6±0.9‰ compared to current results -21.5±0.1‰ at the same location, and he also noted that *O. karongae* at the site were isotopically lighter that specimens caught away from the site. Bootsma et al. (1996) noted a broad spectrum of $\delta^{13}C$ signals on wild *O. karongae,* ranging between -19.0 and -17.2‰ and a narrow variation in $\delta^{15}N$ at between 2.5 and 3.0‰. The $\delta^{13}C$ recorded at fishing site 1, a remote site from the farm falls within the range recorded by Bootsma et al. (2012) and suggests that planktivores at fishing site 1 forage on natural planktonic diets, hence, they are significantly more enriched in $\delta^{13}C$ than that recorded at fishing site 2. In contrast, the $\delta^{15}N$ of *O. karongae* was higher at the farm site than at remote site 1 and higher than the $\delta^{15}N$ reported by Bootsma for this species. This suggests that *O. karongae* in the vicinity of the farm are benefiting from food resources which are also richer in $\delta^{15}N$ such as the farm feed.

L. lethrinus was the only benthivorous species present at the three fishing sites, and it had with a narrow $\delta^{13}C$ range between -18.3±0.5 and -17.2±0.6‰ which was significantly heavier than farmed fish (Figure 4-5). There was no significant difference in the $\delta^{13}C$ values among the fishing sites (p>0.05) (Figure 4-5, Table 4-3). Likewise, the $\delta^{15}N$ of this species was consistently higher than that of farmed fish, and there was a

small range in $\delta^{15}N$ between 8.3±0.4 and 9.0±0.5‰ that resulted in non-significantly different $\delta^{15}N$ among the sites ($p>0.05$) (Table 4-3). Their significantly enriched $\delta^{13}C$ and $\delta^{15}N$ signatures compared to the caged fish ($p<0.05$), in addition to similar and narrow variation in isotopic composition among different fishing sites, suggest that *L. lethrinus* forage on similar diets at all fishing sites with little variation in isotopic composition; and these natural diets are different in isotopic composition from commercial feeds. Thus, *L. lethrinus* seem not to exhibit any direct effect from the cage aquaculture farm. Another benthic fish with narrow $\delta^{13}C$ and $\delta^{15}N$ is *T. placodon*, is an endemic molluscivorous species. The $\delta^{13}C$ signal of this species ranged between -17.7±0.9 and -16.3±1.3‰ and was not significantly different among the fishing sites ($p>0.05$) (Figure 4-6, Table 4-3). Likewise, their narrow difference in $\delta^{15}N$ which ranged between 7.3±0.7 and 8.5±0.6‰ resulted in no significant difference among the fishing sites ($p>0.05$). The mollucivores $\delta^{13}C$ and $\delta^{15}N$ were significantly enriched compared to caged fish ($p<0.05$), indicating that they were not dependent on cage aquaculture wastes regardless of its availability. Zoobenthivorous species (*P. livingstonii and P. elegans*) had a wider $\delta^{13}C$ range than the other benthic feeding groups, but had a narrow $\delta^{15}N$ variation (Figure 4-7, Table 4-3). Fishing site 1 was significantly enriched in $\delta^{13}C$ compared to fishing sites 2 and 3 ($p<0.05$), but the $\delta^{13}C$ of fishing sites 2 and 3 were not significantly different ($p>0.05$) (Table 4-3). No significant difference in $\delta^{15}N$ of the zoobenthivorous species was detected among the fishing sites ($p>0.05$) (Table 4-3). All $\delta^{13}C$ and $\delta^{15}N$ of zoobenthivorous fish were significantly different than that of caged fish ($p<0.05$), suggesting that the cage aquaculture effluent does not affect the trophic status of zoobenthivorous fish. Variability in $\delta^{13}C$ of zoobenthivorous which resulted in enriched

$\delta^{13}C$ in fishing site 1 is probably related to their local feeding strategies at these sites (Figure 4-7).

The zooplanktivorous *C. chrysonotus* was the most abundant species at all sites and was represented by 52, 16, and 5 individuals in fishing sites 2, 3, and 1 respectively (see Chapter two). Its presence within the farm is obvious to the unaided eye due to its shiny bluish color and dark spots. The reason for high abundance at the farm might be explained by utilization of uneaten feed emanating from the farm as it does forage on fine particles. *C. chrysonotus* was the only fish species with relatively depleted $\delta^{13}C$ values at all three fishing sites compared to the benthic groups. However, the $\delta^{13}C$ and $\delta^{15}N$ values were not significantly different among all fishing sites ($p>0.05$) (Figure 4-8, Table 4-3) for this trophic group. The $\delta^{13}C$ of this zooplanktivore was not statistically different from that of farmed fish, probably due to relatively high variability of $\delta^{13}C$ within the groups. Regardless of their significantly higher $\delta^{15}N$ than that of farmed fish ($\delta^{15}N=6.0\pm0.1‰$) ($p<0.05$) the zooplantivores $\delta^{13}C$ signal at the farm site is closest to the farm fish $\delta^{13}C$ signal suggesting that zooplanktivores in the vicinity of the farm may be taking a portion of uneaten cage aquaculture feed. Gondwe et al. (2012) analyzed *C. chrysonotus* samples in vicinity of the farm and noted enriched $\delta^{13}C$ =-20.8±0.1‰ and $\delta^{15}N=8.1\pm0.1‰$ signatures in relation to previous assessments of this species in native habitats of $\delta^{13}C$=-21.4‰ and $\delta^{15}N=6.5‰$ before the establishment of cage farm in Lake Malawi (Kidd et al., 2003); the current study confirms such enrichment by finding almost identical results with those of Gondwe ranging between -20.5±0.6 and -19.8±0.5‰ for $\delta^{13}C$ and between 7.6±0.4 and 8.7±0.5‰ for $\delta^{15}N$. These results indeed show a shift in isotopic composition of *C. chrysonotus* at site 2 (although not significantly different from the other two sites)

suggesting that *C. chrysonotus* may also forage on cage aquaculture effluents. The lighter $\delta^{13}C$ and lighter $\delta^{15}N$ for this species at site 2 compared to the other two sites (Figure 4-8) would be consistent with some consumption of farm feeds; but this utilization, if it occurs, did not result in a significant difference from the sites away from the farm.

Table 4- 3 Mean (±SE) $\delta^{13}C$ and $\delta^{15}N$ of wild fish populations from fishing sites 1, 2, and 3.

Trophic group	**Fishing site 1**		**Fishing site 2**		**Fishing site 3**	
	$\delta^{13}C$±SE	**$\delta^{15}N$**±SE	**$\delta^{13}C$**±SE	**$\delta^{15}N$**±SE	**$\delta^{13}C$**±SE	**$\delta^{15}N$**±SE
Planktivores	-17.7±0.4^{a}	4.9±1.5^{a}	-21.5±0.1^{b}	7.8±0.2^{b}		
Benthivores	-18.3±0.5^{abc}	8.3±0.4^{abc}	-18.1±0.6^{abc}	8.9±0.6^{abc}	-17.2±0.6^{abc}	9.0±0.5^{abc}
Zoobenthivores	-14.3±0.1^{a}	9.1±0.6^{abc}	-19.2±0.6^{bc}	9.6±0.7^{abc}	-18.6±0.4^{bc}	8.8±0.8^{abc}
Molluscivores	-16.7±1.2^{abc}	8.5±0.6^{abc}	-16.3±1.3^{abc}	8.2±0.4^{abc}	-17.7±0.9^{abc}	7.3±0.7^{abc}
Zooplanktivores	-20.1±0.4^{abc}	8.3±0.7^{abc}	-20.5±0.6^{abc}	7.6±0.4^{abc}	-19.8±0.5^{abc}	8.7±0.5^{abc}

Different letters (p<0.05) indicates significant differences between isotopic signatures at different sites.

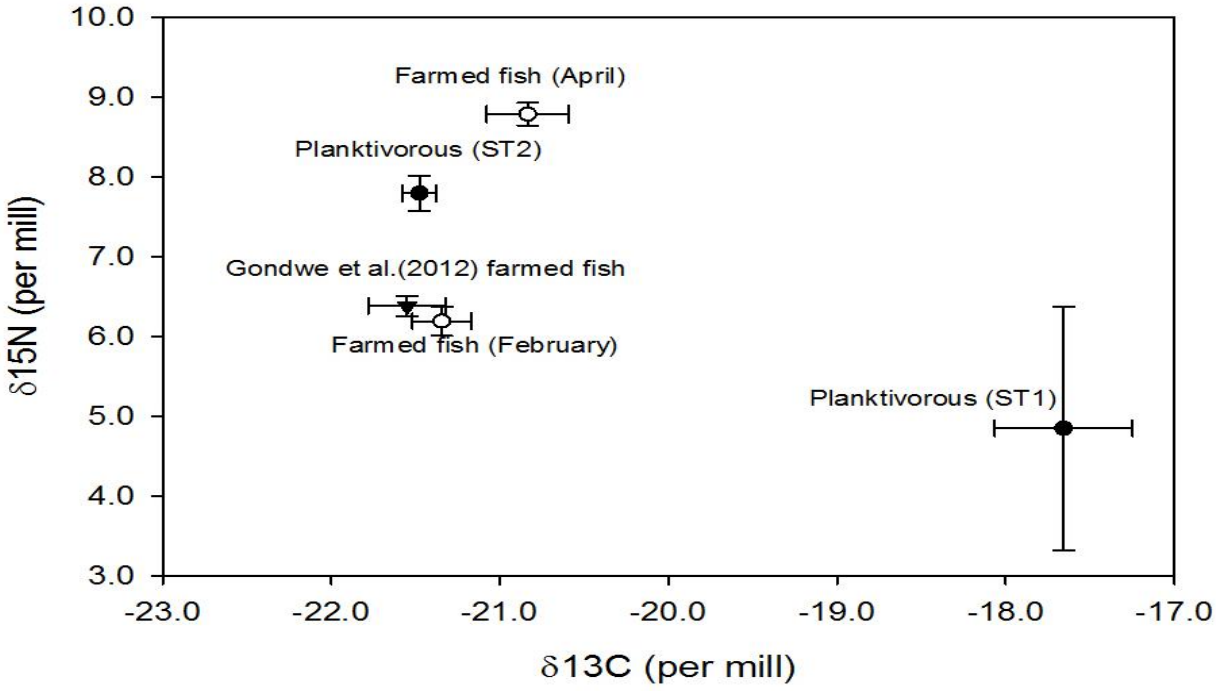

Figure 4- 4 Mean stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) of caged fish and planktivorous fish sampled in February, April, June, and August 2012 at fishing site 1 (ST1), fishing site 2 (ST2), and fishing site 3 (ST3). Mean ($\delta^{13}C$ and $\delta^{15}N$) of caged fish measured by Gondwe et al. 2012 are included.

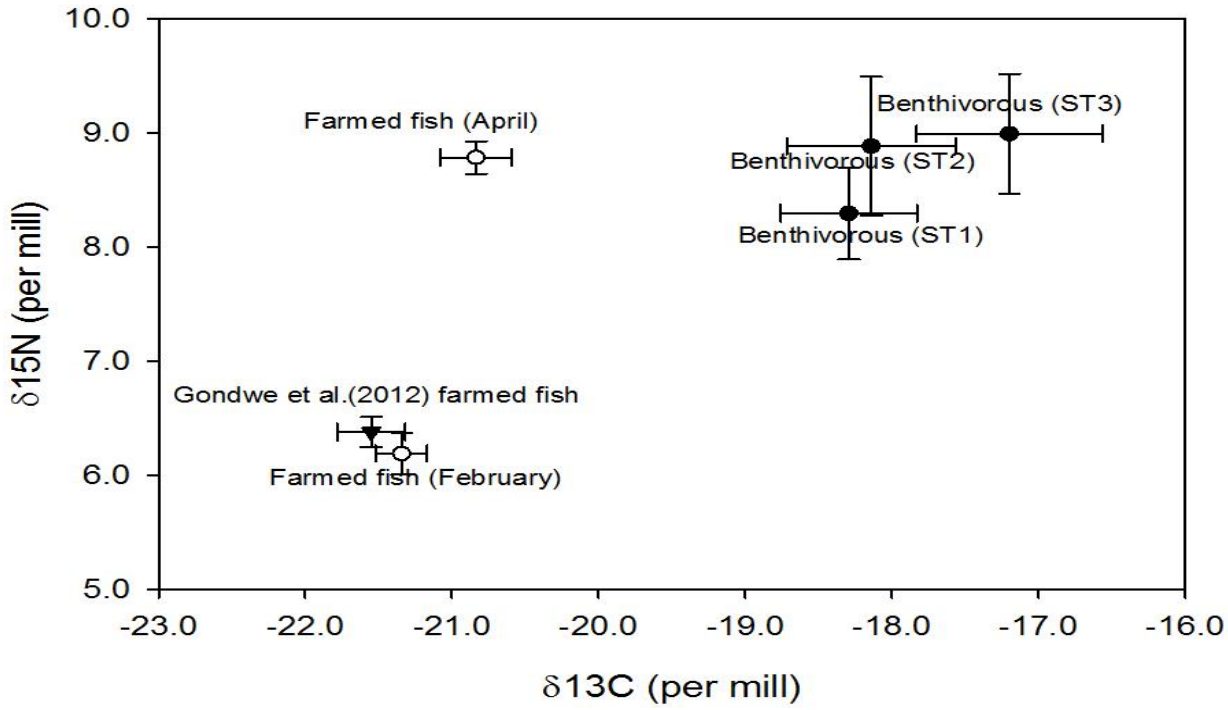

Figure 4- 5 Mean stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) of caged fish and benthivorous fish sampled in February, April, June, and August 2012 at fishing site 1 (ST1), fishing site 2 (ST2), and fishing site 3 (ST3). Mean ($\delta^{13}C$ and $\delta^{15}N$) of caged fish measured by Gondwe et al. 2012 are included.

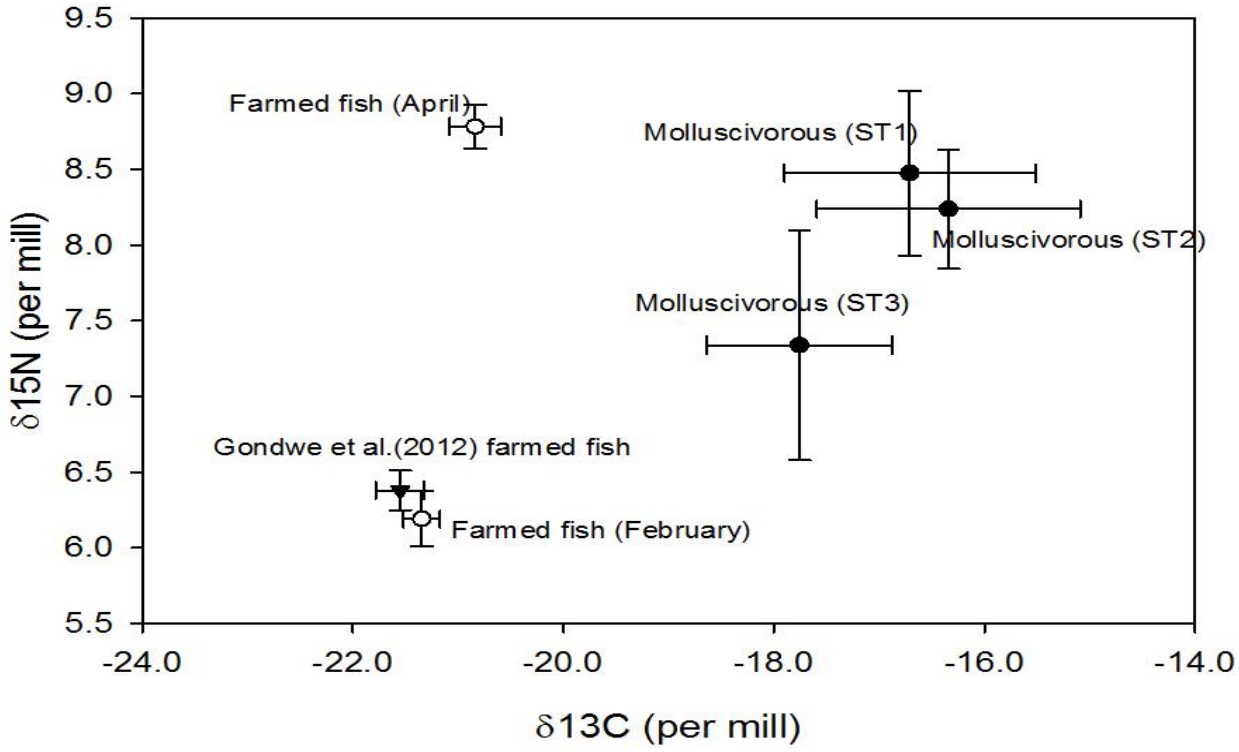

Figure 4- 6 Mean stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) of caged fish and molluscivorous fish sampled in February, April, June, and August 2012 at fishing site 1 (ST1), fishing site 2 (ST2), and fishing site 3 (ST3). Mean ($\delta^{13}C$ and $\delta^{15}N$) of caged fish measured by Gondwe et al. 2012 are included.

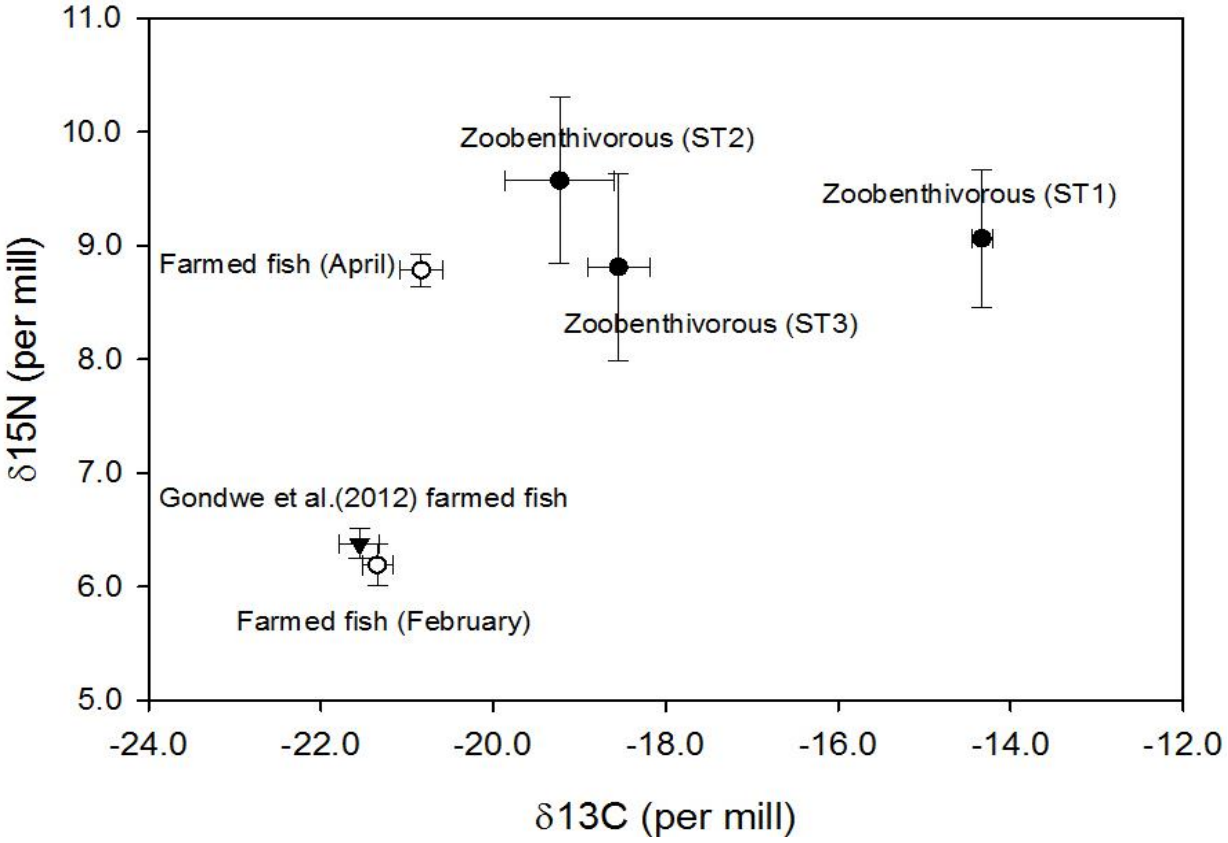

Figure 4- 7 Mean stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) of caged fish and zoobenthivorous fish sampled in February, April, June, and August 2012 at fishing site 1 (ST1), fishing site 2 (ST2), and fishing site 3 (ST3). Mean ($\delta^{13}C$ and $\delta^{15}N$) of caged fish measured by Gondwe et al. 2012 are included.

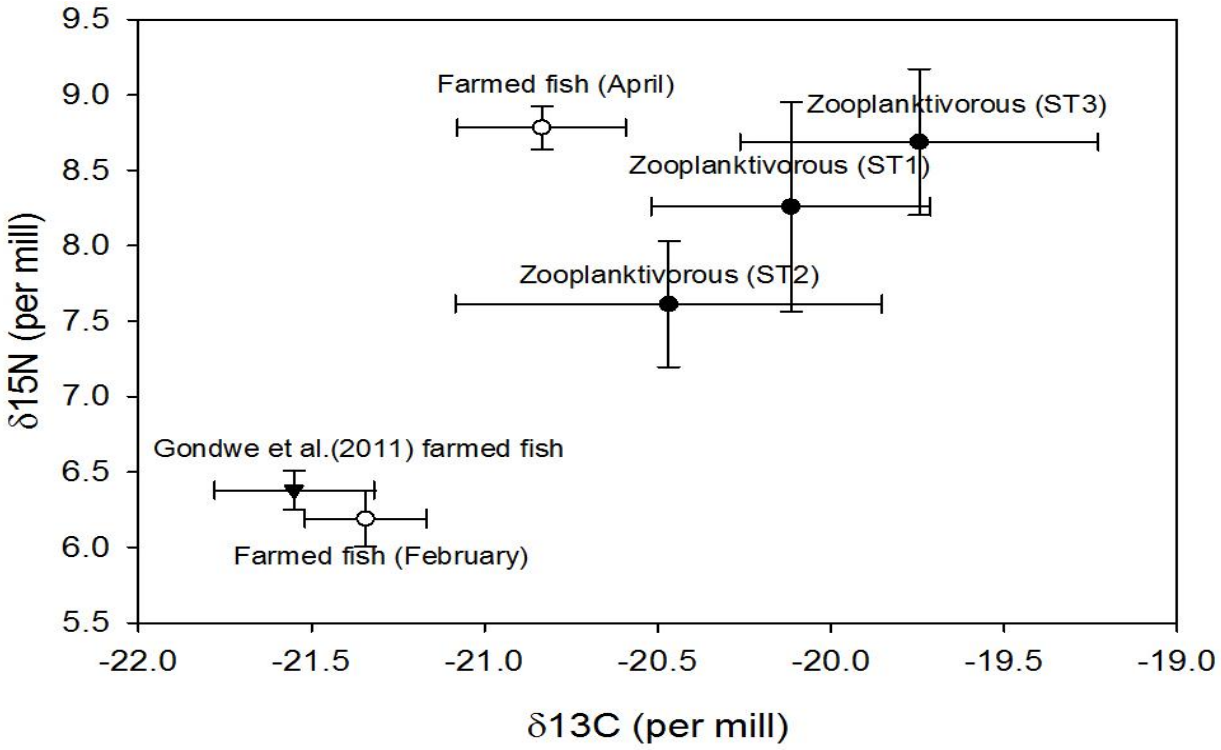

Figure 4- 8 Mean stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) of caged fish and zooplanktivorous fish sampled in February, April, June, and August 2012 at fishing site 1 (ST1), fishing site 2 (ST2), and fishing site 3 (ST3). Mean ($\delta^{13}C$ and $\delta^{15}N$) of caged fish measured by Gondwe et al. 2012 are included.

4.3.4 *Trophic interactions among wild fish populations*

The food web structure at the farm and remote sites were broadly similar indicating little impact of the farm on the natural diets of the wild fish. Possible impacts on the planktivorous and perhaps zooplanktivous trophic groups were suggested by the similarity of their $\delta^{13}C$ to that of farmed fish while significant differences between the $\delta^{13}C$ values of benthic fish and farmed fish indicate that there was no significant influence of cage wastes on these benthic trophic groups. Consequently, these results do

not support the hypothesis "*the trophic interactions in the food web around the farm area are complex but overall different from similar coastal habitats in the South East Arm"*. Confidence in this result is somewhat reduced by the anomalous high $\delta^{15}N$ of farmed fish sampled in April which was highly enriched in relation to commercial feed and significantly higher than that recorded in farmed fish in February. These anomalous results would require assimilation of a food source highly enriched in $\delta^{15}N$, but with similar carbon signals with those of commercial feed. No such food source is available to the farmed fish which can only accomplish their growth at such high population densities by consuming the feed provided. The farmed fish were harvested with an average weight of 202.43g in February and 207.67g in April and were farmed at cages moored next to each other, at similar depth. Average body weight increment during the production period was different, but there were no signs of starvation of farmed fish at cage 45 harvested in April nor at cage 46 harvested in February; therefore, the anomalous $\delta^{15}N$ cannot be explained by starvation. In any case, this anomalous result does not affect the conclusion that the wild fish at the farm in four of the five trophic groups sampled were not significantly different from wild fish in these trophic groups sampled away from the farm.

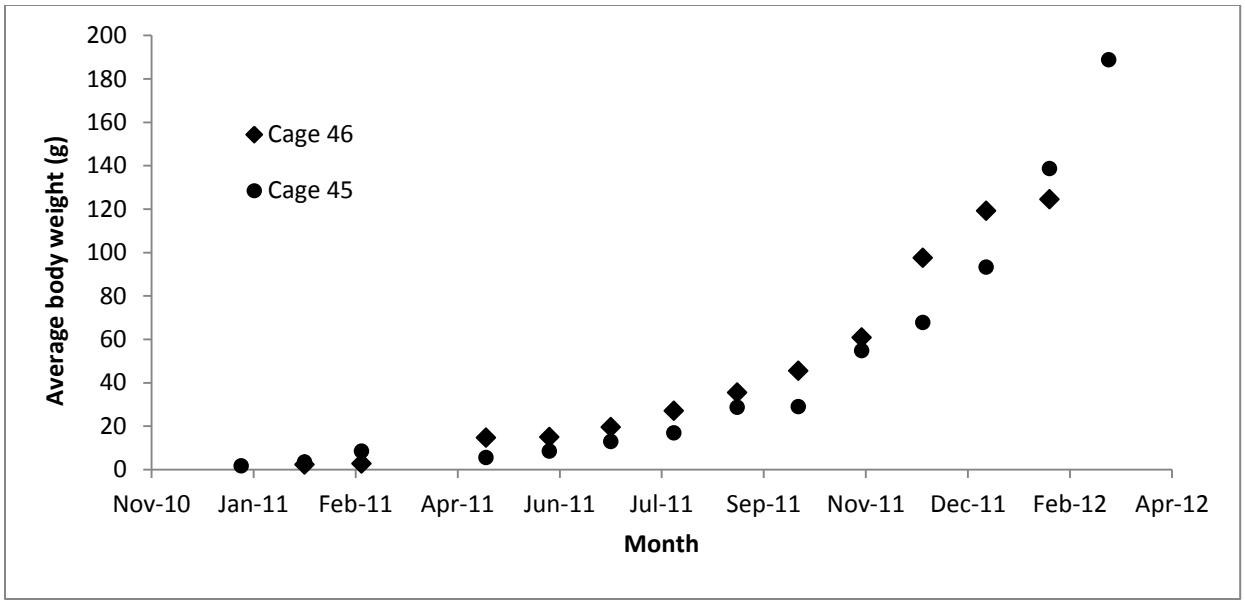

Figure 4- 9 Average body weight of farmed fish in cages 45 and 46 harvested in February and April 2012 respectively at Maldeco Aquaculture farm.

4.4 Conclusion

Results from the current study confirm previous findings of Gondwe et al. (2012) that wild planktivore, *O. karongae* may benefit from utilizing farm waste. For the other four trophic groups in this study, the wild fish taken at the farm site were not significantly different in their stable isotope signatures from those of wild fish caught away from the farm. In the absence of a trophic benefit to wild fish being present at the farm, the increased abundance of wild fish at the farm is more likely a result of reduced fishing pressure or predation on some of the species within the farm boundaries. Overall, the stable isotope composition of the trophic groups at the cages did not differ significantly from those from more remote locations which indicates that these trophic groups are remaining faithful to their natural diets and are not incorporating significant amounts of feed or waste from the cages. Consequently it is unlikely that these wild fish, even if resident at the cages, are actually reducing the possible environmental impact of cage effluent by their feeding activities as proposed by Gondwe et al. Rather more likely the relatively high current velocities (mean 9.3 cm s^{-1}) measured by Gondwe et al. (2011b) advect cage effluent away from the farm before they are incorporated into the local food web. Consequently, any impact of organic waste and nutrients would be distributed over a much broader area and such dilution would make it difficult to assess any negative impacts. However, this study did observe the farm during a down period of operation with only about 20 of the 50 cages at the site stocked during our observational period. It is possible that operation of the farm over several years at nearly full capacity could have more substantial impacts on the food webs of the wild fish at the cages. Continued monitoring of conditions would be warranted as the farm approaches fuller operation.

Clear fidelity to their natural diets was observed for the benthivorous, zoobenthivorous and molluscivorous fish which, although they can be readily found at the vicinity of the farm, they did not rely on farm feed available at the farm. The benefits of the cage farm to these groups may be indirect, perhaps by increased availability of their natural food promoted by continuous supply of nutrients from a new point source that fuels primary producers in this lake that has with low nutrient concentrations in the surface and high in the bottom (Bootsma and Hecky, 1993). Any addition of nutrients will increase lake's productivity and broaden the impact at remote sites from the cage farm. The impact of cage aquaculture on trophic shifts of benthic fish was not detected. Therefore, similar studies should focus on non-benthic fish species such as the planktivorous wild *O. karongae* which did seem to respond to the cage wastes. This species may be useful in providing a biomonitor of the ecological impact footprint of the cages by collecting this species at fixed distances from the farm.

Chapter 5

Oxygen consumption rates of *Oreochromis karongae* (Trewavas, 1941) and *Oreochromis shiranus* (Boulanger, 1896)

Abstract

1. Changes in dissolved oxygen concentrations (DO) were continuously measured over a two hour period to estimate the oxygen consumption rate (OCR) of *Oreochromis karongae* and *O. shiranus* in 14 experiments conducted in February, April, June, and August 2012.
2. Dissolved oxygen concentration continuously declined from high initial concentrations to as low as 0.1 mg/l at the end of the experiments.
3. *O. shiranus* OCR (132.8±6.7 $mgO_2\,kg^{-1}\,h^{-1}$) was higher than *O. karongae* (96.4±3.5 $mgO_2\,kg^{-1}\,h^{-1}$); however, the *O. karongae* used in the experiments were significantly larger than the *O. shiranus*.
4. Using all the experiments for both species, there was not a significant correlation between fish weight and OCR, and so carrying capacity analysis (Chapter 6) used average OCR estimates for each species regardless of fish sizes in the cages. Further experiments using different fish sizes are recommended to determine OCR-fish weight relationships for these species.

5.1 Introduction

The declining trend in capture fisheries stocks in Malawian water bodies has led the Government of Malawi and partners to find alternatives to offset the deficit between fish supply and demand in Malawi. The endemic *Oreochromis karongae* and native *O. shiranus* which are the bulk of species introduced into aquaculture farming in Malawi since 1940 (Maluwa and Gjerde, 2006) along with *Clarias gariepinus* continue to be irreplaceable even after decades of aquaculture farming in Malawi. *O. karongae* is a pelagic cichlid tilapiine endemic to Lake Malawi, breeding in shallow waters (0.5-28.0m) (Msiska and Costa-Pierce, 1997) and preferentially feeds on low trophic level diets, mostly diatoms (*Surirella* and *Melosira*) (Mwanyama, 1992). *O. shiranus* is another cichlid tilapiine species found in shallow ecological habitats of Lake Malawi, Malombe, Shire River, and wetland- dominated, shallow Lake Chilwa where oxygen content in water can be low. It is the most prolific farmed species in Malawi with over 90% of farmers using it under different farming practices (Maluwa and Gjerde, 2006). The two tilapiine species are good candidates for aquaculture farming as they are easy to handle for stocking in cages or ponds and routine sampling, can be transported for long distances and bred naturally with minimum effort, can be farmed in shallow fish ponds (less than a 1 m deep) and achieve marketable sizes even when fed on natural diets achieved by fertilization of fish ponds with organic or inorganic fertilizers. High protein levels in commercial feeds are required when the availability of natural feeds can no longer meet commercial stocking densities in ponds or cages for optimum growth rates.

The current study was conducted to estimate the rate of oxygen consumption (OCR) of *O. karongae* and *O. shiranus* to support estimates of the carrying capacity of

cage aquaculture farms in Lake Malawi (Chapter 6) as the estimates require knowledge of species specific OCR of farmed organisms to achieve fish growth rates and better health of cultured fish. To date there is no information on metabolic expenditure of these species; yet such knowledge is valuable to estimate adequate dietary energy requirements to support the growing aquaculture industry, and more importantly, in predicting their physiological responses in different ecological systems or when changes in environmental factors occur. Optimum environmental conditions that maximize utilization of input energy for better growth performances and high survival rates in organisms (Meade et al., 2002; Shi et al., 2011) can also be determined, by defining optimum oxygen concentrations, and optimum water temperatures for survival (Bellgraph et al., 2010). Optimum environmental conditions can also reduce production costs in aquaculture operations and other related animal husbandry practices.

5.2 Materials and methods

Farmed *O. karongae* and *O. shiranus* were supplied by Maldeco Aquaculture Limited in February, April, June, and August 2013. Fish were collected early in the morning before any feeding and then, acclimated at least an hour before conducting the indoor experiments between 8:00 am and 6:00 pm at Maldeco hatchery to avoid drastic changes in water temperature and avoid interference of noise that would potentially stress the experimental fish. Water was oxygenated via an airstone connected to an electric air-pump during the acclimation period. Selected fish specimens with similar average weight and a total weight close to a kilogram were placed inside the respirometer, a low cost opaque cooler box with a capacity of 46 liters. The respirometer was filled up with lake water and a Conductivity Temperature and Depth (CTD) sonde (Brancker, XR-620) was placed to record changes in dissolved oxygen concentrations for two hours inside the respirometer. The respirometer was tightly closed and sealed with a duct tape to avoid air exchange with atmosphere. The opaque walls avoided any visual contact of fish with surroundings and avoided disturbances during the experiment. Total weight of fish was estimated before the experiment while weight and length of individual fish were recorded after the experiment. The oxygen consumption rate (OCR) of farmed fish was estimated according to (Valverde et al., 2006) as:

$OCR = ([O_2]\ t_o - [O_2]\ t_1) \bullet V/t / BW$

Where:

OCR = oxygen consumption rate (mg O_2/kg/hour)

$[O_2]\ t_o$ = oxygen concentration at time t_o (mg O_2/liter)

$[O_2]\ t_1$ = oxygen concentration at time t_1 (mg O_2/liter)

V = respirometer volume minus volume of experimental fish (liter)

$t = t_o - t_1$ (hour), duration of the experiment, initial time minus final time

BW = body weight of fish (kg).

A linear portion of the oxygen change recorded in the respirometer was used to estimate the OCR beginning 10 minutes from the initial starting time. Data were analyzed by ANOVA and linear regression for (OCR and weight) and (OCR and time) relationships were performed using IBM SPSS Statistics v-20 to test for significant differences at $p \leq 0.05$ between means of experiments conducted for different months and species.

5.3 Results and discussion

The experimental fish were subject to relatively high initial DO to very low concentrations at the end of the experiment (Figure 5-1). Out of 14 experiments, 10 ended with DO bellow 1.0 mg/l and only 4 had DO between 1.0 and 2.8 mg/l (Figure 5-1)), and no fish died although a few fish had unbalanced locomotion at the end of the experiment with lowest DO, but recovered soon after the rise of DO. These results suggest that *O. shiranus* and *O. karongae* can withstand hypoxic conditions for short period. However, longer exposure to low DO may suppress growth potentials of the cultured fish and mortality. Oxygen concentrations of 2.8 mg/l and 3.2 mg/l were found to reduce feed intake and consequently the growth performance of *O. niloticus* with an average weight of 37 and 190g, respectively (Tran-Duy et al., 2008). Oxygen content also defines fish distribution and survival of farmed fish (Ahmed and Magid, 1968) and must be maintained high enough to sustain aerobic respiration for better locomotion, feeding and biosynthesis in aquaculture production (Pauly, 1981; van Dam and Pauly, 1995) and to minimize energy expenditure on stress. Undesirable dissolved oxygen concentrations in fish farms prevent fish from eating and depending on oxygen requirements; deficiency in DO may cause asphyxiation and death (Svobodavá et al., 1993). Tilapias are known to tolerate low dissolved oxygen concentration (Teichert-Coddington and Green, 1993) as low as between 0.1 to 0.3 mg/l for *O. niloticus* (Ahmed and Magid, 1968; Magid and Babiker, 1975) although a newer study suggests 0.8 mg/l as the extreme value *O. niloticus* (Teichert-Coddington and Green, 1993).

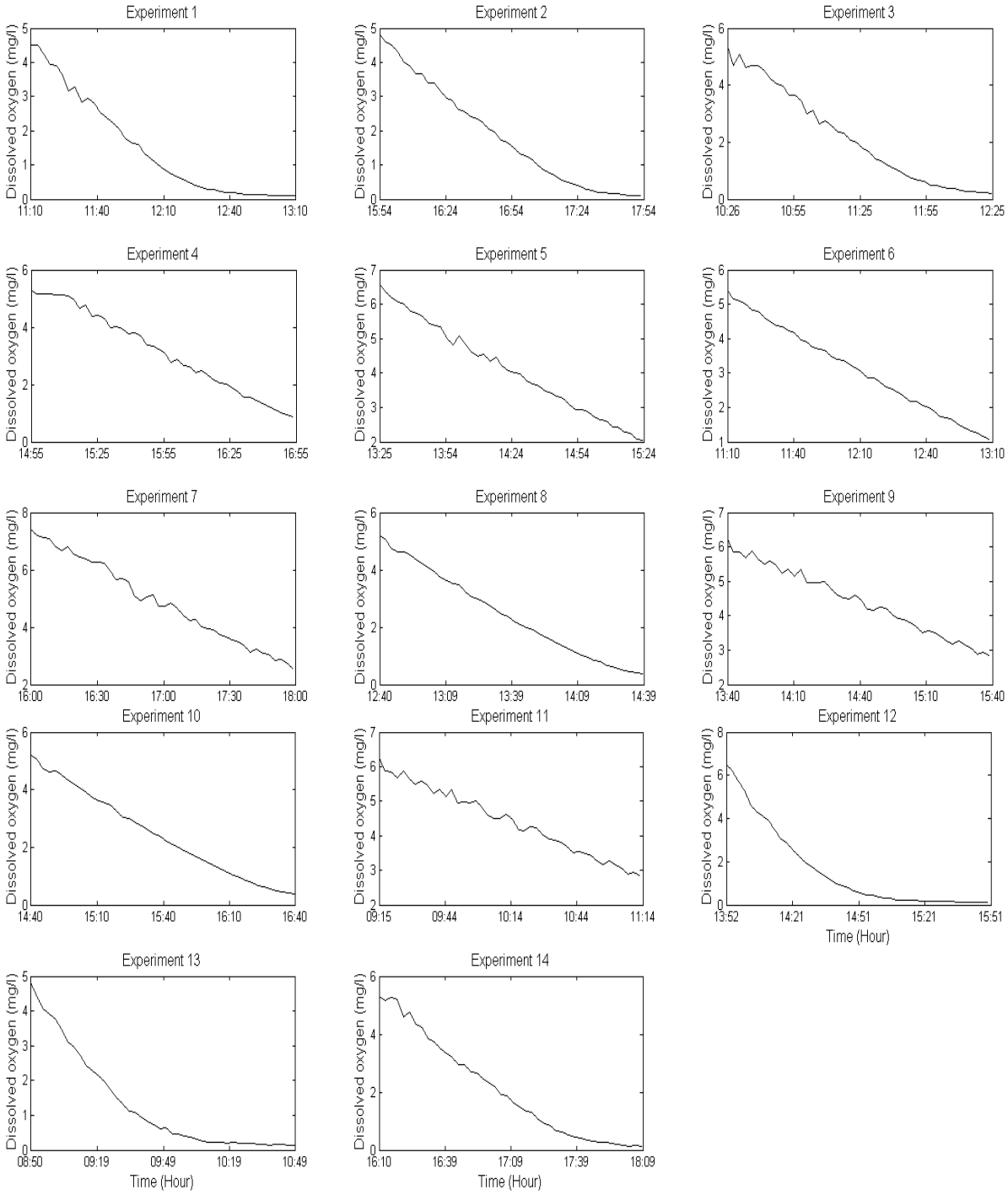

Figure 5- 1 Change in dissolved oxygen concentration in the respirometer oxygen consumption by *O. shiranus* and *O. karongae* in the respirometer.

The average OCR estimated based on the linear portion of declining dissolved oxygen for *O. shiranus* and *O. karongae* were 132.8±6.7 and 96.4±3.5 $mgO_2kg^{-1}h^{-1}$ respectively (Table 5-1). OCR values were significantly different (F=18.209, p=0.002) for the species; however, the average weight of the species was also significantly different (F=5.220, p=0.045), suggesting that differences in OCR might be associated with different sizes. If this were true, then the two species could have similar metabolic rates. The lower OCR in *O. karongae* compared to *O. shiranus* may also be attributed to significantly lower water temperatures than those subject to *O. shiranus* (F=15.290; p=0.003) or inherently different basal metabolic rates.

Tilapias, especially *Oreochromis* species exhibit variations in OCR, but overall, estimates from the current study fall within the ranges reported in the literature. For instance, comparable results between 80 and 110 $mgO_2\,kg^{-1}\,h^{-1}$ with an average of 90 $mgO_2\,kg^{-1}\,h^{-1}$ were obtained in *O. niloticus* (70-120g) under normal (12 h light: 12 h dark) experiments and those between 90 and 100 mg $O_2\,kg^{-1}\,h^{-1}$ with an average of 95 mg $O_2\,kg^{-1}\,h^{-1}$ under continuous light (Ross and McKinney, 1988). Woo et al. (1997) obtained somewhat higher OCR in *O. niloticus* (124.7g average fish weight; 174±4.3 mg $O_2\,kg^{-1}\,h^{-1}$). Similarly, Iwama et al. (1997) found higher OCR of (110.8±17g average weight) of 177.2±16.9 mg $O_2\,kg^{-1}\,h^{-1}$ in O. *massambicus* than *O. shiranus* and *O. karongae*.

Table 5- 1 Oxygen consumption rates of *O. karongae* and *O. shiranus* from 14 experiments conducted in February, April, June, and August 2012 at Maldeco Aquaculture Farm. Only experiments with a linear portion of change in DO for at least an hour was used to estimate the OCR. $[O_2]$ t_o is the initial dissolved oxygen concentration, is the $O_2]$ t_1 final dissolved oxygen concentration at the end of the experiment.

Experiment	Month	Species	Total weight (Kg)	Mean weight (g)	WT (^oC)	$[O_2]$ t_o (mg/l)	$[O_2]$ t_1 (mg/l)	OCR (mg/kg/h)
1	February	*O. shiranus*	1.0	100.0	24.0	4.0	0.5	161.4
2	February	*O. shiranus*	1.1	56.9	24.9	4.1	1.1	118.9
3	April	*O. shiranus*	1.3	147.2	24.0	4.8	1.3	120.1
4	April	*O. shiranus*	1.2	165.8	24.0	5.4	2.6	110.2
5	June	*O. karongae*	1.2	241.6	23.1	6.0	3.4	99.0
6	June	*O. karongae*	1.1	219.1	21.3	4.8	2.7	89.4
7	June	*O. karongae*	1.1	224.3	23.0	7.0	4.4	105.4
8	June	*O. karongae*	1.3	146.7	22.7	4.7	1.9	101.2
9	June	*O. karongae*	0.9	135.6	22.5	6.0	4.2	86.8
10	August	*O. shiranus*	1.5	210.1	23.9	5.0	0.4	145.2
11	August	*O. shiranus*	1.1	110.4	23.1	3.6	0.4	135.8
14	August	*O. shiranus*	1.2	39.7	25.3	4.9	1.2	137.7

Comparisons of OCR with average fish weight for each experiment were made and the two species exhibited different trends in OCR and weight relationship (Figure 5-2). The OCR tended to decrease with weight in *O. shiranus.* While decreasing trend in OCR with weight was noted in *O. mossambicus* (Sparks et al., 2003) and increasing trend in *O. niloticus* (Ahmed and Magid, 1968). Because of the low number of experiments and expected similar physiology in these closely related species, all the experimental results were combined (Fig. 5-2) to test for a relationship between OCR and average fish weight. There was no significant correlation. Carrying capacity estimates (Chapter 6) will be based solely on the average OCR for each species regardless of the size of the fish in the cage. Challenges in obtaining clear relationships between OCR and body weight of poikilothermic organisms including fish was noted in previous studies (Mitz and Newman, 1989) due to influence of various factors including water temperature, day time, season, sex, weight and level of activity affect the metabolic rates of organisms (Wares II and Igram, 1979), and experimental conditions during the experiment (Mitz and Newman, 1989). Further studies involving different fish sizes with larger sample size are recommended for better estimates of OCR for better estimates of carrying capacities in cages, fish ponds, and circulatory aquaculture systems.

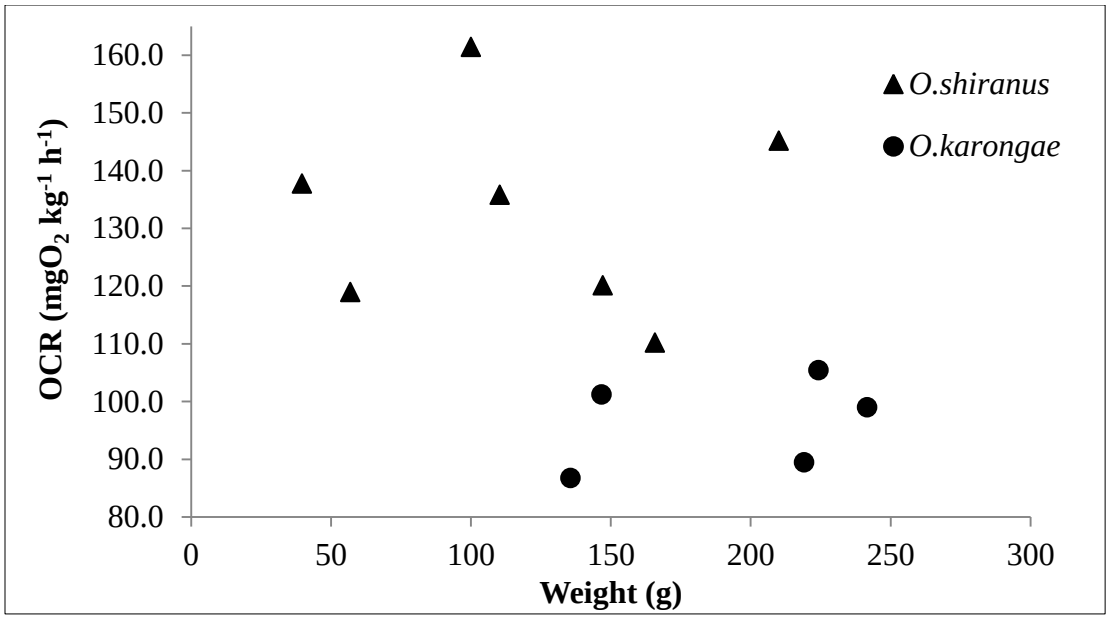

Figure 5- 2 Oxygen consumption rates and weight relationship of *O. shiranus and O. karongae*.

Chapter 6

Assessing the impact of a tilapia cage aquaculture farm and development of a carrying capacity model for sustainable cage aquaculture in Lake Malawi

Abstract

1. The study was conducted between November 2011 and September 2012 in the South East Arm of Lake Malawi (SEA) to provide information on characteristics and dynamics of ambient dissolved oxygen in a tilapia cage aquaculture farm during the day and night periods and to estimate the carrying capacity of cages and the farm.
2. Seasonal changes in dissolved oxygen concentrations (DO) in SEA had a strong influence at the farm. Fortunately, such influence did not reduce DO to concentrations that affect fish culture operations at the farm. Surface waters remained with DO above 6.5 mg/l most of the time, except in June and July.
3. Sampling during the day and night was importantant for understanding the differences in DO concentrations in both periods. Significantly higher night DOs were recorded in March, May, and June in all sites and in February, April, and August in few sites while significantly higher DO during the day was then observed in July and September. The nearshore sites had higher DO than offshore sites, most of the months.
4. Nearshore sites seem to be more oxygenated than offshore sites within the farm. However, a full hydrodynamic model is needed to confirm current observations.

5. Oxygen consumption of fish at the cages (OX1), oxygen transport (OT), and carrying capacity (CC) were variable and showed no pattern as regard to positioning of the cage (i.e. nearshore-offshore) at the farm.
6. Based on biomass estimates, none of the cages was overstocked and the CC estimated was much higher than existing biomass at the farm. To allow normal fish growth rates and attainment of desirable marketable sizes within production cycle that would reduce the residence time of the fish in the cages, mean stocking density of 23,389 ±44 kg and 1,866,689±95,678 kg are recommended for individual cages and for the entire Maldeco Aquaculture farm respectively.

6.1 Introduction

The cage aquaculture industry necessarily uses large amounts of feed and releases unused feed as well as excretory products containing P and N from cultured fish that contribute to eutrophication of lakes (Folk et al., 1994) and which can result in increased lake productivity, occurrence of dense algal blooms causing turbidity, disruption of food webs, increased rates of sedimentation of plant material and increased anoxic conditions in the deeper parts of the lake (Schindler et al., 2008), increased biological oxygen demand (Ye et al., 1991) and cause negative effects to farmed fish species and to the immediate surrounding environment (Stigebrandt, 2011). The potential eutrophication resulting from cage culture can only be addressed if we are able to understand and quantify the interaction between aquaculture and the environment (Stigebrandt, 2011) to minimize environmental impacts as much as possible. Responsible aquaculture investment requires predictive tools that measure the capacity of projected areas that will support the biomass of cultured species (Byron et al., 2011). Such information is important to potential investors and resource management interested in the production capacity and stakeholders concerned about the status of the environment or about potential negative effects that may arise in the future (Jiang and Gibbs, 2005).

Most environmental impact studies have been conducted in temperate climate locations especially marine locations but only a few on inland tropical waters. Tropical waters are at a higher risk compared to temperate waters because dissolved oxygen concentration are already low because warm temperatures lower the oxygen solubility of water and warmer waters have higher rates of biological oxygen demand (Hecky, 2000). The current study is relevant to various aquaculture program initiatives in Malawi as

Africa is considered to have a higher annual increase in the number of people engaged in fish farming (estimated at 5.9 percent between 2000 and 2010 period), higher than Asia (4.8 percent) and Latin America and the Caribbean (2.6 percent) (FAO, 2012). Such an increased growth in fish farming and related activities, coupled with lack of information on environmental effects pose concerns for sustainable farming in the tropics (Tacon and Halwart, 2007).

The Government of Malawi is aware of potential negative impacts of cage aquaculture on the environment and has taken a precautionary approach by allowing only one private cage operator, the Maldeco Aquaculture Limited to operate at a commercial scale. However, it is not known how long the government of Malawi will maintain its commitment to preserve existing waters bodies owing to requests from the private sector to use existing water bodies for fish farming. In addition, being a shared water resource, where there is little or no collaboration among the riparian countries (Malawi, Mozambique, and Tanzania) for its sustainable management. It becomes complex to manage Lake Malawi ecosystem as each country maximizes exploitation without taking into account the other side of the lake. As of now, the major concern is the expansion of cage aquaculture industry in Lake Malawi which requires wise decisions to be made for its sustainability. The impacts of cage farms may be immediately at the farm on which farmed fish at high stocking densities (overcrowding) may lack adequate amounts of oxygen to support growth. However at larger scales of operation, the impacts may extend to larger areas with regional magnitude.

Malawi is one among many African countries currently without decision-support tools to accompany the expansion of cage aquaculture in Lake Malawi and other potential

water bodies. The large scale commercial cage aquaculture initiated in Lake Malawi waters in 2004 by the Maldeco Aquaculture Limited which is also the only commercial capture fishing industry in Lake Malawi is growing and has contributed to total fish production in Malawi although some problems have set back its potential. The Company started operating with 11 cages (circular with 16 m diameter, 6 m deep) in 2004 to farm the endemic *Oreochromis karongae* as well as native *O. shiranus* in the shallow southeast arm (SEA) of Lake Malawi. As of July-August 2010, the number of cages had increased to 58 and then, reduced to 51 in 2012. Not all the cages were continuously stocked with fish. Initially, each cage was stocked at high densities. e.g. 130,000 fish per cage (Gondwe et al., 2011) and sometimes over 140,000 fish, but the densities have been reduced to less than 120,000 probably due to concerns related to either reduced growth rates or lack of fingerlings of uniform sizes to replenish the harvested fish. Decisions about stocking density per cage have economic consequences, but stocking densities are also important to estimate the maximum permissible production capacity of each cage or the capacity of the entire farm while avoiding environmental impacts that may limit the farm's productivity. It is also important to set the ecological limits, and social acceptability of aquaculture while maintaining the functioning of the natural ecosystem and social structures (Byron et al., 2011) for sustainable farming.

The aim of the current study was to test a model for site specific carrying capacity in Lake Malawi. Successful application of the model is expected to be used as a decision supporting tool to guide the private sector with appropriate stocking densities at farms and also to use as a monitoring tool by the government and other regulatory authorities concerned with aquatic ecosystem health.

6.1.1 *Carrying capacity models*

Increased degradation of small, enclosed, and poorly flushed waters bodies due to nutrient enrichment by cage aquaculture waste and increased social conflict with other user groups was a major driver for carrying capacity models (Byron et al., 2013). Predictive models that use the background phosphorous concentrations in lakes and those released by existing or potential fish farms into aquatic environment (Dillon and Rigler, 1974; Håkanson et al., 1988; Beveridge, 1996) have been extensively used in environmental impact assessment and in the assessment of environmental effects of fish farms. However, despite their importance in preventing adverse impacts on water quality the existing phosphorus models do not provide detailed information on the materials that enter the environment, their fate and impact, how much waste is dissolved, how much of the waste is organic or inorganic (Beveridge, 2004). Traceability of cage effluent may be effective in isolated, poorly flushed semi-enclosed or closed small lakes, estuaries, and fjords (Alongi et al., 2009), but not in lakes where human activities have a considerable contribution to nutrient loading (Kelly, 1995) and in strongly flushed systems. A recent study in Lake Malawi found no significant differences in ammonium, nitrate, phosphorous, particulate carbon, nitrogen, and phosphorous, dissolved oxygen, Secchi depth, and chlorophyll a concentrations among the cage aquaculture site (considered as a point source of pollution) and control stations located up to 5 km away from it (Gondwe et al., 2011), despite active farming activities. That study concluded that high flushing rates and/or effective recycling of waste materials by wild fish prevented a buildup of materials that would have impacted the cage farm area. But this study did not specifically

propose a model of oxygen use and renewal that could be used to define the carrying capacity of the site and that could be used to guide siting decisions for other locations.

Four types of carrying capacity models: physical, production, ecological, and social capacity (Inglis et al., 2000; McKindsey et al., 2006) have been successfully used for sustainable aquaculture in both freshwater and marine environment. The *physical carrying capacity* is the total physical geographical space available to accommodate certain type of aquaculture farm. The physical properties of the area and those required by the candidate species should be synchronized (e.g. size, type of substrate, depth, and hydrodynamics) (McKindsey et al., 2006). The physical carrying capacity model does quantify the ecosystem capacity, but the assumption of complete ownership of the water body for aquaculture development (Byron et al., 2011) makes this model ineffective in water bodies having multiple uses. The model quantifies the areas available for aquaculture in the ecosystem, but addresses little about aquaculture limits within the water body (Byron at al., 2011), nor does this model considers biological and chemical aspects considered in production and ecological carrying capacities (McKindsey et al., 2006). *Production carrying capacity* is the maximum harvestable biomass from aquaculture production for a target species in a specific location of the water body (McKindsey et al., 2006). It depends on the *physical carrying capacity* and the response of the water body to nutrient additions, primary productivity, and ecosystem responses to cultured organisms (McKindsey et al., 2006). The *ecological carrying capacity* estimates the maximum biomass permissible in an area for aquaculture production without leading to significant changes to ecological processes, species, population, and community in the environment (Byron et al., 2011; McKindsey et al., 2006). Finally, the s*ocial carrying*

capacity is usually evaluated only after the preceding levels of carrying capacity have been completed to ensure unbiased assessment (McKindsey et al., 2006). It has been defined as the amount of aquaculture which considers the values of local communities and avoids conflicts due to expansion of cage aquaculture (Byron et al., 2011). Local communities and traditions play an important role on social carrying capacity (Ferreira et al., 2014) since environmental degradation may reach states that prohibits local fishermen from deriving their livelihood from impacted water bodies and may well prevent tourists from visiting the areas, thereby, reducing local economies.

The current study uses a sub-model for water quality, an appropriate model for site specific carrying capacity estimates and does not assume complete ownership of the lake. It incorporates aspects of physical, production, and ecological carrying capacities. It does not address the social carrying capacity directly, but social carrying capacity is taken care of by ensuring the balance between production estimates and preservation of the environment. The sub-model is an integrated component of the MOM model (Modelling-Ongrowing fish farms-Monitoring) system (Ervik et al., 1997) and follows MOM's requirements which include (i) keeping the benthic fauna at the farm regardless of accumulation of particulate or dissolved organic matter, (ii) the quality of the water should be optimum for the fish and benthic fauna, and (iii) the water quality in the area must not deteriorate at the expense on farmed fish (Stigebrandt et al., 2004). In general, these requirements are made to maintain the whole water column with enough oxygen to support farmed organisms in the surface and the benthic fauna, simultaneously. While the MOM system is a multiple parameter system based on four sub-models (the fish model, the dispersion sub-model, the benthic sub-model, and the sub-model of water quality)

(Stigebrandt et al., 2004), the current study focused on oxygen concentration for two reasons. Firstly, oxygen concentrations are already low in tropical lakes compared to temperate systems and fish metabolic rates and BOD rates are also high so that risk of low oxygen affecting fish growth is of concern. Secondly the sub-model applied requires relatively simple measurements, e.g. water currents, depth, size of the cages and the farm which can be measured by farm owners using relatively simple and inexpensive conventional instruments. This is an important consideration for developing countries where regulating agencies as well as communities interested in development have limited resources for evaluating and monitoring aquaculture operations.

6.2 Materials and methods

6.2.1 *Study area*

Lake Malawi is located in south/central Africa and is shared among Malawi, Mozambique, and Tanzania. The lake has a surface area of 29,500 km^2, a mean depth of 264 m, maximum depth of 700 m and a volume of water of 7,775 km^3 (Hecky and Bootsma, 2003). It is the most species rich lake in the world in fish with an estimated 500-1, 000 fish species (Fryer and Iles, 1972) with more than 90% of fish being haplochromine cichlids (Fryer and Iles, 1972; Ribbink et al., 1983; Snoeks, 2000). The northern and central regions of the lake are deeper than the southern basin. Complete mixing of surface and bottom waters in the deep northern basin has never been observed (Eccles, 1974; Snoeks, 2000). Annual mixing driven by seasonal cooling and wind action occurs above 200 m while below 200 m, the water remains anoxic (Bootsma and Hecky, 2003). The study was conducted in south east arm of Lake Malawi near where the Shire River exits the lake just south of the Maldeco Aquaculture farm (Figure 6-1). The farm is located in shallow waters where the cages are moored between 11 and 30 m of water depth. The farm covers an area demarcated with red and orange buoys of approximately 115, 500 m^2 (length of 875 m and with of 132 m). The 51 cages are lined in 12 rows on which the 9 rows have 4 cages each and 3 rows have 5 cages. The distance from the first row to the shore is about 412 m.

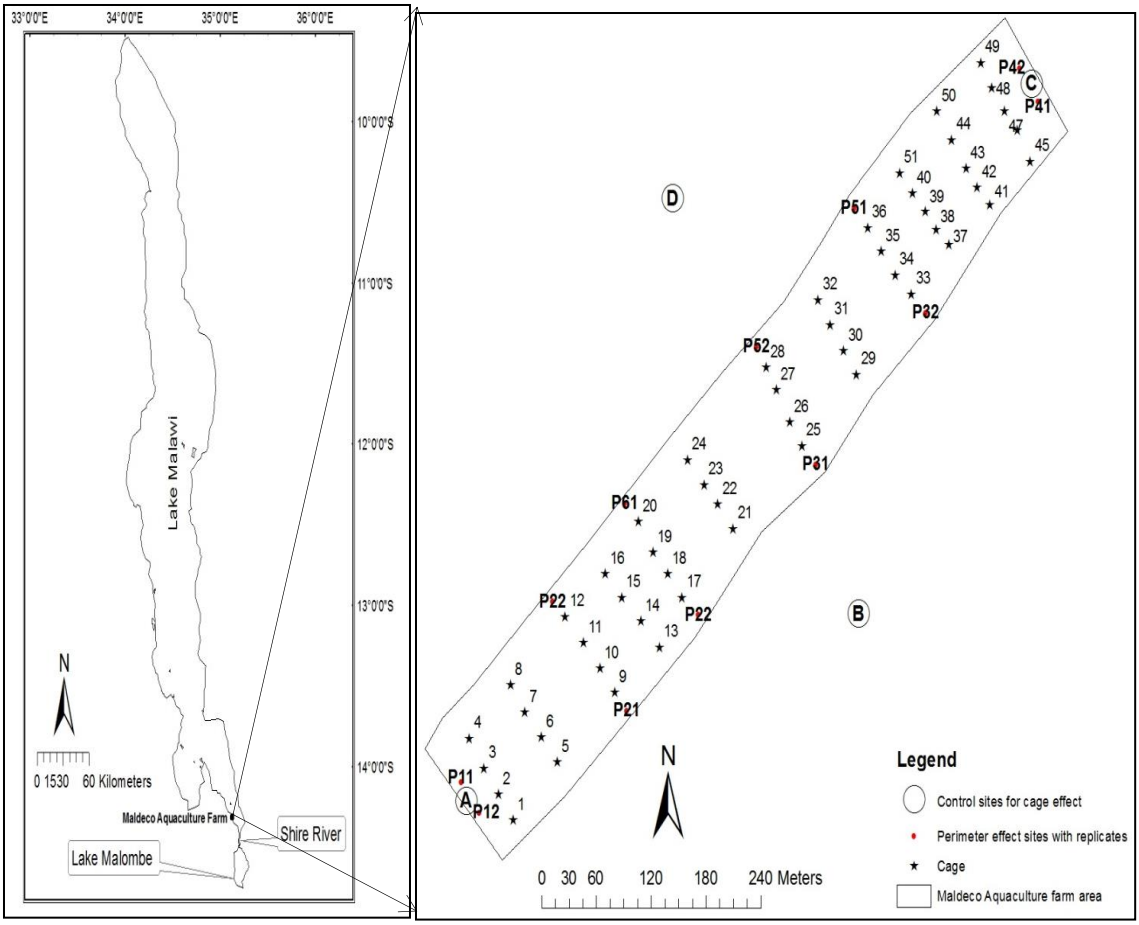

Figure 6- 1 Map of the location of Lake Malawi and location of Maldeco Aquaculture Farm (left panel) showing locations of cages (1 to 51), reference sites (A, B, C, and D) for cage effect studies, and perimeter effect sites (P1 to P6) (right panel). Perimeter effect sites were designated as: P11 (site 1, replicate 1), P12 (site 1, replicate 2), P21 (site 2, replicate 1), P22 (site 2, replicate 2), P31 (site 3, replicate 1), P32 (site 3, replicate 2), P41 (site 4, replicate 1), P42 (site 4, replicate 2), P51 (site 5, replicate 1), P52 (site 5, replicate 2), P61 (site 6, replicate 1), and P62 (site 6, replicate 2).

6.2.2 *Sampling procedure*

Temperature and oxygen concentration sampling was done at Maldeco Aquaculture farm between November 2011 and September 2012. The sampling followed two approaches, the first to test for a farm effect on oxygen concentration and the second to test for individual cage effects on oxygen concentrations. In both studies, data was also collected for carrying capacity estimates starting from December 2011. Initially, samples were collected during the day, but starting from February, night samplings were initiated to examine the diurnal effects of the farm and farm carrying capacity:

Perimeter effect: Six sampling locations along the perimeter with two replicates each (P1, P2, P3, P4, P5, and P6) were selected to investigate spatial and temporal changes in dissolved oxygen concentrations owing to oxygen demand by the farmed fish. Dissolved oxygen profiles were measured with a Conductivity Temperature and Depth (CTD) sonde (Branckner, XR-620). Day and night samplings were done with purpose of investigating oxygen concentrations not only during the day, but also at night when photosynthesis is shut off and also to estimate the farm carrying capacity of the farm during an expected nightly minimum in oxygen concentrations. Water currents and oxygen concentrations flowing in and out of the farm were recorded at each sampling with a Global Water Flow Probe (FP211) flow meter and wind direction was detected by a Suunto A-30L GPS compass as well as the positioning of anchored boats and canoes. Sampling was done during the day between 8:00 am to 5:00 pm and at night between 10:00 pm and 3:00 am using a plank boat provided by Maldeco Aquaculture Limited to test differences in carrying capacities between day and night.

Carrying capacity estimates based on the farm perimeter were based on total length of the farm, depth of the cage and two sites, one inside the farm and another outside it but in the neighborhood of it (Stigebrandt, personal communications). In addition to six sites at the farm perimeter, there are four reference sites for cage effect (A, B, C, and D) (Figure 6-1) positioned outside the farm. Site B was also used for carrying capacity of the farm as the neighborhood representative site for water entering the farm during periods of south east winds and site P52 was used as the outlet site from the farm. Under northern winds, which occurred once, site D (control site for cage effect) and site P31 were also used for carrying capacity estimates. The four sites (P52, P31, B, and D) are nearly at similar distance from the lake shoreline.

The total depth at each sampling location was recorded by the CTD and a depth sounder (Hummingbird) (788CI COMBO) on a monthly basis between December 2011 to September 2012. The coordinates of the cages and the locations of the sampling sites were recorded by a Geographical Positioning System (GPS) and (Hummingbird) (788CI COMBO). This data was then used to estimate the area and length L_F of the farm using the Geographic Information System (GIS) (ArcMap v-10.1).

C*age effect:* Between 7 to14 cages were selected based on their farmed fish biomass with the target being for small, medium, and large fish to investigate the effect of biomass on the cage effect and to estimate the carrying capacity of individual cages. Sampling was done only during the day between 8:00 am to 5:00 pm. Water currents flowing in and out of the cage were recorded, based on wind direction, at four locations at 90^o increments clockwise around the cages. CTD profiles were done inside (downstream)

and outside (upstream) the cages for cage effect and also done to the bottom at the reference sites for cage effect (Figure 6-1).

Monthly fish biomass data of individual cages was provided by Maldeco Aquaculture Limited. Biomass estimates are based on the initial number of fish stocked at the cages (Initial number), fish mortalities (Death), and the average body weight (ABW) of the fish recorded at regular sampling intervals. The estimates translated into the formulas for monthly biomass: Biomass (kg) = (Initial fish number-Death)*ABW (g)/1000.

The water depth of the six sampling sites around the perimeter of the farm differed from shallowest to deepest and fluctuated somewhat over the sampling period (Figure 6-2) responding to seasonal water level change and sediment movement at this sandy bottom location. In all sites, water depths increased from November to peaks reached between March and May as a result of annual change in lake level. Sites P1, P2, P3, P5, and P6 reached their peak in March, site P3 in April, and site P4 reached its peak in May (Figure 6-2) suggesting some sediment movement at site P4. Water depths increased from site P1, the closest to the shoreline, to site P4 the farthest offshore. The water depth at site P1, fluctuated between 12.01±0.1 and 13.05±0.0 m. Sites P2 and P6 were located at similar depths (14.9±0.7 and 17.7±0.9 m) as there was no significant difference in their depth (p>0.05). Similarly, there was no significant difference between sites P3 and P5 (p>0.05) located at offshore area with depth ranging between 17.8±0.3 and 20.8±0.3 m. Finally, site P4, the most offshore site with depth ranging between 19.0±0.1 and 22.1±0.2 m had significantly higher depth compared to all sampling

locations (p<0.05), except between July and September when the depth at sites P3, P4, and P5 were not significantly different (p<0.05) (Figure 6-2).

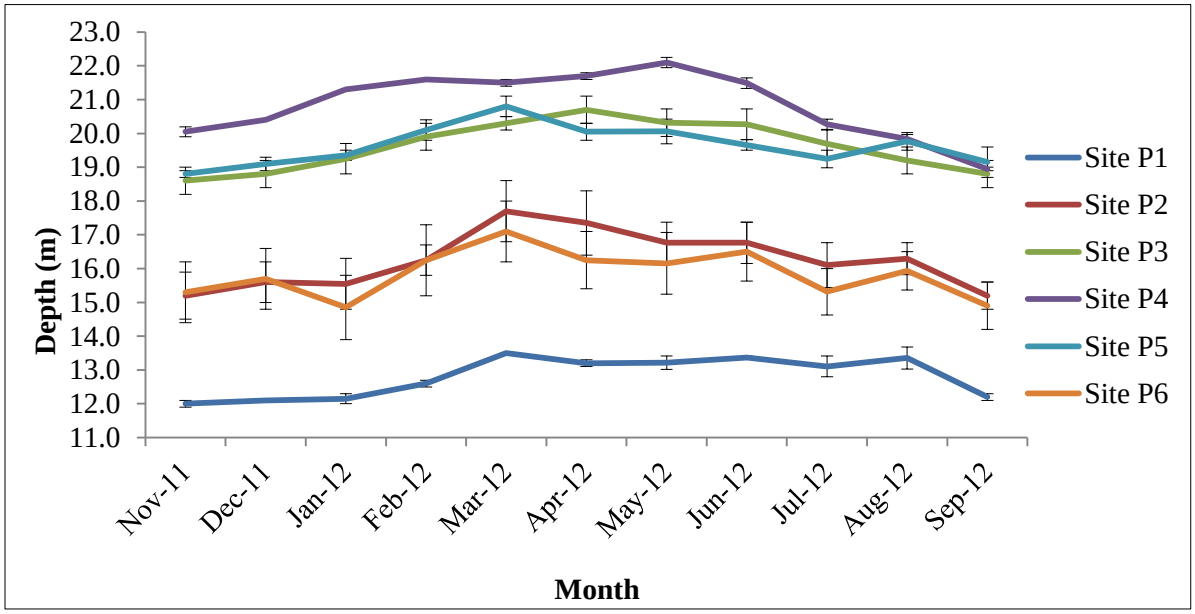

Figure 6- 2 Fluctuations in water depth within the farm perimeter sampling locations between November 2011 and September 2012 (mean±se).

6.2.3 *The sub-model of water quality in fish cages*

The rate of oxygen consumption of fish at the farm or a cage (OX1) can be given by:

$$OX1\ (kg/h) = (O_{2IN} - O_{2OUT})*L_F*D*U_{MIN} \quad (1)$$

Where O_{2IN} is the oxygen concentration flowing in (kg/m^3) to the cage or farm, O_{2OUT} is oxygen concentration flowing out (kg/m^3). O_{2OUT} should not fall below O_{2MIN} or

estimate of fish O_2 consumption will be affected by oxygen stress. Maximum oxygen supply available to the farm or cage is utilized when $O_{2OUT} = O_{2MIN}$. The O_{2MIN} for tilapias is 3.0 kg/l (Ross, 2000). L_F is length of the farm (m). The L_F did not vary with orientation of the currents. D is the depth of the farm (m) at sampling location, and U_{MIN} is the minimum water currents (m/s) recorded over the duration of data collection which should be a few months to a year. The U_{MIN} of 0.004 m/s estimated at the same farm between May and December 2007 with a 2D-ACM Falmouth Scientific Inc. (FSI) acoustic water current meter by Gondwe et al. (2011) is used in the current study.

The oxygen transport (OT) given in kg O_2/h is the amount of useful oxygen transported to the farm or cage per hour:

$$OT\ (kg\ O_2/h) = (O_{2IN} - O_{2MIN})*L_F*D*U_{MIN}*P_F \quad (2)$$

$$P_F(t) = U_i(t)/U_o(t) \quad (3)$$

Where: P_F is permeability of the farm estimated from empirical measurements. $U_i(t)$ is the current in the cage (or current flowing out of the cage or farm) and $U_o(t)$ is the current outside the cage or farm. The floating cages and their netting and fish reduce the water flow as it passes though the cages. Such a measure that quantifies how much flow enters and passes the farm or cages is the permeability of the farm (eq. 3) P_F ($0< P_F <1$). P_C was used as permeability of the cage. Likewise, L_c was used as the length of cage.

The carrying capacity of the farm or cage (CC) was estimated as:

$$CC\ (kg) = OT/OCR \quad (4)$$

Where: OCR is the specific oxygen consumption rate of fish (*O. karongae* and *O. shiranus*). Both OX1 and OCR are oxygen consumption rates of fish. However, OX1 is a

measure of oxygen consumption in the field while OCR was experimentally estimated using a respirometer (Chapter 5).

Renewal of oxygen inside the cages is mainly done through external waters passing through the cages by currents (Beveridge, 2004) although exchange with the atmosphere and photosynthesis can also modify in situ oxygen concentrations in the cage. Possible oxygen diffusion through water surface and fish-induced motions that may increase oxygen concentrations over the bottom are neglected in the sub-model (Stigebrandt et al., 2004). The carrying capacity of the individual cage is determined using the same formulae for farm carrying capacity.

6.2.4 *Data analysis*

Detailed DO profiles were made monthly and a subsample of those profiles were selected here to provide exemplary profiles for different times. Hence, additional profiles from December, January, April, and July samplings are not described here. Mean DO data between 0 and 1.0 m depth was extracted from the profiles to test significant spatial and temporal differences at the farm perimeter. This was the depth on which greatest differences in DO in the profiles were noted at the cages due to oxygen consumption, especially during the feeding periods when fish are most active and congregate at the surface. Daytime sampling at the cages was done during feeding periods with presence of Maldeco employees for security purposes. Analysis of Variance (ANOVA) using SPSS Statistics v-20 was applied to identify significant differences in oxygen concentrations and the depth of the six perimeter sampling sites and to identify the significant differences in estimated carrying capacity. The *p*-values provided by ANOVA; Post Hoc

multiple comparison using the Least Significant Difference (LSD) discriminated significantly different sites, at a significance level of 0.05. Mean monthly values were plotted to visualize changes in seasonal trends and day/night DO concentrations.

6.3 Results

6.3.1 *Spatial and temporal changes in dissolved oxygen concentrations at the farm perimeter*

November: DO profiles in November around the farm perimeter exhibited similar spatial patterns between replicates and among the sites (Figure 6-3) located at different depths (Figure 6-2). A DO increase with depth was noted at all sites. Site P1 reached a peak DO between 5 and 6 m whilst the peaks in other sites were below 6m. The upper surface waters (0-1 m) showed no significant differences in DO among sites (Table 6-1, Figure 6-10).

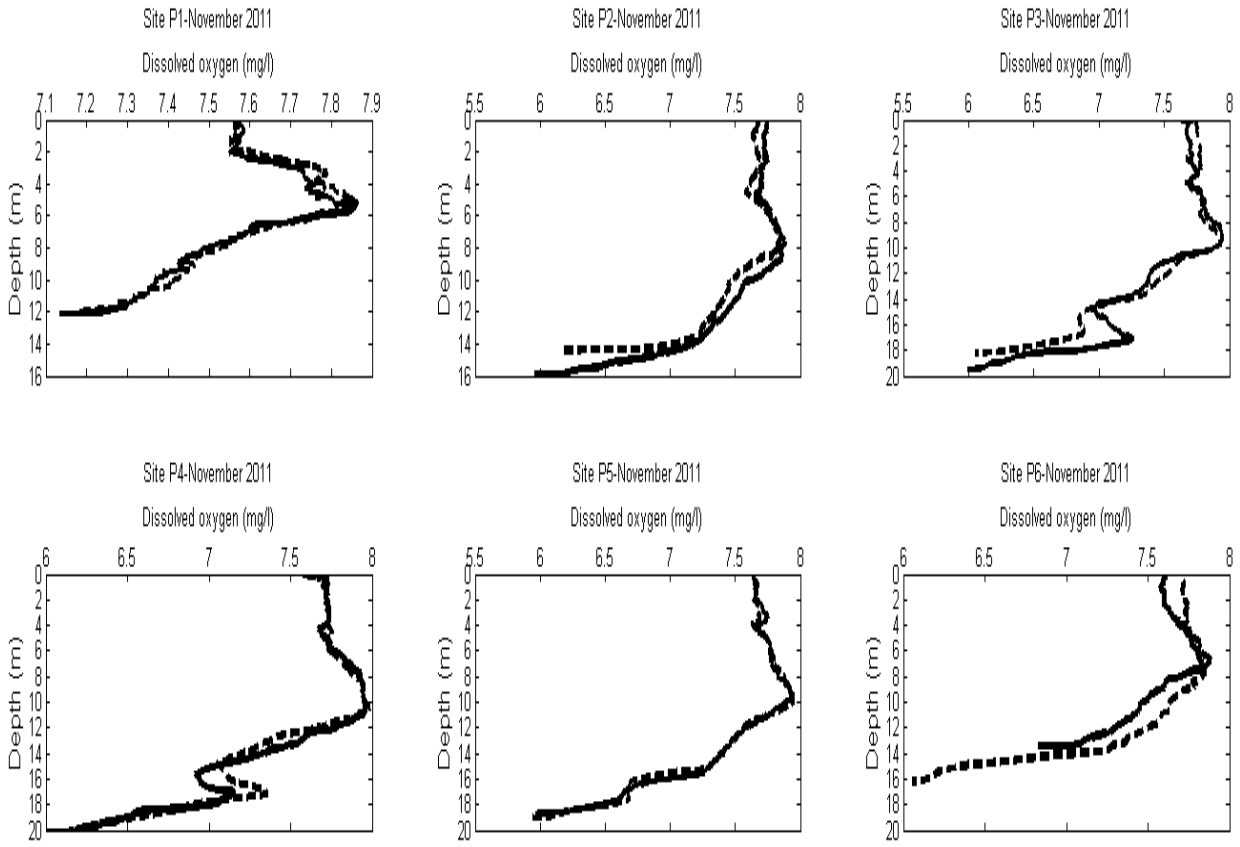

Figure 6- 3 Spatial changes in dissolved oxygen at Maldeco Aquaculture farm perimeter during the day in November 2011. Solid black line is replicate 1 and black dashed line is replicate 2.

December and January: There was significant spatial difference in DO in December and January (Table 6-1). Sites P5 and P6 had significantly lower DO than sites P1 and P3 in December (Table 6-1). The DO at site P5 was also significantly lower DO than site P4. Opposite results were seen in January. Sites P5 and P6 had similar DO, but significantly higher than sites P2, P3, and P4 (Table 6-1).

February: Day and night DO profiles show similar trends characterized by high and low DO at the surface and bottom, respectively (Figure 6-4). Day profiles overlap at

sites and this is confirmed statistically by non-spatial significant differences in DO sampled February 10, 2011 between 9:20 and 12:20 pm (Table 6-1). The difference between the lowest DO of 7.51±0.4 mg/l recorded at site P4 and the highest of 7.64±0.9 mg/l at site P5 was small (Figure 6-4), despite some variability, there were not spatial differences during the day. Night sampling in February 11, 2012 conducted between 01:08 and 3:00 am, shows significant spatial difference (Table 6-1). Site P1 located nearshore had significantly lower DO than sites P2, P3, P4, P5, and 6 ($p<0.05$), while the DO at sites P2, P3, P4, P5, and P6 was not significantly different (Table 6-1, Figure 6-10). Significant spatial differences in February were also noted between day and night samplings (Table 6-1). DO was significantly higher at night in sites P1, P3, and P4 compared to day samplings (Table 6-1). Figure 6-4 shows overlapping of non-significantly different sites and differences in those that found significantly different.

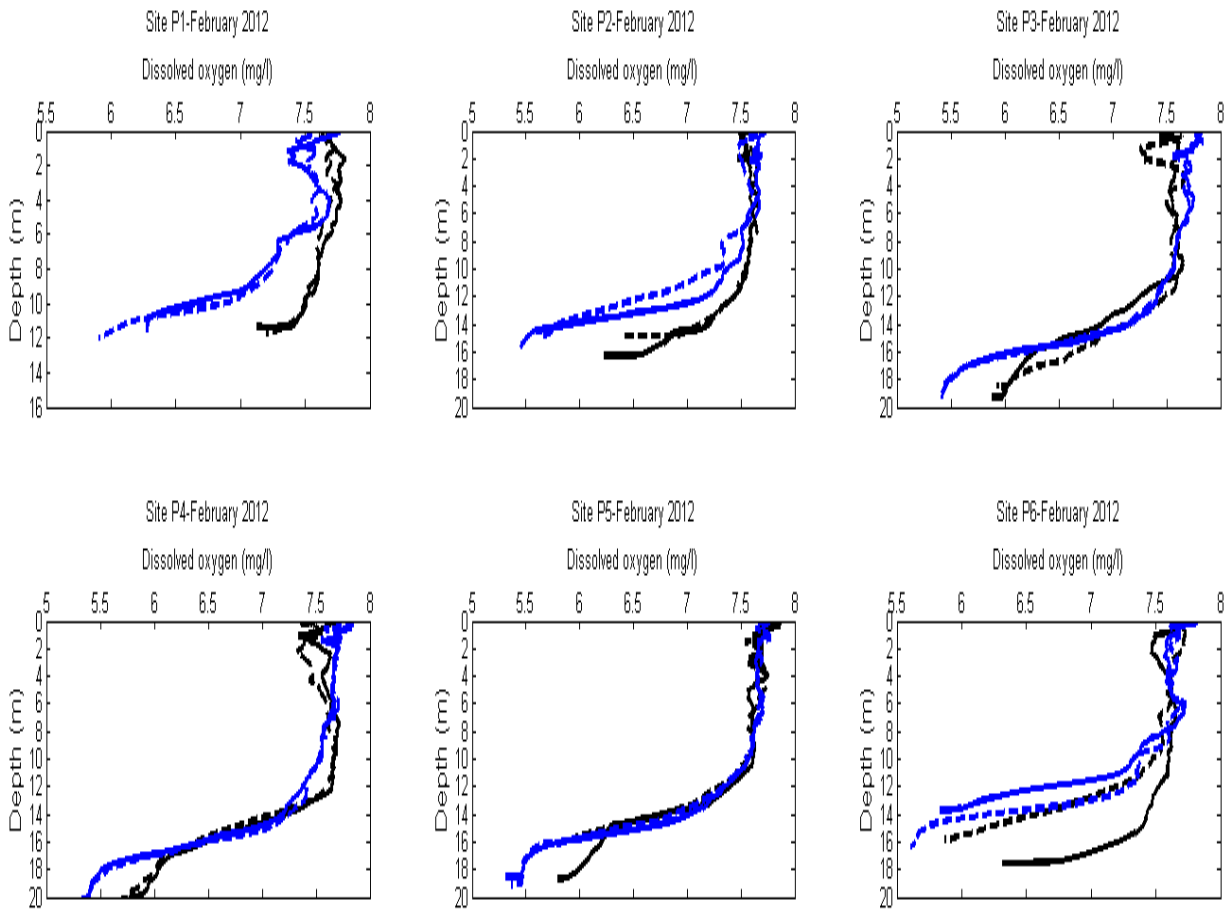

Figure 6- 4 Spatial and temporal changes in dissolved oxygen at Maldeco Aquaculture farm perimeter in February 2012. Solid black line is day site replicate 1, dashed black is day site replicate 2, solid blue is night site replicate 1 and dashed blue line is night site replicate 2.

March: Profiles recorded in March 28, 2012 during the day between 9:22 am and 12:20 pm show a similar declining pattern with depth in all sampling sites (Figure 6-5) and no spatial significant difference in DO was found during the day (Table 6-1, Figure 6-10). Night sampling was conducted in the same day, but between 22:20 pm and 1:00 am and show significant spatial differences (Table 6-1). Contrary to February, site P1 had

significantly higher DO than sites P2, P3, P4, P5, and P6 (p<0.05) while the concentrations at sites P2, P3, P4, P5, and P6 were not significantly different from each other (Table 6-1). Significant temporal differences were noted (Table 6-1). Day concentrations were low and varied between 6.95±0.03 mg/l (site P4) and 7.07±0.01 mg/l (site P1) while night DO varied between 7.16 ±0.03 mg/l (site P5) and 7.30±0.02 mg/l (site P1) (Figure 6-10). Such an increase of night DO at all sites resulted in significantly higher DO at night (Table 6-1).

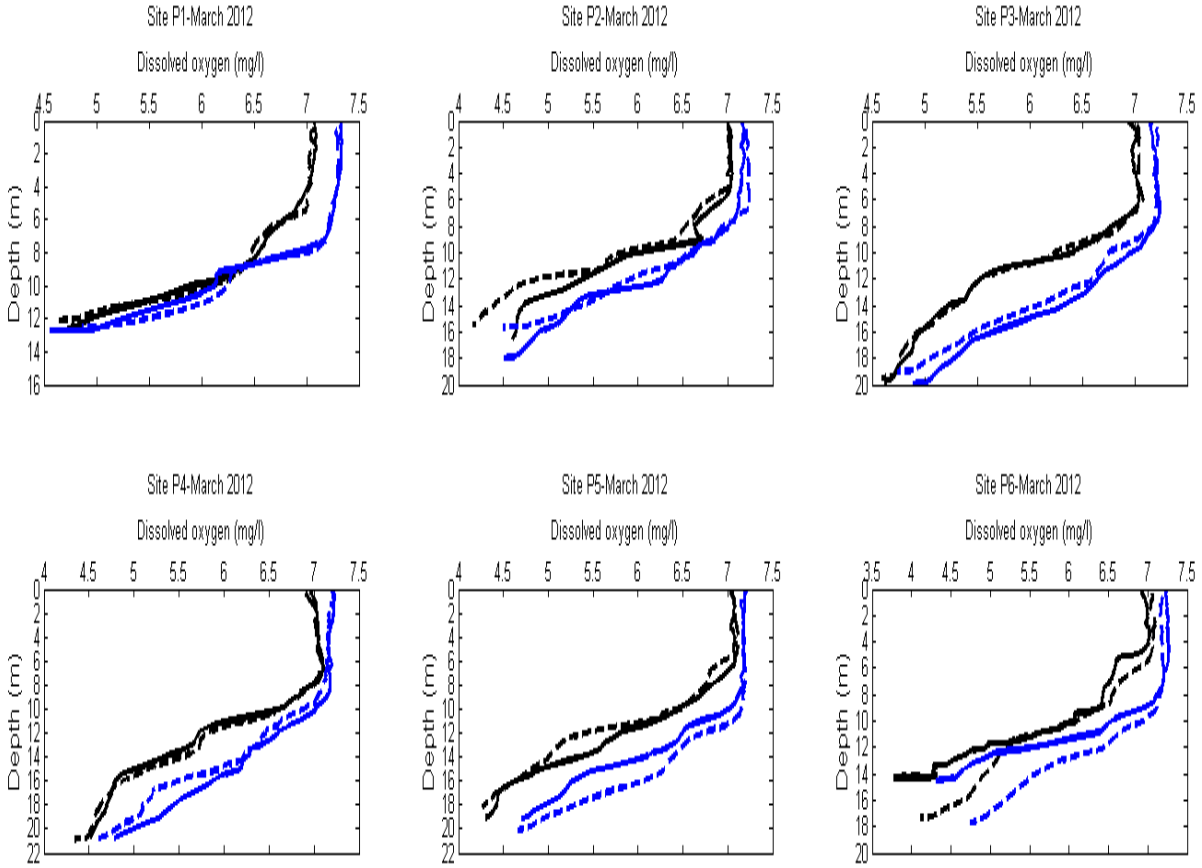

Figure 6- 5 Spatial and temporal changes in dissolved oxygen at Maldeco Aquaculture farm in March 2012. Solid black line is day site replicate 1, dashed black is day site replicate 2, solid blue is night site replicate 1 and dashed blue line is night site replicate 2.

April: DO profiles for April are not provided. Day sampling from April, 19, 2012 between 9:03 and 11:45 am showed significant spatial difference in DO (Table 6-1). Sites P3, P4, and P5 had similar DO concentrations (Figure 6-10), but were significantly lower than those from sites P1, P2, and P6 ($p<0.05$). Significant spatial difference in DO was also noted at night (Table 6-1). Site P1 had significantly higher DO than sites P2, P3, P4, P5, and P6 ($p<0.05$). Site P4 located offshore had the lower DO than sites P3 and P6 (Figure 6-10). The lowest and highest DO was recorded at sites P4 and P1 respectively during the day and at night (Figure 6-10). Sites P1, P3, and P6 located nearshore had significantly higher DO during the day and low at nigh (Figure 6-10). However, the offshore sites P3 and P4 had significantly lower DO during the day.

May: Day and night profiles show an increse of DO with depth in all sampling sites (Figure 6-6). The upper surface waters during the day had DO less than 6.8 mg/l while at night, upper surface waters had DO more than 6.8 mg/l. Significant spatial differences in DO were noted during the day, but not at night (Table 6-1). During the day, sites P3, P4, and P5 had similar DO concentrations, but their DO were significantly lower than those from sites P1, P2, and P6 ($p<0.05$) (Figure 6-10). A similar pattern was seen during the day in April (Figure 6-10). DO varied between 6.63±0.01 and 6.75±0.02 mg/l during the day and between 7.01±0.00 and 7.05±0.02 mg/l at night (Figure 6-10). This significant night increase in DO resulted in significant differences between day and night DO (Table 6-1). The profiles (Figure 6-6) confirm significant differences between the two periods.

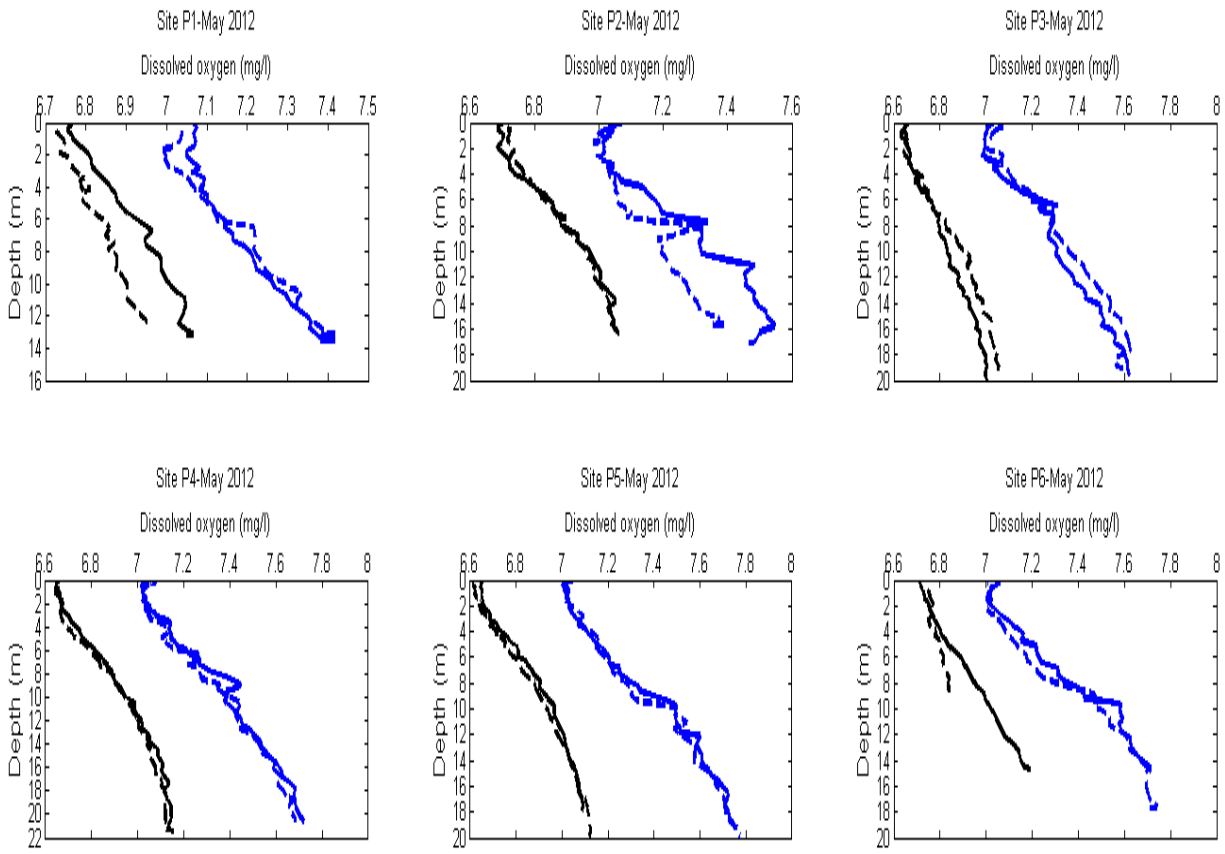

Figure 6- 6 Spatial and temporal changes in dissolved oxygen concentrations at Maldeco Aquaculture farm perimeter in May 2012. Solid black line is day site replicate 1, dashed black is day site replicate 2, solid blue is night site replicate 1 and dashed blue line is night site replicate 2.

June: Day and night DO profiles in June (Figure 6-7) exhibited similar trend with the profiles in May (Figure 6-6), but with relatively lower DO concentrations compared to those recorded in May (Figure 6-6). There was no significant spatial difference in surface DO during the day and at night (Table 6-1). The lowest DO of 6.24±0.00 mg/l was recorded at site P3 and the highest of 6.27±0.02 mg/l at site P4 (Figure 6-10). Similarly, site P1 had the highest DO at night (6.42±0.02 mg/l) and the lowest of

6.34±0.01 mg/l was recorded at site P6. In both cases small spatial differences resulted in non-significant differences in each of the periods (Table 6-1). Significant differences were noted between day and night samplings (Table 6-1). Night surface DO concentrations were significantly higher than day concentrations (p<0.001) (Figure 6-7).

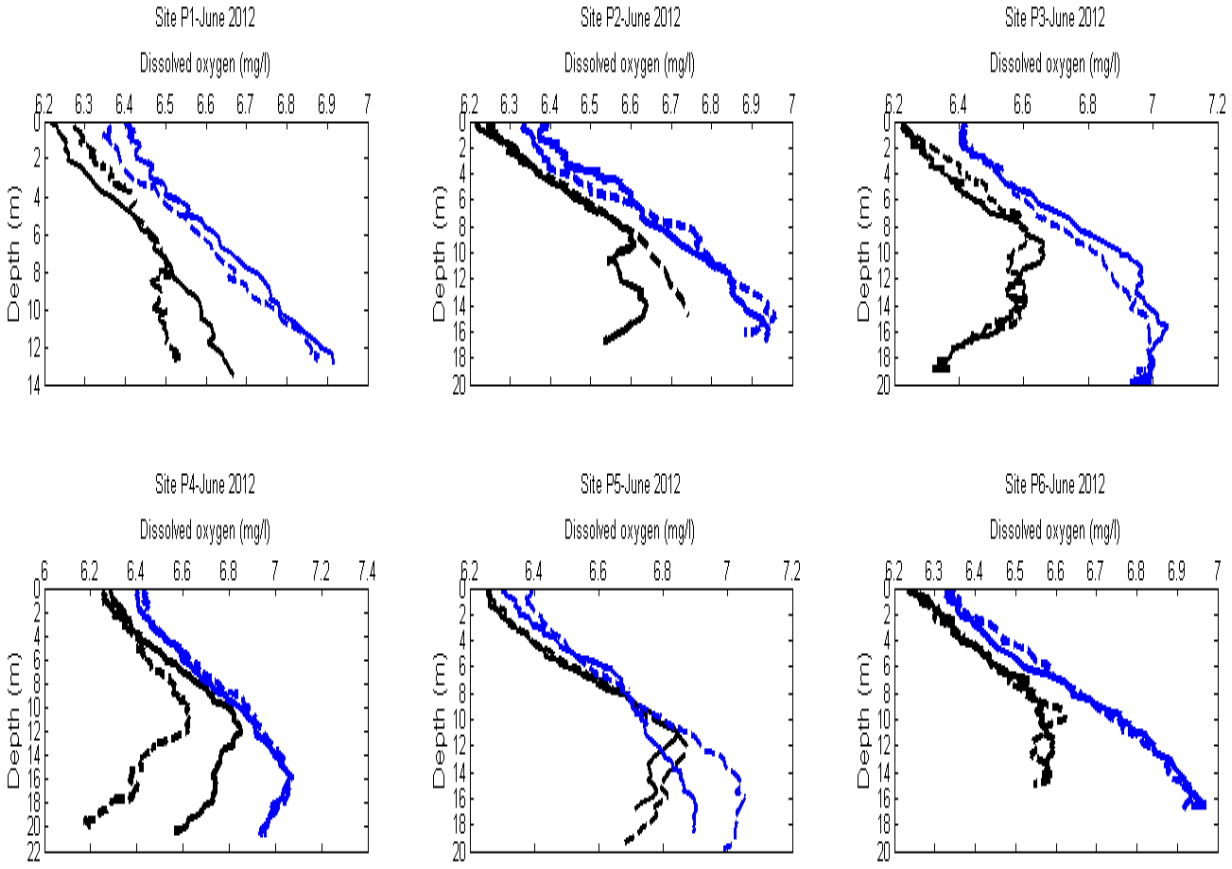

Figure 6- 7 Spatial and temporal changes in dissolved oxygen concentration at Maldeco Aquaculture farm perimeter in June 2012. Solid black line is day site replicate 1, dashed black is day site replicate 2, solid blue is night site replicate 1 and dashed blue line is night site replicate 2.

July: DO concentrations varied between 6.39±0.01 and 6.45±0.47 mg/l during the day and between 5.98±0.01 and 6.25±0.03 mg/l at night (Figure 6-10). Significant spatial

significant differences were seen at night but not during the day (Table 6-1, Figure 6-10). Sites P1 and P6 located nearshore had high and similar DO (Table 6-1). Their concentrations were significantly higher than those at sites P2, P3, P4, and P5 ($p<0.05$). Sites P4 and P5, located offshore had similar DO which was significantly lower DO than the concentrations at sites P2 and P3 ($p<0.05$). The concentrations were significantly higher during the day than at night at all sampling locations (Table 6-1) (Figure 6-10).

August: Day and night sampings cnducted in August 28, 2012 between 8:38 and 11:40 am during the day and between 10:43 and 12:00 am at night show high variability in DO between replicates, especially during the day (Figure 6-8). Variability between the replicates was also seen at night. August was the only month on which day and night differences were not not seen (Table 6-1) (Figure 6-11).

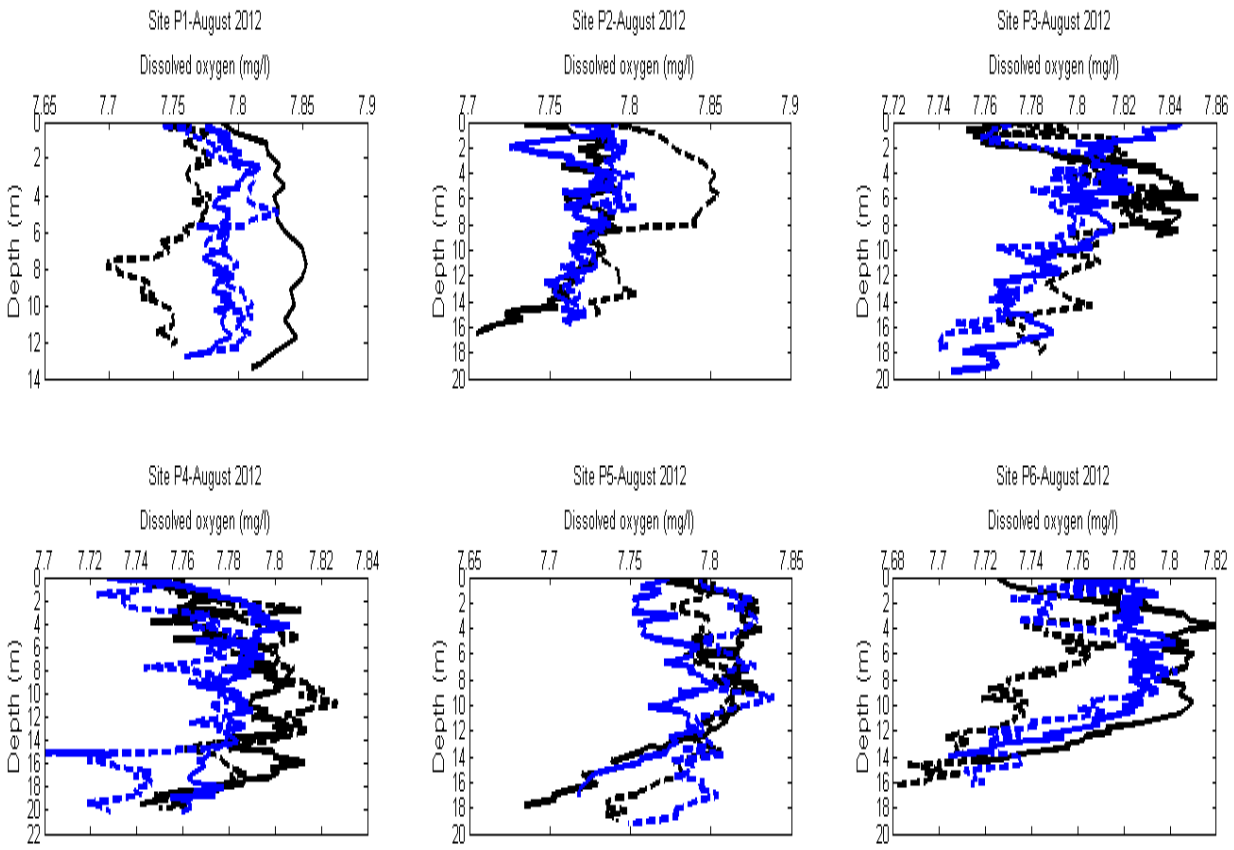

Figure 6- 8 Spatial and temporal changes in dissolved oxygen concentrations at Maldeco Aquaculture farm perimeter in August 2012. Solid black line is day site replicate 1, dashed black is day site replicate 2, solid blue is night site replicate 1 and dashed blue line is night site replicate 2.

September: Night sampling was done between 11:28 pm and 2:05 am on September 6, 2012 while night sampling was done in the following morning between 7:40 and 10:42 am. Day sampling was discontinued half way through the stations due to strong northern winds so that sites P1 and P4 were not sampled. Site P2 had significantly lower DO compared to sites P3, P5, and P6 during the day (Table 6-1) while at night. The offshore sites P3 and P4 had significantly lower DO than sites P1, P2, P5, and P6 (Table

6-1, Figure P-11). All DO profiles showed an increase of DO with depth, except in sites P3 sampled during the day (Figure 6-9). The concentrations during the day had increased compared to night ones and resulted in significant difference between the two periods (Table 6-1).

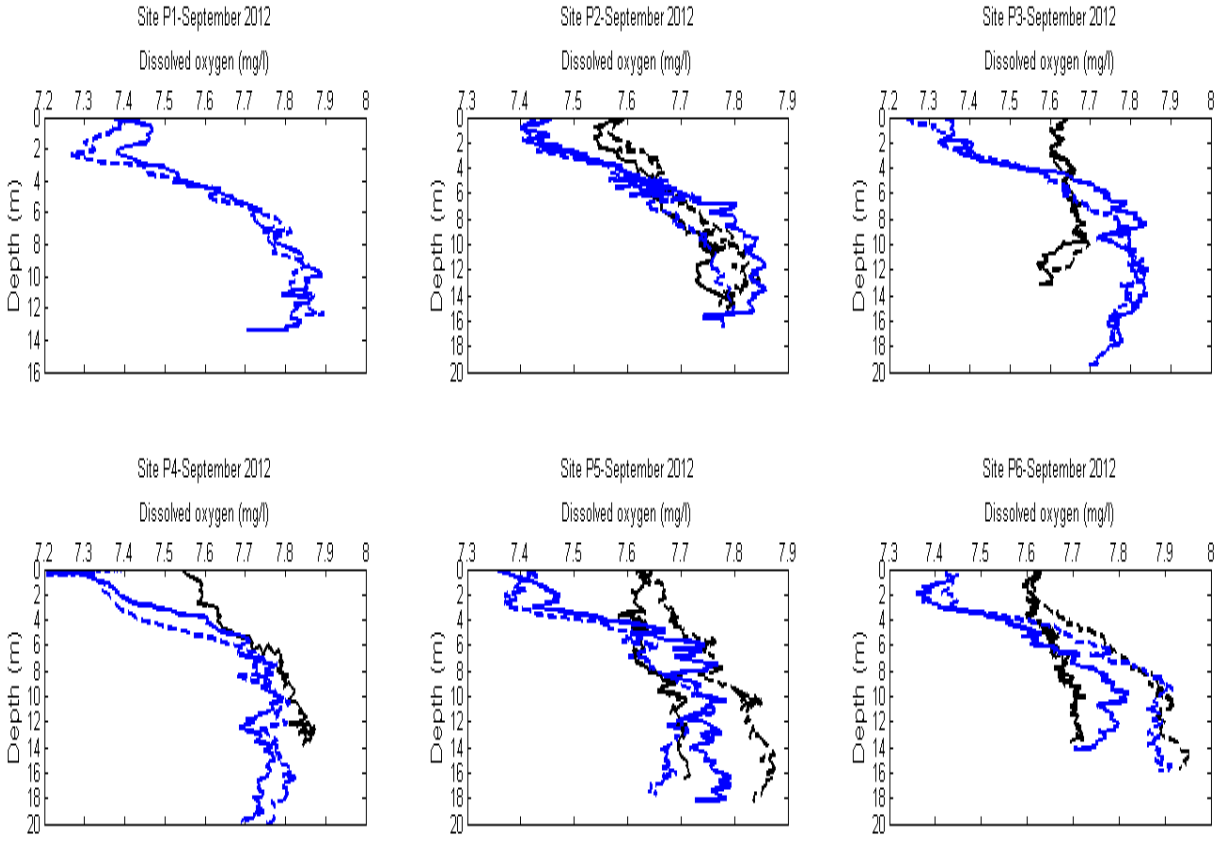

Figure 6- 9 Spatial and temporal changes in dissolved oxygen concentrations at Maldeco Aquaculture farm perimeter in September 2012. Solid black line is day site replicate 1, dashed black is day site replicate 2, solid blue is night site replicate 1 and dashed blue line is night site replicate 2.

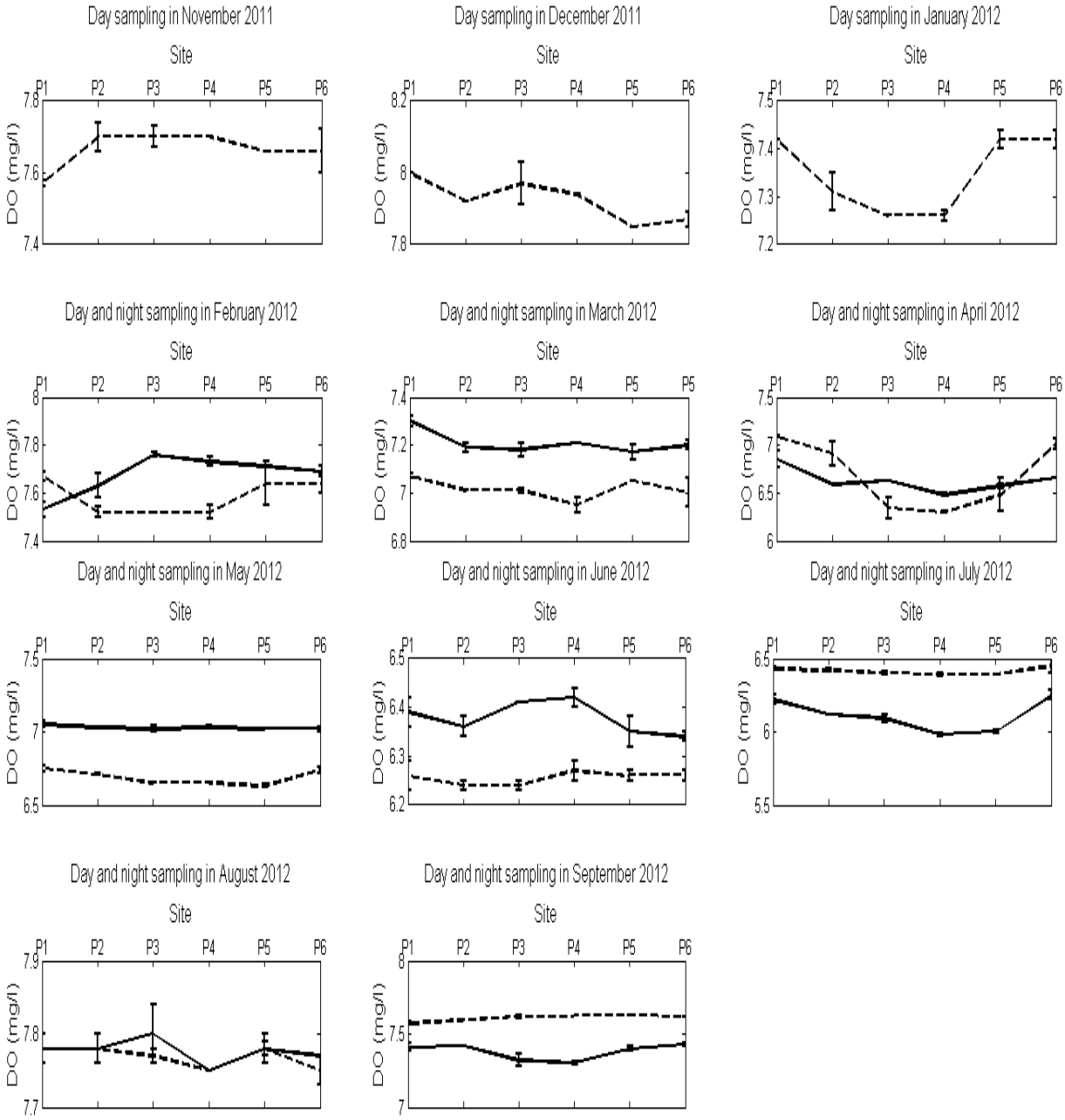

Figure 6- 10 Spatial and temperal variations in 0-1 m dissolved oxygen concentrations at Maldeco Aquaculture farm perimeter bettween November 2011 and September 2012. Day sampling (dashed line) and night sampling (solid line) (mean±se).

Table 6- 1 One-way ANOVA for spatial (between sites) and temporal (day and night) data for average DO between 0 and 1 m extracted from the profiles between November 2011 and September 2012.

Month	**Period**	**F**	***p***	**Pairwise significant difference**
November	D	2.003	0.211	Not different
December	D	5.574	0.029	P5xP1, P5xP3, P5xP4, P6xP1, P6xP3
January	D	15.060	0.002	P1xP2, P1xP3, P1xP4, P2xP3, P2xP4, P2xP5, P2xP6, P3xP5, P3xP6, P4xP5, P4xP6
February	D	2.718	0.128	Not significant
	N	7.362	0.015	P1xP2, P1xP3, P1xP4, P1xP5, P1xP6
	D x N	5.395	0.004	P1DxP1N, P3DxP3N, P4DxP4N
March	D	2.194	0.183	No significant difference
	N	5.439	0.003	P1xP2, P1xP3, P1xP4, P1xP5, P1xP6
	D x N	19.268	0.001	P1DxP1N, P2DxP2N, P3DxP3N, P4DxP4N, P5DxP5N, P6DxP6N
April	D	12.663	0.004	P1xP3, P1xP4, P1xP5, P2xP3, P2xP4, P2xP5, P6xP3, P6xP4, P6xP5
	N	11.005	0.006	P1x P2, P1x P3, P1xP4, P1xP5, P1xP6, P4xP3, P4xP6
	D x N	11.485	0.001	P1DxP1N, P2DxP2N, P3DxP3N, P6DxP6N
May	D	13.189	0.003	P1xP3, P1xP4, P1xP5, P2xP3, P2xP4, P2xP5, P6xP3, P6xP4, P6xP5,

	N	0.899	0.537	No significant difference
	D x N	195.071	0.001	P1DxP1N, P2DxP2N, P3DxP3N, P4DxP4N, P5DxP5N, P6DxP6N
June	D	0.684	0.653	No significant difference
	N	2.736	0.126	No significant difference
	D x N	14.056	0.001	P1DxP1N, P2DxP2N, P3DxP3N, P4DxP4N, P5DxP5N, P6DxP6N
July	D	1.409	0.341	No significant difference
	N	24.979	0.001	P1xP2, P1xP3, P1xP4, P1xP5, P2xP4, P2xP5, P2xP6, P3xP4, P3xP5, P3xP6, P6xP4, P6xP5
	D X N	67.429	0.001	P1DxP1N, P2DxP2N, P3DxP3N, P4DxP4N, P5DxP5N, P6DxP6N
August	D	1.082	0.455	No significant difference
	N	1.111	0.443	No significant difference
	D x N	1.074	0.450	No significant difference
September	D	19.168	0.008	P2xP3, P2xP5, P2xP6
	N	7.671	0.014	P1xP3, P1xP3, P2xP3, P2xP4, P3xP5, P4x5P, P6xP3, P6xP4
	D x N	60.896	0.001	P2DxP2N, P3DxP3N, P4DxP4N, P5DxP5N, P6DxP6N

Only significantly different sites during the day (D) and night (N) at (p<0.05) are included. Temporal comparisons (D x N) were only reported for the same sites.

6.3.2 *Carrying capacity estimates based on perimeter observations*

Total biomass of fish in farm cages was over 120, 000 kg between November 2011 and March 2012 (Figure 6-11). Peak biomass was reached at 155,738 kg in March 2012, and then was reduced to below 70, 000 kg between April and September (Figure 6-11) following a large harvest of mature fish. Continuous stockings of new fish and growth of existing fish increased biomass from 41,092 in June to 69,442 kg in September, the last sampling month.

Day and night samplings indicate periods of low DO at night and high DO during the day and vice-versa (Table 6-2) depending on the season. The period between December and March was characterized by inflowing waters containing DO above 7.0 mg/l during the day and at night (Table 6-2). The extended period between April and July had inflowing waters containing DO below 7.0 mg/l, with exception of the night sampling in May. The DO increased again to above 7.8 mg/l in August and September (Table 6-2). High DO increased the CC of the farm as it depends on DO content of waters entering the farm. The highest CC of 2,495,289 kg for a fully active farm was estimated in December during the highest DO concentrations entering the farm (Table 6-2) and the lowest CC of 1,385,632 kg was estimated in July with night DO of 6.29 mg/l.

In addition to monthly variations in CC, small variability between day and night CC was observed during the sampling period. High night CC were estimated in February, March, May, June, and August (Figure 6-12). In some cases, the driving parameter was the inflowing DO. For instance, in February, night inflowing waters had 0.5 mg/l higher DO than day inflowing and had P_F of 0.67 at night compared to 0.50 during the day. Differences in inflowing DO and P_F resulted in different CC between day and night

samplings (Table 6-2) due to different OX1 and OT. A lower P_F during the day resulted in an OX1 of 17.3 kg/h compared to 6.9 kg/h. A marginal difference in inflowing waters in April (0.07 mg/l) during day and night sampling in April and similar P_F (0.75) resulted in similar OX1 and OT and consequently similar CC (Table 6-2) while a large differences in P_F during the day (0.67) and night (0.75) in March coupled with high inflowing DO at night resulted in a larger difference in CC between day and night samplings (Table 6-2). May is an exceptional case of high P_F. The inflowing DO and water currents were low, but because the waters residence at the farm was low as estimated by a P_F of 1.00, the farm had an increased CC compared to April and July (Figure 6-12).

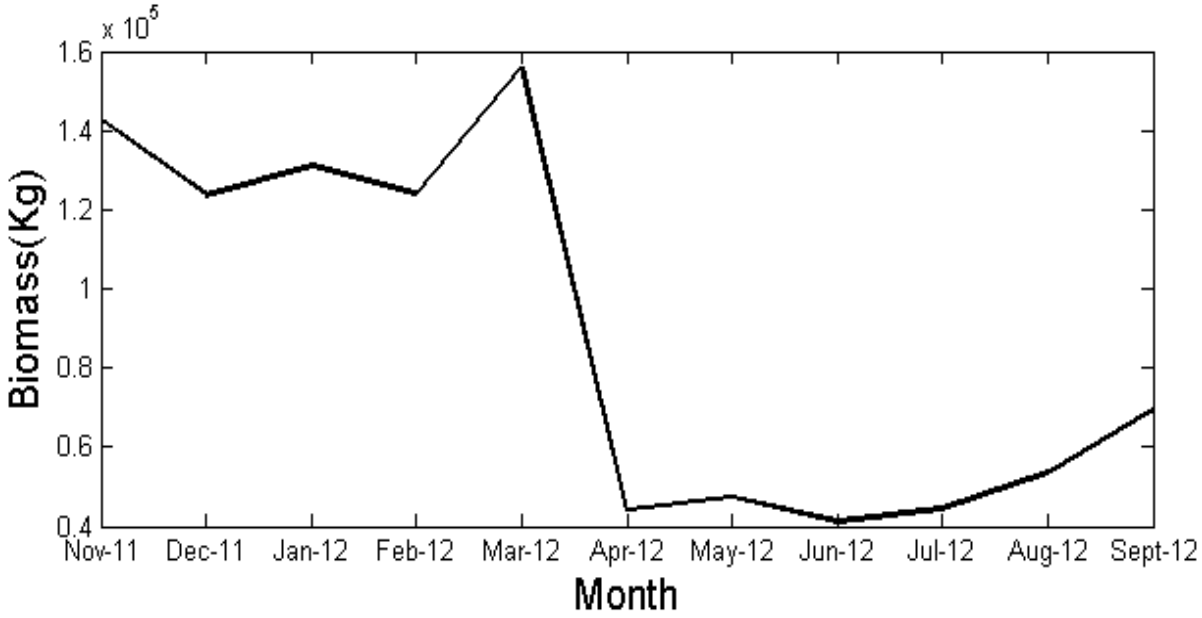

Figure 6- 11 Total fish biomass at Maldeco Aquaculture farm between November 2011 and September 2012.

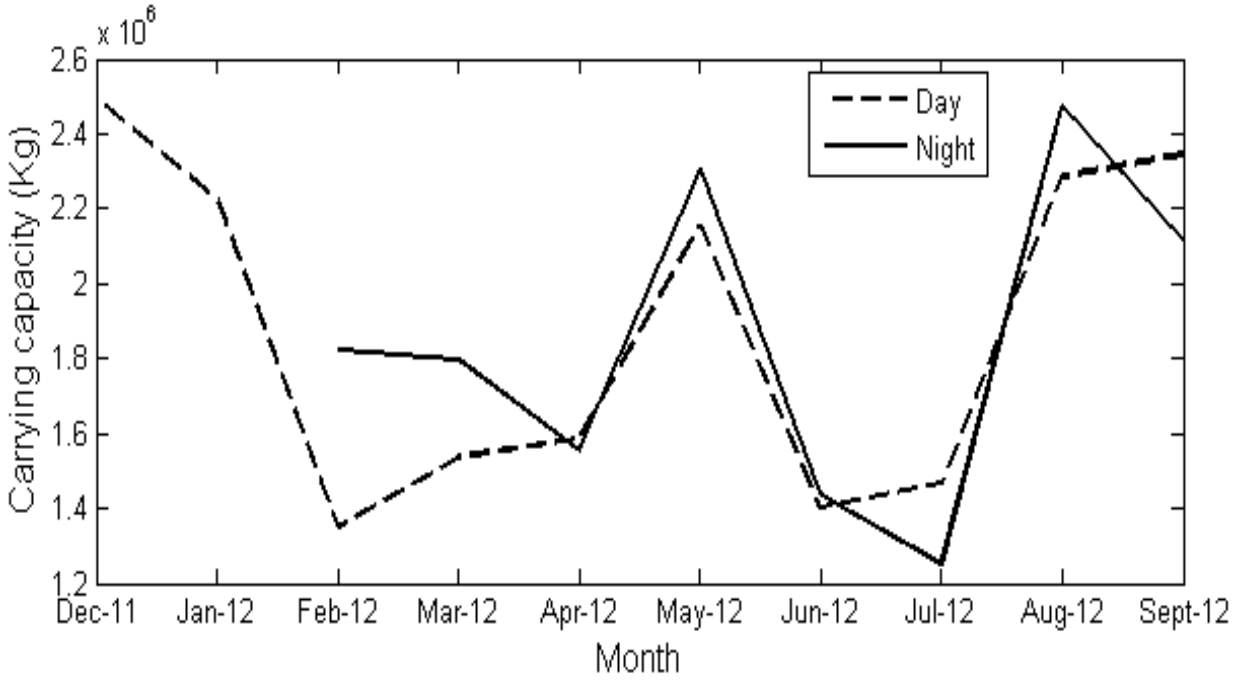

Figure 6- 12 Farm carrying capacity estimates based on perimeter observations.

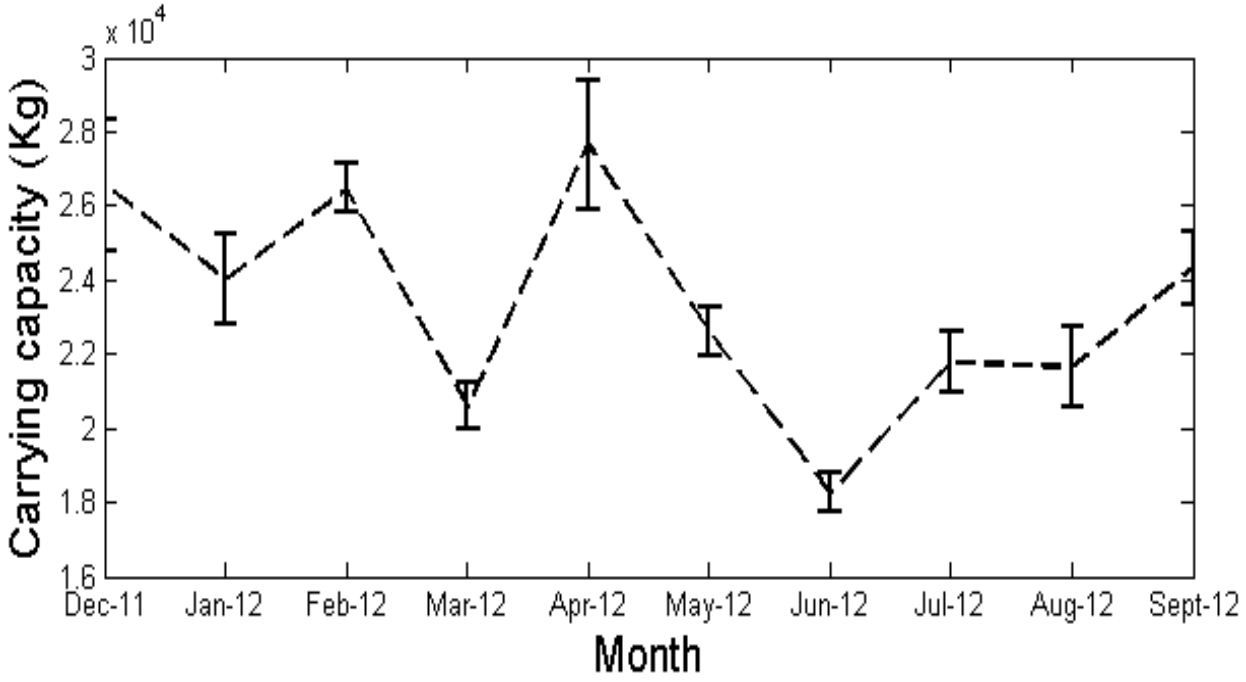

Figure 6- 13 Carrying capacity estimates for cages based on individual cage observations.

6.3.3 *Cage effect and cage based carrying capacity estimates*

Assessment of individual cages indicated varying CC capacities (Table 6-3 to 6-12) which were significantly different over the sampling period (F=6.798, p=0.001). The highest mean cage CC of 27, 442±659 kg was estimated in April 2011 (Figure 6-13), but it was not significantly different from the CC estimates from December and February (p>0.05). The lowest CC of 18,247±247 kg estimated in June corresponded to the period of lowest DO in the lake (Figure 6-13, Table 6-9). There was no significant statistical differences in CC estimates in January, May, July, August, and September (p>0.05).

December: Analysis of oxygen content of waters inside and outside the cages including the reference sites for cage effect showed changes in oxygen content over the sampling period (Tables 6-3 to 6-12). Figure 6-14 shows DO profiles from six selected cages in December 2011. The reference sites had higher DO concentrations compared to those recorded inside and outside the cages. Among the six cages sampled, cage 2 had the lowest biomass (3, 146 kg) and lowest OX1 (0.06 kg O_2/h) compared to other cages stocked with higher biomasses. DO profiles of cage 2 show high DO content inside and outside it and similar to those recorded at reference sites (Figure 6-14). The difference between DO inside and out the cage was smaller in cage 2 compared to cages 6, 21, and 8 due to oxygen consumption by the fish in these cages which had oxygen consumption rates of 0.64, 0.57, and 0.57 kg O_2 /h, respectively. High inflowing DO and high OT (3.50 kg O_2/h) at cage 8 stocked with a small fish biomass (276 kg) allowed a high CC of 36,350 kg. It is interesting to note that cages 1, 24, 45, and 48 located nearshore and offshore respectively had inflowing DO of over 8.0 mg/l, low OX1, and similar P_C, high OT and more importantly similar CC (Table 6-3). Their CC was lower than CC estimated

in cage 8 which had lower inflowing DO, but had much lower biomass of *O. karongae* while cages 1, 24, 45, and 48 were stocked with *O. shiranus*.

January: The profiles from cages 4, 12, 49, and 2 show higher DO in waters outside than inside the cages whilst cages 46 and 24 show otherwise (Figure 6-15). This trend was observed in a few other cages especially during the period when wind direction changes to southern or eastern winds occurred and vice-versa. The position of inflowing and outflowing waters direction estimated by a hand GPS compass had to be adjusted whenever there was changes in wind direction, but changes in wind direction did not necessarily result in immediate changes in the direction of inflowing and outflow waters at the cages during the sampling. That is why the sampling between February and September included sampling four positions around the circumference of the cages to better understand the sites of inflowing and outflowing waters within the cage, then two positions were selected.

Cage 4 stocked with a biomass of 14, 454 kg had the highest OX1 (1.35 kg O_2 /h), but also a high CC (27,830 kg) due to high OT of 2.68 kg O_2/h. The OX1 of cages 46, 49, 2, and 24 was low and less than 0.30 kg O_2/h (Table 2), but their CC varied considerably, with cages 49 and 24 having CC over 30, 000 kg and low biomass in others. Cage 46 had high biomass in it and had a P_C of 0.50. Cage 2 had a biomass similar to that of cages 49 and 24, but because of low P_C, its estimated CC was lower by about 10, 000 kg than cages 49 and 24 that had a P_C of 0.67 and 0.75 respectively.

April: Cage 16 was sampled on April 18, 2011 in the morning between 9:15 and 11:55 am. Cages 6, 17, and 24 were sampled in the same day, but between 2:30 and 5:20 pm and finally, cages 5 and 45 were sampled on April 16, 2011 (Figure 6-16). The

morning and afternoon DO profiles had similar trend characterized by increasing DO with depth with higher DO at site A and low DO at site C. Peak DO at sites B and D was achieved bellow 10 m, then the DO reduced with depth. The increase in DO with depth was observed earlier on April 16, 2012. Cages 45 and 5 had increasing DO with depth with peaks observed near 10 m at sites A, B, and D, expect at site C which the peak was observed near 5 m (Figure 6-16).

In general, April had low and high OX1 and OT, respectively (Table 6-7) especially on April 18, 2012. OX1 ranged between 0.01 and 0.64 kg O_2/h while OT ranged between 2.18 and 4.65 kg O_2/h (Table 6-7). The effect of strong winds is visibly seen from DO profiles (Figure 6-3). The DO of inflowing waters was similar to the DO recorded at sites A, B, C, and D (Figure 6-16). Variations in DO were noted inside the cages. Table 6-7 shows that the highest CC of 35,039 kg was estimated at cage 17 which had a biomass of 171 kg in it. Cage 6 with a biomass of 180 kg had an estimated CC of 33,830 kg.

June: All DO profiles were recorded on June 26, 2012 and had similar trends (Figure 6-17). The profiles in the cages and at reference sites had surface DO below 6.6 mg/l, but increased with depth. Total fish biomass in the cages was very low in June (Figure 6-11). Out of 30 cages stocked with fish, only cage 11 had relatively high biomass. At low biomass, the DO of inflowing waters was in all cases similar to those from reference sites. The maximum surface DO was less than 6.5 mg/l in all profiles while the waters inside the cages had DO below 6.2 mg/l. The OX1 was below 1.00 kg O_2/h in all cages, and the OT was almost similar in all cages (Table 6-9). The CC

became lower owing to the decline on DO in Southeast Arm (SEA) with minimum CC being 17, 192 kg in cage 18 and the maximum of 21,659 kg in cage 15 (Table 6-9).

August and *September*: Similar to observations made in June, DO profiles exhibited increased concentrations with depth at control sites and at the cages in August (Figure 6-18). The DO content outside the cages was similar to that of reference sites while the DO inside the cages was relatively lower than the outside (Figure 6-18). One important observation is that while in June, reference site C had relatively higher DO than site A, in August sites A and C had similar surface DO, but DO increased more at site A than at site C in cages 19, 28, 26, and 20, but not in cages 4 and 6 (Table 6-11). The rise of DO in SEA increased the CC at the farm in September (Table 6-12). The minimum CC of 21,582 kg estimated at cage 7 and maximum of 29,124 kg are higher than those recorded in July and August.

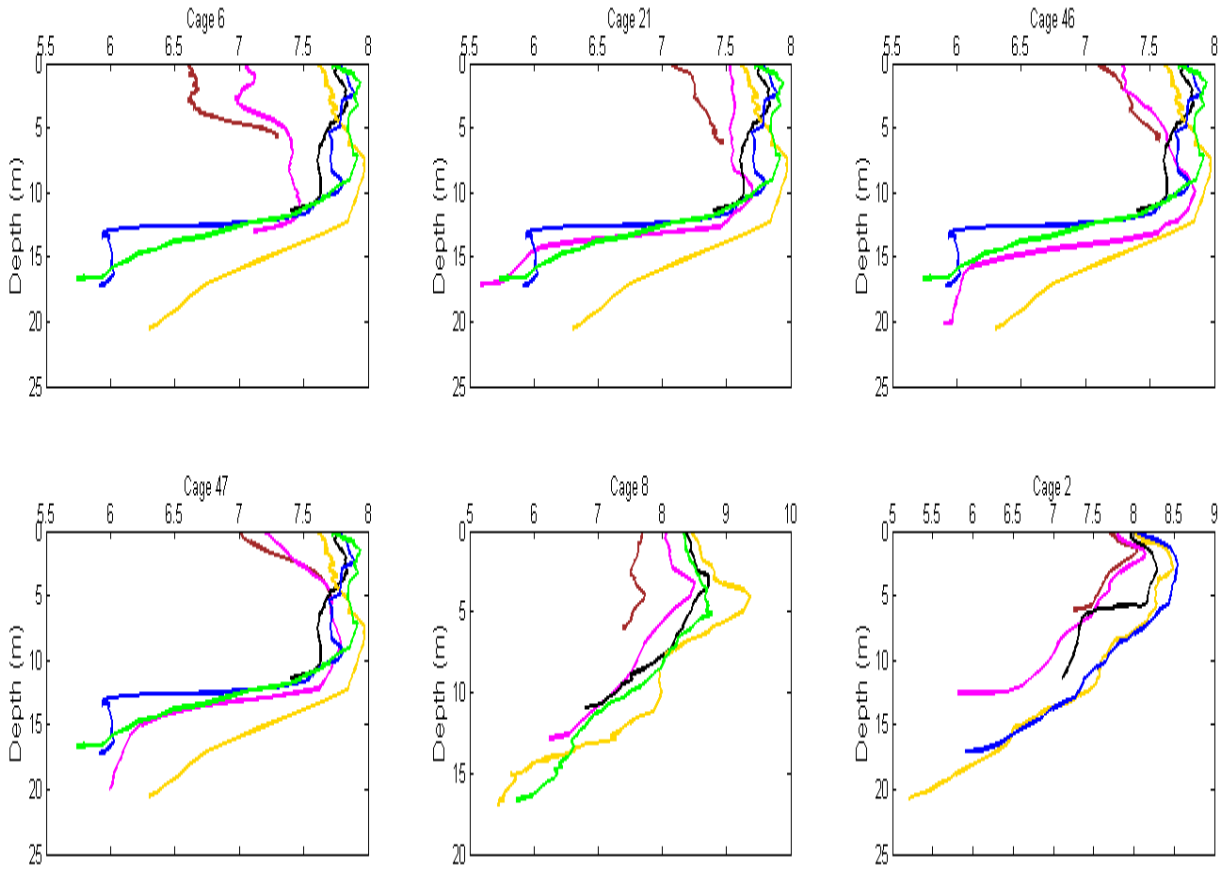

Figure 6- 14 Dissolved oxygen profiles recorded at Maldeco Cage Aquaculture farm in December 2011. DO inside the cage (brown), DO outside the cage (pink), DO at control site A (black), DO at control site B (blue), DO at control site C (yellow), and DO at control site D (green).

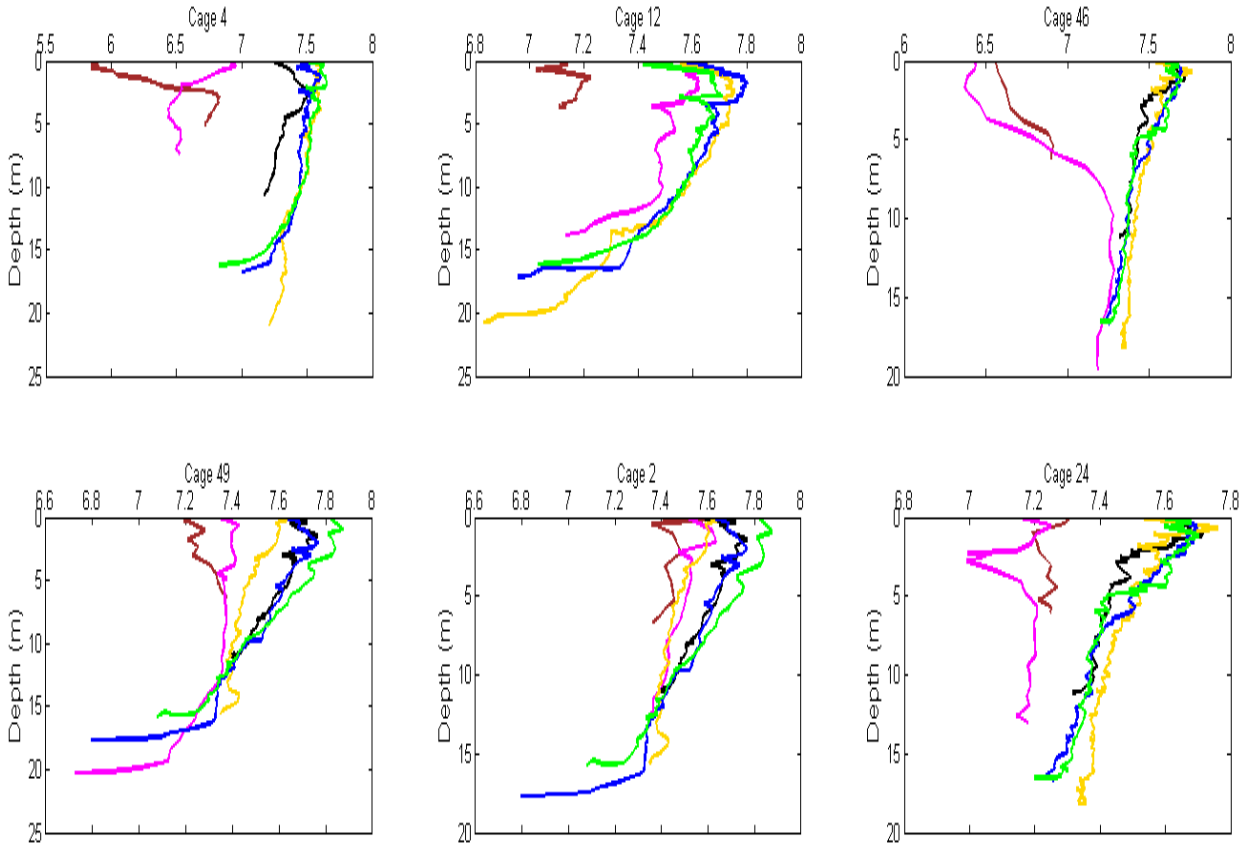

Figure 6- 15 Dissolved oxygen profiles recorded at Maldeco Cage Aquaculture farm in January 2012. DO inside the cage (brown), DO outside the cage (pink), DO at control site A (black), DO at control site B (blue), DO at control site C (yellow), and DO at control site D (green).

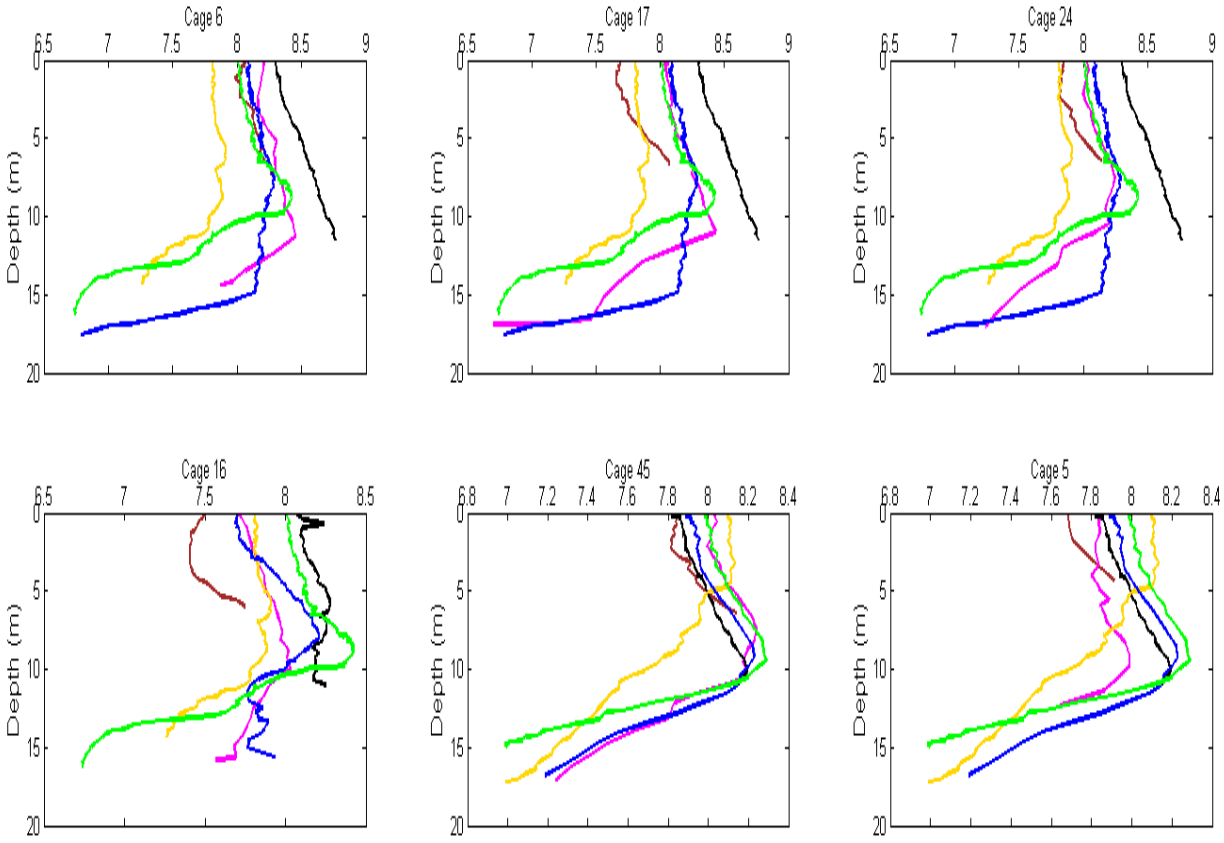

Figure 6- 16 Dissolved oxygen profiles recorded at Maldeco Cage Aquaculture farm in April 2012. DO inside the cage (brown), DO outside the cage (pink), DO at control site A (black), DO at control site B (blue), DO at control site C (yellow), and DO at control site D (green).

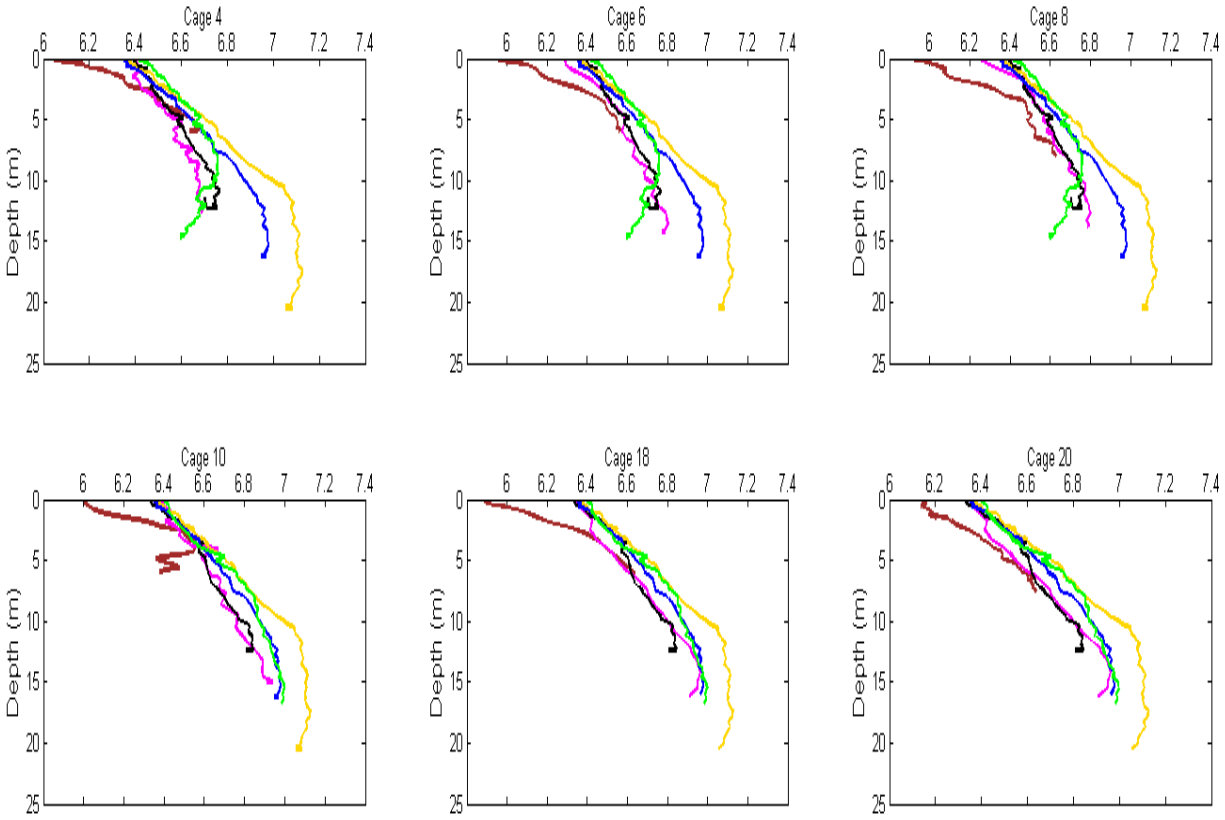

Figure 6- 17 Dissolved oxygen profiles recorded at Maldeco Cage Aquaculture farm in June 2012. DO inside the cage (brown), DO outside the cage (pink), DO at control site A (black), DO at control site B (blue), DO at control site C (yellow), and DO at control site D (green).

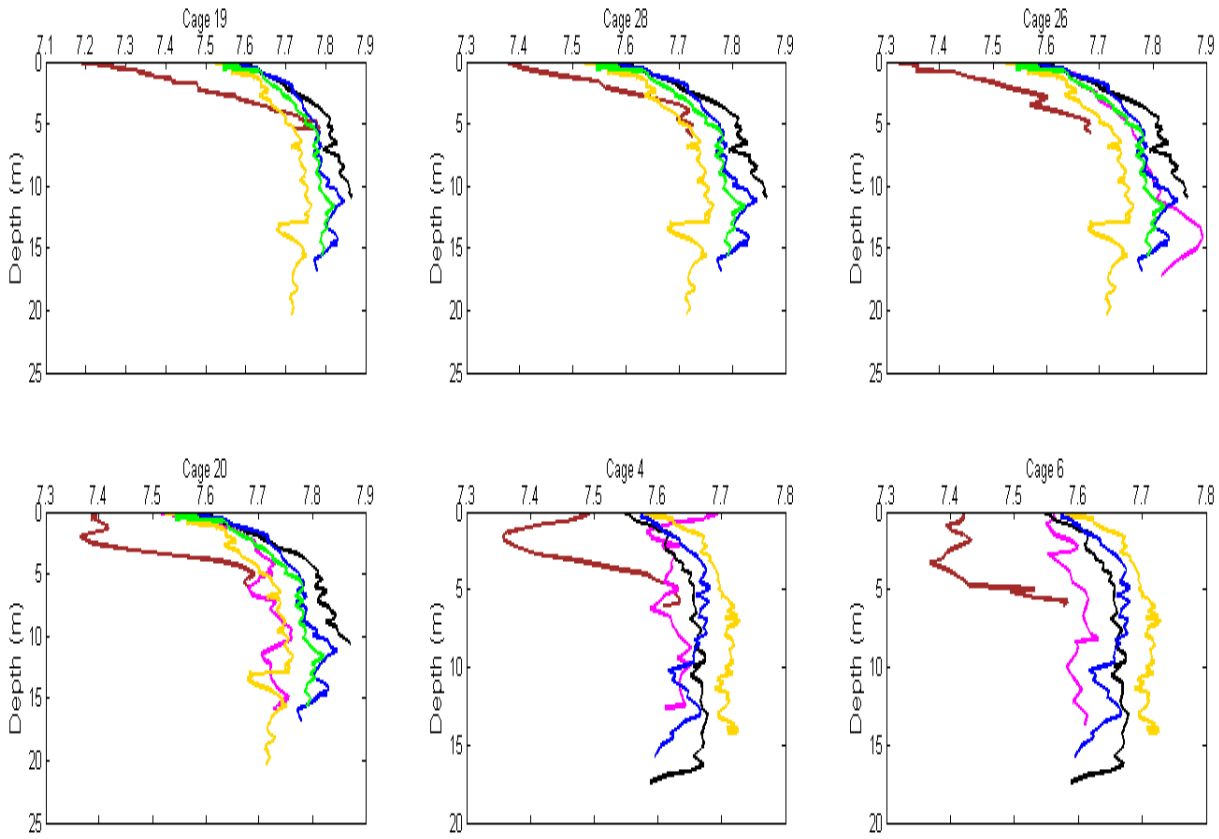

Figure 6- 18 Dissolved oxygen profiles recorded at Maldeco Cage Aquaculture farm in August 2012. DO inside the cage (brown), DO outside the cage (pink), DO at control site A (black), DO at control site B (blue), DO at control site C (yellow), and DO at control site D (green).

Table 6- 2 Monthly carrying capacity estimates of Maldeco aquaculture farm between December 2011 and September 2012. O_{2IN}/O_{2OUT} is DO flowing in/out of the farm, O_{2MIN} is the minimum DO, $U_i(t)/U_o(t)$ is the current flowing/outside the farm, U_{MIN} is the minimum current, P_F is permeability of the farm, L_F is length of the farm. OCR is the specific oxygen consumption of fish, OX1 is oxygen consumption of fish at the farm, and CC is the carrying capacity of the farm.

Month	Period	O_{2IN} (mg/l)	O_{2OUT} (mg/l)	$U_o(t)$ (m/s)	$U_i(t)$ (m/s)	P_F	Depth (m)	U_{MIN} (m/s)	L_F (m)	O_{2MIN} (mg/l)	OX1 (kg/h)	OT (Kg/h)	OCR (mg/kg/h)	CC (Kg)
December	Day	7.93	7.84	0.27	0.24	0.89	6	0.004	875	3	7.16	331.37	132.8	2,495,289
January	Day	7.39	7.30	0.27	0.24	0.89	6	0.004	875	3	7.36	295.20	132.8	2,222,871
February	Day	7.75	7.52	0.18	0.09	0.50	6	0.004	875	3	17.31	179.58	132.8	1,352,245
	Night	7.80	7.71	0.18	0.12	0.67	6	0.004	875	3	6.93	242.08	132.8	1,822,923
March	Day	7.05	7.05	0.18	0.12	0.67	6	0.004	875	3	0.04	203.98	132.8	1,535,977
	Night	7.21	7.18	0.24	0.18	0.75	6	0.004	875	3	1.78	238.62	132.8	1,796,855
April	Day	6.71	6.65	0.24	0.18	0.75	6	0.004	875	3	4.79	210.58	132.8	1,585,682
	Night	6.64	6.59	0.24	0.18	0.75	6	0.004	875	3	4.12	206.52	132.8	1,555,136
May	Day	6.79	6.65	0.24	0.24	1.00	6	0.004	875	3	10.42	286.20	132.8	2,155,114
	Night	7.05	7.04	0.18	0.18	1.00	6	0.004	875	3	0.53	306.29	132.8	2,306,390
June	Day	6.28	6.26	0.24	0.18	0.75	6	0.004	875	3	1.42	186.02	132.8	1,400,758
	Night	6.37	6.32	0.24	0.18	0.75	6	0.004	875	3	3.70	190.96	132.8	1,437,919
July	Day	6.44	6.38	0.24	0.18	0.75	6	0.004	875	3	4.22	194.77	132.8	1,466,634
	Night	6.29	6.01	0.18	0.12	0.67	6	0.004	875	3	21.27	165.92	132.8	1,249,368
August	Day	7.82	7.78	0.18	0.15	0.83	6	0.004	875	3	2.89	303.70	132.8	2,286,829
	Night	7.89	7.77	0.27	0.24	0.89	6	0.004	875	3	9.04	328.28	132.8	2,471,956
September	Day	7.64	7.58	0.27	0.24	0.89	6	0.004	875	3	4.48	311.65	132.8	2,346,783
	Night	7.45	7.39	0.18	0.15	0.83	6	0.004	875	3	4.77	280.4304	132.8	2,111,675

Table 6- 3 Carrying capacity estimates of individual cages in December 2012. O_{2IN}/O_{2OUT} is the DO flowing in/out of the cage, O_{2MIN} is the minimum DO, $U_i(t)$/$U_o(t)$ is the current flowing in/outside the cage, U_{MIN} is the minimum current, P_C is permeability of the cage, L_C is length of the cage. OCR is the specific oxygen consumption of fish, OX1 is oxygen consumption inside the cage, and CC is the carrying capacity of the cage.

Cage#	O_{2IN} (mg/l)	O_{2OUT} (mg/l)	$U_o(t)$ (m/s)	$U_i(t)$ (m/s)	*Pc*	Depth (m)	L_C (m)	U_{MIN} (m/s)	O_{2MIN} (mg/l)	OX1 (kg/h)	OT (kg/h)	OCR (mg/kg/h)	CC (kg)	Biomass (kg)
6	7.08	6.62	0.18	0.09	0.5	6	16	0.004	3	0.64	2.82	96.4	29,265	11,941
21	7.53	7.11	0.18	0.09	0.5	6	16	0.004	3	0.57	3.13	132.8	23,552	7,766
46	7.29	7.15	0.18	0.06	0.3	6	16	0.004	3	0.19	1.98	132.8	14,878	10,920
47	7.21	7.02	0.18	0.06	0.3	6	16	0.004	3	0.26	1.94	132.8	14,608	7,131
1	8.21	7.48	0.12	0.06	0.5	6	16	0.004	3	1.01	3.60	132.8	27,095	5,990
2	7.88	7.84	0.12	0.06	0.5	6	16	0.004	3	0.06	3.37	132.8	25,408	3,146
21	7.93	7.26	0.12	0.06	0.5	6	16	0.004	3	0.92	3.41	132.8	25,647	7,766
45	8.21	7.49	0.12	0.06	0.5	6	16	0.004	3	0.99	3.60	132.8	27,103	6,769
8	8.07	7.65	0.24	0.12	0.5	6	16	0.004	3	0.57	3.50	96.4	36,350	276
24	8.24	8.21	0.24	0.12	0.5	6	16	0.004	3	0.04	3.62	132.8	27,257	12,851
48	8.21	7.94	0.24	0.12	0.5	6	16	0.004	3	0.37	3.60	132.8	27,103	5,454
9	7.54	7.27	0.12	0.06	0.5	6	16	0.004	3	0.38	3.14	96.4	32,588	12,851[x]
23	7.83	7.73	0.12	0.06	0.5	6	16	0.004	3	0.13	3.34	96.4	34,600	15,229[x]

[x]Biomass taken from previous month. The cages were harvested before the end of the month.

Table 6- 4 Carrying capacity estimates of individual cage in January 2012. O_{2IN}/O_{2OUT} is the DO flowing in/out of the cage, O_{2MIN} is the minimum DO, $U_i(t)$/$U_o(t)$ is the current flowing in/outside the cage, U_{MIN} is minimum current, P_C is permeability of the cage, L_C is length of the cage. OCR is the specific oxygen consumption of fish, OX1 is oxygen consumption inside the cage, and CC is the carrying capacity of the cage.

Cage#	O_{2IN} (mg/l)	O_{2OUT} (mg/l)	$U_o(t)$ (m/s)	$U_i(t)$ (m/s)	P_C	Depth (m)	U_{MIN} (m/s)	L_C (m)	O_{2MIN} (mg/l)	OX1 (kg/h)	OT (kg/h)	OCR (mg/kg/h)	CC (kg)	Biomass (kg)
8	7.27	7.19	0.12	0.06	0.5	6	16	0.004	0.10	3	2.95	132.8	22,206	455
13	7.50	7.35	0.12	0.06	0.5	6	16	0.004	0.21	3	3.11	132.8	23,435	255
4	6.88	5.90	0.12	0.06	0.5	6	16	0.004	1.35	3	2.68	96.4	27,830	14,454
45	7.44	7.27	0.12	0.06	0.5	6	16	0.004	0.23	3	3.07	132.8	23,120	9,301
47	7.10	6.90	0.12	0.06	0.5	6	16	0.004	0.27	3	2.83	132.8	21,325	8,074
1	7.29	7.24	0.12	0.06	0.5	6	16	0.004	0.07	3	2.96	132.8	22,307	6,743
24	7.13	7.01	0.12	0.09	0.8	6	16	0.004	0.16	3	4.28	132.8	32,223	6,814
46	6.57	6.40	0.12	0.06	0.5	6	16	0.004	0.23	5	2.46	132.8	18,561,	13,350
49	7.42	7.23	0.18	0.12	0.7	6	16	0.004	0.27	3	4.07	132.8	30,664	7,584
2	7.62	7.47	0.15	0.06	0.4	6	16	0.004	0.20	3	2.56	132.8	19,244	5,741
48	7.45	7.26	0.12	0.06	0.5	6	16	0.004	0.26	3	3.07	132.8	23,141	5,830
12	7.61	7.11	0.12	0.06	0.5	6	16	0.004	0.69	3	3.19	132.8	24,006	7,591

Table 6- 5 Carrying capacity estimates of individual cage in February 2012. O_{2IN}/O_{2OUT} is the DO flowing in/out of the cage, O_{2MIN} is the minimum DO, $U_i(t)/U_o(t)$ is the current flowing in/outside the cage, U_{MIN} is the minimum current, P_C is permeability of the cage, L_C is length of the cage. OCR is the specific oxygen consumption of fish, OX1 is oxygen consumption inside the cage, and CC is the carrying capacity of the cage.

Cage#	O_{2IN} (mg/l)	O_{2OUT} (mg/l)	Uo(t) (m/s)	$U_i(t)$ (m/s)	P_C	Depth (m)	U_{MIN} (m/s)	L_C (m)	O_{2MIN} (mg/l)	OX1 (kg/h)	OT (Kg/h)	OCR (mg/kg/h)	CC (Kg)	Biomass (kg)
45	7.01	6.65	0.36	0.12	0.67	6	0.004	16	3	0.50	3.69	132.8	27,809	13,840
6	7.03	6.86	0.17	0.09	0.50	6	0.004	16	3	0.24	2.79	96.4	28,899	11,918[x]
8	7.16	6.85	0.31	0.12	0.67	6	0.004	16	3	0.43	3.83	132.8	28,875	930
3	7.32	7.00	0.33	0.09	0.50	6	0.004	16	3	0.45	2.99	132.8	22,509	11,692
48	7.07	7.01	0.06	0.12	0.67	6	0.004	16	3	0.08	3.75	132.8	28,240	10,715
47	6.93	6.81	0.13	0.12	0.67	6	0.004	16	3	0.18	3.63	132.8	27,305	12,410
46	7.21	6.94	0.27	0.12	0.67	6	0.004	16	3	0.38	3.88	132.8	29,228	13,944
49	7.37	7.14	0.23	0.06	0.50	6	0.004	16	3	0.32	3.02	132.8	22,739	13,658
45	6.85	6.73	0.11	0.12	0.67	6	0.004	16	3	0.16	3.55	132.8	26,698	13,840
16	7.49	6.83	0.66	0.09	0.60	6	0.004	16	3	0.91	3.72	132.8	28,047	782
24	7.20	7.14	0.06	0.09	0.60	6	0.004	16	3	0.09	3.49	132.8	26,261	9,851
48	7.28	7.03	0.25	0.09	0.60	6	0.004	16	3	0.35	3.55	132.8	26,739	10,715
12	7.24	6.41	0.84	0.06	0.50	6	0.004	16	3	1.16	2.93	132.8	22,082	10,600
7	6.99	6.83	0.16	0.09	0.60	6	0.004	16	3	0.22	3.31	132.8	24,931	599

[x]Biomass taken from previous month. The cages were harvested before the end of the month.

Table 6- 6 Carrying capacity estimates of individual cage in March 2012. O_{2IN}/O_{2OUT} is the DO flowing in/out of the cage, O_{2MIN} is the minimum DO, $U_i(t)$/$U_o(t)$ is the current flowing in/outside the cage, U_{MIN} is the minimum current, P_C is permeability of the cage, L_C is length of the cage. OCR is the specific oxygen consumption of fish, OX1 is oxygen consumption inside the cage, and CC is the carrying capacity of the cage.

Cage#	O_{2IN} (mg/l)	O_{2OUT} (mg/l)	$U_o(t)$ (m/s)	$U_i(t)$ (m/s)	P_C	Depth (m)	U_{MIN} (m/s)	L_C (m)	O_{2MIN} (mg/l)	OX1 (kg/h)	OT (kg/h)	OCR (mg/kg/h)	CC (kg)	Biomass (kg)
3	6.53	6.38	0.12	0.06	0.50	6	0.004	16	3	0.21	2.44	132.8	18,377	17,113
7	6.38	6.14	0.15	0.09	0.60	6	0.004	16	3	0.33	2.80	132.8	21,106	1,350
12	6.76	6.71	0.12	0.06	0.50	6	0.004	16	3	0.06	2.60	132.8	19,550	14,328
10	6.62	6.23	0.18	0.12	0.67	6	0.004	16	3	0.55	3.34	132.8	25,153	462
45	6.80	6.78	0.12	0.06	0.50	6	0.004	16	3	0.02	2.63	132.8	19,783	18,824
47	7.18	6.78	0.15	0.09	0.60	6	0.004	16	3	0.55	3.47	132.8	26,133	16,200
48	6.79	6.70	0.12	0.06	0.50	6	0.004	16	3	0.13	2.62	132.8	19,709	15,159
13	6.82	6.67	0.18	0.09	0.50	6	0.004	16	3	0.22	2.64	132.8	19,894	1,249
14	6.82	6.55	0.18	0.09	0.50	6	0.004	16	3	0.37	2.64	132.8	19,873	518
49	6.54	6.49	0.12	0.06	0.50	6	0.004	16	3	0.07	2.45	132.8	18,436	18,864
24	6.82	6.55	0.12	0.06	0.50	6	0.004	16	3	0.38	2.64	132.8	19,896	14,566
16	6.84	6.82	0.12	0.06	0.50	6	0.004	16	3	0.03	2.65	132.8	19,965	1,379
6	6.90	6.65	0.12	0.06	0.50	6	0.004	16	3	0.35	2.69	132.8	20,281	240
2	6.89	6.77	0.12	0.06	0.50	6	0.004	16	3	0.17	2.69	132.8	20,231	12,947

Table 6- 7 Carrying capacity estimates of individual cage in April 2012. O_{2IN}/O_{2OUT} is the DO flowing in/out of the cage, O_{2MIN} is the minimum DO, $U_i(t)$/(t) is the current flowing in/outside the cage, U_{MIN} is the minimum current, P_C is permeability of the cage, L_C is length of the cage. OCR is the specific oxygen consumption of fish, OX1 is oxygen consumption inside the cage, and CC is the carrying capacity of the cage.

Cage#	O_{2IN} (mg/l)	O_{2OUT} (mg/l)	$U_o(t)$ (m/s)	$U_i(t)$ (m/s)	P_C	Depth (m)	U_{MIN} (m/s)	L_C (m)	O_{2MIN} (mg/l)	OX1 (kg/h)	OT (kg/h)	OCR (mg/kg/h)	CC (kg)	Biomass (kg)
5	7.85	7.69	0.12	0.06	0.50	6	0.004	16	3	0.22	3.35	132.8	25,226	639
15	7.70	7.59	0.12	0.06	0.50	6	0.004	16	3	0.15	3.25	132.8	24,446	779
45	7.73	7.42	0.18	0.06	0.33	6	0.004	16	3	0.43	2.18	132.8	16,427	18,824[x]
1	7.83	7.49	0.12	0.06	0.50	6	0.004	16	3	0.47	3.34	132.8	25,150	10,139
8	7.85	7.84	0.15	0.09	0.60	6	0.004	16	3	0.01	4.02	132.8	30,270	1,654
16	7.74	7.46	0.12	0.06	0.50	6	0.004	16	3	0.38	3.28	132.8	24,663	1,723
48	7.49	7.02	0.18	0.09	0.50	6	0.004	16	3	0.64	3.10	132.8	23,366	15, 159[x]
2	8.05	7.97	0.24	0.15	0.63	6	0.004	16	3	0.11	4.36	132.8	23,855	8,903
6	8.20	8.03	0.24	0.15	0.63	6	0.004	16	3	0.23	4.49	132.8	33,830	180
17	8.05	7.67	0.27	0.18	0.67	6	0.004	16	3	0.52	4.65	132.8	35,039	171
24	8.03	7.84	0.24	0.15	0.63	6	0.004	16	3	0.26	4.35	132.8	32,733	9,806

Cages biomasses marked with x are from the previous months. The cage was sampled in the current month and harvested before month end.

Table 6- 8 Carrying capacity estimates of individual cage in May 2012. O_{2IN}/O_{2OUT} is the DO flowing in/out of the cage, O_{2MIN} is the minimum DO, $U_i(t)$/$U_o(t)$ is the current flowing in/outside the cage, U_{MIN} is the minimum current, P_C is permeability of the cage, L_C is length of the cage. OCR is the specific oxygen consumption of fish, OX1 is oxygen consumption inside the cage, and CC is the carrying capacity of the cage.

Cage#	O_{2IN} (mg/l)	O_{2OUT} (mg/l)	$U_o(t)$ (m/s)	$U_i(t)$ (m/s)	P_C	Depth (m)	U_{MIN} (m/s)	L_C (m)	O_{2MIN} (mg/l)	OX1 (kg/h)	OT (kg/h)	OCR (mg/kg/h)	CC (kg)	Biomass (kg)
22	7.36	7.32	0.12	0.06	0.50	6.00	0.004	16	3	0.05	3.01	132.8	22,695	767
13	7.33	7.25	0.15	0.06	0.40	6.00	0.004	16	3	0.10	2.39	132.8	18,023	1,123
11	7.49	7.32	0.12	0.06	0.50	6.00	0.004	16	3	0.22	3.10	132.8	23,354	8, 313
2	7.52	7.29	0.12	0.06	0.50	6.00	0.004	16	3	0.31	3.12	132.8	23,522	10,042
28	7.51	7.37	0.06	0.03	0.50	6.00	0.004	16	3	0.19	3.12	132.8	23,457	253
19	7.42	7.28	0.12	0.06	0.50	6.00	0.004	16	3	0.19	3.05	132.8	23,000	431
10	7.44	7.10	0.06	0.03	0.50	6.00	0.004	16	3	0.47	3.07	132.8	23,118	908
4	7.54	7.45	0.06	0.03	0.50	6.00	0.004	16	3	0.12	3.14	132.8	23,620	688

Table 6- 9 Carrying capacity estimates of individual cage in June 2012. O_{2IN}/O_{2OUT} is the DO flowing in/out of the cage, O_{2MIN} is the minimum DO, $U_i(t)$/$U_o(t)$ is the current flowing in/outside the cage, U_{MIN} is the minimum current, P_C is permeability of the cage, L_C is length of the cage. OCR is the specific oxygen consumption of fish, OX1 is oxygen consumption inside the cage, and CC is the carrying capacity of the cage.

Cage#	O_{2IN} (mg/l)	O_{2OUT} (mg/l)	$U_o(t)$ (m/s)	$U_i(t)$ (m/s)	P_C	Depth (m)	U_{MIN} (m/s)	L_C (m)	O_{2MIN} (mg/l)	OX1 (kg/h)	OT (kg/h)	OCR (mg/kg/h)	CC (kg)	Biomass (kg)
4	6.41	6.16	0.06	0.03	0.50	6	0.004	16	3	0.09	2.35	132.8	17,732	799
1	6.38	6.19	0.06	0.03	0.50	6	0.004	16	3	0.07	2.33	132.8	17,570	441
6	6.30	6.19	0.12	0.06	0.50	6	0.004	16	3	0.04	2.28	132.8	17,192	1,144
8	6.31	6.01	0.06	0.03	0.50	6	0.004	16	3	0.11	2.28	132.8	17,205	3,117
10	6.40	6.03	0.06	0.03	0.50	6	0.004	16	3	0.14	2.35	132.8	17,714	1,140
11	6.35	6.18	0.06	0.03	0.50	6	0.004	16	3	0.06	2.31	132.8	17,418	4,003
13	6.35	6.22	0.06	0.03	0.50	6	0.004	16	3	0.05	2.32	132.8	17,441	1,922
15	6.12	5.73	0.09	0.06	0.67	6	0.004	16	3	0.15	2.88	132.8	21,659	1,533
18	6.03	5.97	0.09	0.06	0.67	6	0.004	16	3	0.02	2.79	132.8	21,029	1056
20	6.37	6.15	0.06	0.03	0.50	6	0.004	16	3	0.08	2.33	132.8	17,516	701

Table 6- 10 Carrying capacity estimates of individual cage in July 2012. O_{2IN}/O_{2OUT} is the DO flowing in/out of the cage, O_{2MIN} is the minimum DO, $U_i(t)$/$U_o(t)$ is the current flowing in/outside the cage, U_{MIN} is the minimum current, P_C is permeability of the cage, L_C is length of the cage. OCR is the specific oxygen consumption of fish, OX1 is oxygen consumption inside the cage, and CC is the carrying capacity of the cage.

Cage#	O_{2IN} (mg/l)	O_{2OUT} (mg/l)	$U_o(t)$ (m/s)	$U_i(t)$ (m/s)	P_C	Depth (m)	U_{MIN} (m/s)	L_C (m)	O_{2MIN} (mg/l)	OX1 (kg/h)	OT (kg/h)	OCR (mg/kg/h)	CC (kg)	Biomass (kg)
1	7.15	6.99	0.12	0.06	0.50	6	0.004	16	3	0.23	2.87	132.8	21,624	916
7	7.14	7.00	0.15	0.06	0.40	6	0.004	16	3	0.19	2.29	132.8	17,221	4,872
16	7.17	6.97	0.12	0.06	0.50	6	0.004	16	3	0.27	2.88	132.8	21,691	4,455
13	7.18	7.14	0.12	0.06	0.50	6	0.004	16	3	0.05	2.89	132.8	21,734	2,213
18	6.34	6.20	0.12	0.06	0.50	6	0.004	16	3	0.20	2.31	96.4	23,956	1,882
29	6.23	5.82	0.12	0.06	0.50	6	0.004	16	3	0.56	2.23	96.4	23,134	190
23	6.22	6.00	0.12	0.06	0.50	6	0.004	16	3	0.31	2.23	96.4	23,112	1,814

Table 6- 11 Carrying capacity estimates of individual cage in August 2012. O_{2IN}/O_{2OUT} is the DO flowing in/out of the cage, O_{2MIN} is the minimum DO, $U_i(t)$/$U_o(t)$ is the current flowing in/outside the cage, U_{MIN} is the minimum current, P_C is permeability of the cage, L_C is length of the cage. OCR is the specific oxygen consumption of fish, OX1 is oxygen consumption inside the cage, and CC is the carrying capacity of the cage.

Cage#	O_{2IN} (mg/l)	O_{2OUT} (mg/l)	$U_o(t)$ (m/s)	$U_i(t)$ (m/s)	P_C	Depth (m)	L_C (m)	U_{MIN} (m/s)	O_{2MIN} (mg/l)	OX1 (kg/h)	OT (kg/h)	OCR (mg/kg/h)	CC (kg)	Biomass (kg)
17	7.90	7.78	0.18	0.06	0.33	6	16	0.004	3	0.17	2.26	96.4	23,441	2,664
18	7.89	7.80	0.12	0.06	0.50	6	16	0.004	3	0.11	3.38	132.8	25,433	2,556
8	7.87	7.42	0.12	0.06	0.50	6	16	0.004	3	0.62	3.36	132.8	25,323	5,531
19	7.55	7.28	0.12	0.06	0.50	6	16	0.004	3	0.37	3.15	132.8	23,696	2,010
28	7.60	7.42	0.18	0.06	0.33	6	16	0.004	3	0.25	2.12	132.8	15,953	545
26	7.60	7.38	0.18	0.09	0.50	6	16	0.004	3	0.31	3.18	132.8	23.956	489
16	7.65	7.54	0.18	0.06	0.33	6	16	0.004	3	0.16	2.14	96.4	22,236	5,766
20	7.56	7.39	0.18	0.06	0.33	6	16	0.004	3	0.23	2.10	132.8	15,815	1,582
14	7.77	7.62	0.12	0.06	0.50	6	16	0.004	3	0.20	3.30	132.8	24,813	3,258
7	7.64	7.19	0.18	0.06	0.33	6	16	0.004	3	0.63	2.14	132.8	16,106	5,715
4	7.64	7.44	0.12	0.06	0.50	6	16	0.004	3	0.28	3.21	132.8	24,168	2,327
6	7.56	7.41	0.15	0.06	0.40	6	16	0.004	3	0.20	2.52	132.8	18,973	2,824

Table 6- 12 Carrying capacity estimates of individual cage in September 2012. O_{2IN}/O_{2OUT} is the DO flowing in/out of the cage, O_{2MIN} is the minimum DO, $U_i(t)$/$U_o(t)$ is the current flowing in/outside the cage, U_{MIN} the is minimum current, P_C is permeability of the cage, L_C is length of the cage. OCR is the specific oxygen consumption of fish, OX1 is oxygen consumption inside the cage, and CC is the carrying capacity of the cage.

Cage#	O_{2IN} (mg/l)	O_{2OUT} (mg/l)	$U_o(t)$ (m/s)	$U_i(t)$ (m/s)	P_C	Depth (m)	U_{MIN} (m/s)	L_C (m)	O_{2MIN} (mg/l)	OX1 (kg/h)	OT (kg/h)	OCR (mg/kg/h)	CC (kg)	Biomass (Kg)
28	6.95	6.89	0.18	0.12	0.67	6	0.004	16	3	0.09	3.64	132.8	27,437	727
16	7.02	6.87	0.09	0.06	0.67	6	0.004	16	3	0.21	3.71	132.8	27,902	7,245
4	7.31	7.16	0.12	0.06	0.50	6	0.004	16	3	0.22	2.98	132.8	22,444	2,927
1	7.26	7.23	0.12	0.06	0.50	6	0.004	16	3	0.04	2.94	132.8	22,174	1,793
5	7.26	7.22	0.12	0.06	0.50	6	0.004	16	3	0.06	2.94	132.8	22,168	3,609
7	7.15	7.03	0.12	0.06	0.50	6	0.004	16	3	0.17	2.87	132.8	21,582	7,182
10	7.18	6.91	0.12	0.06	0.50	6	0.004	16	3	0.37	2.89	132.8	21,754	3,445
15	7.19	7.04	0.18	0.12	0.67	6	0.004	16	3	0.21	3.86	132.8	29,087	4,144
19	7.20	6.99	0.18	0.12	0.67	6	0.004	16	3	0.28	3.87	132.8	29,124	2,792
23	7.23	6.98	0.12	0.06	0.50	6	0.004	16	3	0.35	2.92	132.8	22,010	3,475
27	7.23	7.07	0.18	0.09	0.50	6	0.004	16	3	0.22	2.92	132.8	21,997	1,021

6.4 Discussion

6.4.1 *Farm perimeter observations and carrying capacity*

The DO of surface waters in the vicinity of the farm was well oxygenated throughout the study period and remained above 6.5 mg/l most months, except in June and July. The highest DO of surface waters flowing into the farm perimeter of 7.93 mg/l was recorded in December (Table 6-3). DO then decreased starting in January and reached the lowest concentrations in June-July (Table 6-2) when the lowest water temperatures were also recorded at the farm and at two sampling sites located 5 km away from the farm (see Chapter two). DO then increased significantly in August and remained high until the end of the sampling in September. These fluctuations in DO, observed over large areas including stations well away from the farm, were controlled by the general circulation and oxygen concentrations in the SEA.

The seasonality of oxygen concentration in SEA (Chapter three) had a significant influence on the CC of the farm. December had the highest DO; hence, it had the highest CC. Decrease in the DO of waters flowing into the farm had consequences to the CC of the farm, further reduction to minimum DO in June and July (Tables 6-9 and 6-10) which resulted in decline in CC. The minimum observed DO of 6.29 mg/l in the farm cages was two times higher than 3.0 mg/l (Ross, 2000) known to suppress tilapia growth rates, therefore, DO conditions were adequate at all times for tilapia fish culture. However, during this study, the farm condition was at a low operational capacity. The study suggests that at full farm operation the CC could have been lower than the values

obtained in the current study as fish biomass had a direct effect on CC estimates based on observations at the scale of the individual cages. Direct correlations on the effect of biomass on CC may not be established in all months since the CC was also dependent on inflowing DO, but in general, April is a good example of the influence of biomass on CC. The DO of inflowing waters was similar to the DO recorded at sites A, B, C, and D and was low inside the cages (Figure 6-16). The highest CC of 35,039 kg was estimated at cage 17 which had low biomass of 171 kg in it in April. Likewise, cage 6 which also had low biomass of 180 kg had high CC of 33,830 kg while cage 45 which had the highest biomass had an estimated CC of 16,427 kg.

Perimeter sites P1 (nearshore) and P4 (offshore) had significantly different DO between in January, but not in December (Table 6-1). In January 2012, the last row of the cages which is near site P4 had an aggregate biomass of 44, 139 kg while the aggregate biomass at row 1 near site P1 was 9,102 kg. The DO at site P1 was significantly higher than at site P4, suggesting that low DO at site P4 was influenced by high OX1 by the fish in the last row. However, non-significant differences between sites P1 and P4 in November and December when the first and last rows had high fish biomasses may be related to high available DO in the lake, especially in November when the DO was uniformly distributed at all sites (Table 6-1). December had the highest inflowing water at the farm, high P_F, highest OT, and high CC (Table 6-2). It is possible that fast renewal of waters prevented significant differences in DO between sites P1 and P4 in December. Significant difference in DO between sites P1 and P4 was detected in February, March,

April, and July (Table 6-1). Site P1 and P4 had similar DO during the day, but DO increase at night at site 4 was significantly higher than the DO at site P1 (Figure 6-10).

Perimeter sites P2 and P3 both located at the eastern side of the farm had significantly different DO in January, April, May, and September (Table 6-1), in all observations, the DO was higher at site P2 than site P3 (Figure 6-10). Similarly, the nearshore site P6 had significantly higher DO than the offshore site P5 (Table 6-1). Sites P3 and P5 are more exposed to offshore waters; so low DO at these sites seem not to be related to the biomass at the cages because the cages near these sites had relatively lower biomass than the cages near sites P2 and P6. More cages had fish near sites P2 and P6, and only four cages were stocked at the seventh row in April, May, and September where site P3 and P5 are located, therefore, the effect of fish biomass on DO differences between nearshore sites (P2 and P6) and offshore (site P3 and P5) cannot be explained by biomass differences in farm.

Significant differences in DO between the nearshore perimeter sites P2 and P6 and between further offshore sites P3 and P5 were noted in January, July, and September (Table 6-1). Field observations noted a dominance of south east winds with occasional eastern winds; northern winds occurred temporarily (less than 30 min) during the day, but were strong in September when day sampling was discontinued. It was expected that the western perimeter sites of the farm were going to experience lower DO than the eastern side because they were down current. This did not happen; site P6 had significant higher DO than site P2 in January, July, and in September. Site P5 had higher DO than site P3 in January and September, but not in July (Table 6-1). Knowledge of differences between

nearshore and offshore DO is important in Lake Malawi cage aquaculture farming and may help in site selection and legal framework for sustainable cage aquaculture. However, it is premature to make conclusive recommendations that nearshore areas are well oxygenated and fish farms should aim at setting their farms in shallow areas. A fuller hydrodynamic-water quality model for the SEA and Lake Malawi would be necessary to confirm these differences between nearshore and offshore waters.

Fish biomass at the farm was over 120, 000 kg between November 2011 and March 2012 and less than 80, 000 kg between April 2012 and September 2012 (Figure 6-11). The first three rows and the last row were fully stocked with farmed fish while a few cages were stocked between the fourth and ninth row November (Figure 6-1). Cages 8, 9, and 10 were harvested while the biomass in other cages increased in December. No significant difference in DO was detected in November among the six sites at the farm perimeter (Table 6-1); differences were detected in December and January. Measurements inside the farm at individual cages showed the influence of fish biomasses at the cages on CC. June is an example of a strong linkage between biomass at the cages and CC. DO profiles (Figures 6-14 to 6-18) show lower surface DO around the cages compared to reference sites. Total fish biomass at the cages was low in June (Figure 6-11). Out of 30 cages stocked with fish, only cage 11 had a high biomass. At low biomass, the DO of inflowing waters was at all cases similar to those from reference sites. The maximum surface DO was less than 6.5 mg/l in all profiles and the waters inside the cages had DO below 6.2 mg/l. The CC estimates per cage reduced owing to decline on DO in SEA with minimum CC being 18,247±521 kg (Figure 6-13). Under low DO

content in inflowing waters, the fish had low OX1, less than 1.00 kg O_2/h and similar OT in all sampled cages (Table 6-9). It is likely that OX1 was low in June due to low biomasses at the cages. It is important to note that while high fish biomass increases OX1, OX1 also depends on DO of inflowing waters.

Despite the fact that the differences found between the sites was small, in many cases, less than 1.0 mg/l DO, the results provide a better idea about spatial effects on DO at the farm under different fish biomasses under seasonal changes in DO and the effect of total biomass. It is also important to know that there were months that the DO was significantly higher at night (Table 6-1). June and July had relatively similar DO, but lower DO than in other months, and consequently the CC was also low since it depends on DO entering the farm or cages, therefore, June and July should be regarded at the months on which the Maldeco Aquaculture Farm had its lowest CC, but this result was imposed by regional changes in DO caused by lake mixing and not by farm operations. When designing fish farms for Lake Malawi, estimates of maximum allowed biomass should be based on the June-July period of low seasonal surface DO.

6.4.2 *Model application* and *recommendations*

The model produced comparable results based on perimeter observations and cage observations. One important observation was seen in December. Cage 21 was sampled twice on December 1st and 24th and only a small difference in CC was observed between the two periods (Table 6-3). The use of 3.0 mg/l as minimum DO for tilapia farms is more favorable to the species under culture, but does not consider the effects on

other organisms living in the same area. This is not a problem for Maldeco Aquaculture sites since the lowest DO was above 6.0 mg/l in the cages and vicinity of the farm, however, the application of the current model in other lakes require an understanding of DO targets set for the water body to protect other water uses or biota.

Historical data from May 2009 indicate that the farm used high stocking densities between 86, 000 to 145, 000 fish per each cage with varying biomasses between 267 and 39,915 kg. The current study was conducted under low stocking densities and biomass due to lack of fish or lack of fish with uniform sizes to be stocked in the same cages as stockings of fish of different fish sizes promote social interactions and it is not commercially viable to have different fish sizes., e.g. In January 2012, the cages were stocked with minimum of 25, 000 and maximum of 111, 000 fish with biomass ranging between 255 and 14, 454 kg per cage. After a major fish harvest in April, the stocking densities varied between 22, 000 and 85, 000 fish with biomasses ranging between 52 and 6, 466 kg in June 2012. The period of low fish biomass at the farm (Figure 6-11) was an opportunity to test the sensitivity of the model. The model provided reasonable estimates per individual cage even after the sharp decline in farmed fish biomass at the farm.

The farm layout in commercial cage farms is usually defined by similar spacing of cages and rows to allow normal farm operation (sampling, harvest, patrolling) and easy circulation of oxygen, as such, the length of the farm is estimated as: L_F (m) N_F /R (L+S)-S, where: N_F is the number of cages, R is the number of rows, S is the distance or separation between rows (Stigebrandt et al., 2004). The spacing of the cages at Maldeco Aquaculture farm is not regular and is affected by strong winds that can move

cages. There is considerable amount of space within the farm with no cages (Figure 6-1), therefore, there should be an overestimations of CC based on perimeter effect due to the fact that the length of the farm was estimated based on the distance of the farm and not the regular spacing of the rows.

Previous study by Gondwe (2011) noted overstocking of the cages and longer residence of fish of about 376±42 days to grow to market size. Reduction of stocking densities suggests that Maldeco is also concerned about the right stocking densities. However, the lack of a model that estimates reliable carrying capacity estimates resulted in stocking cages at different densities with application of a trial and error approach. As a guideline, the mean stocking density per cage estimated to allow rapid growth to a carrying capacity biomass 23,389 ±441 kg and 1,866,689±95,678 kg for the whole farm is recommend at Maldeco Aquaculture Farm to allow normal fish growth rates and attainment of desirable marketable size of fish within a shorter production period in the cages, thereby reducing impact of cages in the environment. It is expected the model will not only improve production efficiency of Maldeco Aquaculture Farm, but will also be used as a monitoring tool by the Department of Fisheries in Malawi and as a tool for setting new cage aquaculture farm in Lake Malawi, but it may also be applicable in other African lakes that are increasingly supporting cage aquaculture farms. The physical aspects such as water temperature and currents, the biological factors such as dissolved oxygen and the nutrients need to be investigated before setting aquaculture operations in the lake. The current model includes physical and biological processes occurring in a specific location of the farm, but it is not a standalone decision tool, cage

aquaculture farms are also known to have localized effects, e.g. accumulation of organic particulate wastes emanating from cage farms alter the benthic substrate and consequently affect the benthic fauna (Brown et al., 1987; Person and Gowen, 1990). Integration of chemical and more biological components in the model is recommended to efficiently preserve the nature and ecology of local and regional environment while promoting sustainable aquaculture is recommended. A growth model that predicts weight gain, mortality, and biomass at the end of the production cycle is proposed to guide the company to stock the right amount of fish to achieve the estimated CC.

6.5 Conclusion

1. The Maldeco Aquaculture farm is well located for tilapia farming. The waters entering and leaving the farm had minimum DO of over 6.0 mg/l and did not fell below the minimum DO recommended for tilapia culture, but a mean CC is important to guide the private sector in stocking and for monitoring the operations.

2. The nearshore sites often had higher DO than the offshore sites.

3. The effect of the farm as an oxygen sink was not detected at farm perimeter probably due to low fish biomass at the farm. The effect was detected inside the farm. Oxygen profiles recorded at the cages reveal oxygen consumption by farmed fish. The DO was lower inside the farm than at reference sites immediately outside the farm.

4. The farm had periods of higher DO during the day than at night and vice-versa. The waters entering cages stocked with small fish biomass tended to have similar DO with control sites and high permeability.

5. Optimum fish growth rates and shorter production cycle will be achieved at a stocking density of 23,389 ±441 kg per cage. The CC of the entire farm should be 1,866,689±95,678 kg. The latter figure may be an overestimation due estimates of the length of the farm of 875 m which the model assume that this whole length is filled up with cages.

6. The CC followed seasonal changes in DO in SEA. It was high at high DO and low at low DO. Cage effect measurements show that CC also depended on the fish biomass in the cages. High biomass reduced P_C and consequently the CC.

7. The current results show the power of one dimensional oxygen based model which determines the CC of the farm and cages using minimum required DO for tilapias and minimum observed water currents at the site, the dimensions of the cage and the size of the farm.

Chapter 7

Thesis conclusions

This is the first study to investigate the impact of cage aquaculture on wild fish communities in African Great lakes which are increasingly being used for cage aquaculture development. In addition, for the first time, a carrying capacity model was evaluated to estimate the maximum allowable carrying capacity for individual cages as well as a farm and it generated reasonable values which will guide both the private sector and regulatory authorities.

Major conclusions:

- The farm affected the fish community structure in SEA. The sites remote from the farm had similar fish community structure, but were different from the community at the farm. Fish abundance was significantly higher at the farm. This high abundance of wild fish causes conflicts with local fishermen who often fish inside the farm without permission.

- Using a biomass-abundance distribution model, the farm site and site 3, located 5 km south of the farm were classed as impacted/disturbed likely due to the effect of farm operations at the farm site and continuous use of illegal fishing gear (kandwindwi) at site 3. However, no significant impact on fish diversity was detected between these sites and site 1 which was classed as un-impacted.

- Changes in water quality parameters at the three study sites were seasonal but did not identify a farm effect, possibly because the level of farm operation was well

under its full operating capacity during the course of the study. Day and night measurements of dissolved oxygen (DO) provided a better understanding about oxygen dynamics at the farm. Night DO were significantly higher than day DO in March, May, June and also higher at some locations around the farm sites in February, April, and August. The oxygen content was above 6.0 mg/l in all months and was optimum for tilapia production which requires at least 3.0 mg/l DO. Nearshore perimeter sites had significantly higher DO than offshore sites most of the time.

- TN and TP showed no consistent effect from the farm activities, and there was no farm effect on chlorophyll *a* concentrations. Changes in these possible indicators of eutrophication were seasonal and responded to lake dynamics rather than farm activities. The period between April and July can be critical for fish growth because of lower temperatures and oxygen during the upwelling season.

- There is no evidence that wild fish seen at the farm including abundant smaller fish benefit significantly from feed emanating from the farm. Fine particle feeding planktivorous tilapia of the same species grown at the farm and possibly zooplanktivorous species seem to consume some commercial feed as well their natural food resources while the benthic groups relied on their natural diets at all sites whether at the farm or remote from the farm.

- The farm and the cages were not overstocked. The current study provides a minimum stocking density guideline of 23,389 ±441 kg per cage and

1,866,689±95,678 kg for the farm to allow optimum fish growth rates and shorter production cycle. The carrying capacity of the whole farm may be an overestimation since the model assumed that entire farm perimeter is filled up with cages.

Several limitations of the study were identified in order to provide guidance to future studies

- More frequent observations on water quality are needed to sustain the cage aquaculture industry in Lake Malawi which depends on good quality water. Instruments or data loggers that record important parameters such as dissolved oxygen and currents hourly or daily would have likely improved and given more confidence in the model output as well as better appreciation of the hydrodynamics of the farm area. For instance, hourly or daily measurements of dissolved oxygen and water currents would have been useful in explaining the reason why the offshore sites had most of the time higher DO than the offshore sites. This information is important to understand fish growth rates subject to different concentrations of dissolved oxygen and currents. It is also important for siting fish farms.
- The potential effect of the farm may have been masked because the farm was running at low fish biomass well below operational design.

- Lack of timely fish biomass data can be a problem when carrying capacity estimates need to be compared to biomass in the cages. A simple growth model that predicts the biomass during the production cycle is recommended. The carrying capacity model provided a guide for maximum biomass at the cages, but did not estimate the number of fish to be stocked to achieve such maximum biomass, nor it provide information about how long the fish should be kept in the cages.

- The concentration of inflowing dissolved oxygen and permeability of the farm were important parameters in defining the carrying capacity of the farm, however, there is a need to include chemical and biological parameters in the model to preserve the nature and ecology of local and regional environment.

- A more confident endorsement of the model would require its testing against other farm designs and locations which are currently not available. It is recommended that if the approval is given for more farms that the efficacy of the model be tested for those farms and validated through monitoring of water temperature and oxygen concentrations.

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