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Tracing the flux of aquaculture-derived organic wastes in the southeast arm of Lake Malawi using carbon and nitrogen stable isotopes

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ABSTRACT

Cage culture of native tilapiine cichlids was initiated in Lake Malawi in 2004. The lake is well known for its highly endemic ichthyodiversity, and it is estimated to have more species of fish than any other lake in the world. Consequently there is concern about the impact of cage farming operations on the wild fish communities. In 2007, high densities of diverse wild fish were observed around the cages and stable isotopes, $\delta^{13}C$ and $\delta^{15}N$ analyses, established that cage wastes were incorporated in the food web that supported diverse wild fishes in the vicinity of the cages. Comparison of $\delta^{13}C$ and $\delta^{15}N$ signals of caged and wild fish caught in 2007 in the vicinity of the fish farm and signals of fish samples caught between 1995 and 1997 before the fish farm was started in 2004 established a shift in the isotopic signatures of wild fish indicating the incorporation of cage wastes into the wild fish diet. Sedimentation of cage wastes collected in sediment traps below the fish cages was also confirmed using the $\delta^{13}C$ and $\delta^{15}N$ analyses. The accumulation of the cage wastes in the sediments below the cages was, however, minimal as indicated by the small differences in the isotopic ratios between the bulk sediments and some sedimentary organisms (bivalves, snails and earthworms) under the cages relative to ratios in similar organisms at control stations. The low impact of cage wastes on underlying sediments and benthic organisms was due to the rapid and efficient dispersion of the cage wastes facilitated by water currents through the fish farm which averaged 9.3 cm s^{-1} as well as the consumption and subsequent dispersion of cage wastes by the large numbers of wild fishes which aggregated around the cages. This study has also shown that in Lake Malawi, fish rather than benthic organisms and plankton material may be a more sensitive monitor of the dispersion of cage wastes.

1. Introduction

Lake Malawi is an extremely important source of fish for domestic consumption as well as clean water for drinking and domestic use by people in the three riparian countries of Malawi, Tanzania and Mozambique. The lake also harbors between 700 and 1000 species of fish (Snoeks, 2000), whose endemism, diversity, breeding and feeding behavior fascinate the scientific community. As a result, Lake Malawi is one of the world's most important hotspots of biodiversity. The capture fishery has, however, declined in the lake during the last two decades due to overfishing and habitat degradation (Banda et al., 2005). In 2004 in an effort to enhance fish production in the lake, Maldeco Aquaculture Ltd introduced cage aquaculture of indigenous *Oreochromis karongae* and *Oreochromis shiranus* in the relatively shallow southeast arm of the lake. One important question raised by the introduction of cage aquaculture in the lake was how the facility and associated waste products would affect the surrounding environment and native biota including the largely (>99%) endemic fish populations which are most abundant in the littoral zone.

Previous studies of the cage aquaculture operation in Lake Malawi (Gondwe et al., 2011a) as well as in many temperate ecosystems elsewhere show that between 70 and 80% of nutrients added to fish cages through feed are lost to the surrounding environment (water column and underlying sediments) in the form of unconsumed feed, fish feces and metabolic wastes (Folke and Kautsky, 1989; Gowen and Bradbury, 1987; Hall et al., 1990, 1992; Holby and Hall, 1991; Kaushik, 1998; Kullman et al., 2009; Troell and Berg, 1997). The discharged wastes, rich in nitrogen (N) and phosphorus (P), have the potential to pollute the surrounding waters and underlying sediments, and may cause problems including eutrophication, toxic algae outbreaks, increased turbidity, decreased oxygen (Anderson et al., 2002), and loss of biodiversity (Beardmore et al., 1997; Diana, 2009).

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Apart from affecting directly the quality of the water and sediments close to the cages, the discharged particulate organic wastes can also be directly utilized by animal consumers in the receiving ecosystem (Roditi et al., 2000). The uptake of the cage-derived organic matter may lead to the modification of planktonic and benthic food webs in the receiving ecosystem (Grey et al., 2004). Mazzola and Sarà (2001) studied the feeding behavior of mussels (*Mytilus galloprovincialis*) and clams (*Tapes* sp.) cultivated around an intensive fish farm of *Dicentrarchus labrax* and *Sparus aurata* in the Gulf of Gaeta, Mediterranean Sea. They showed that the cage-derived organic matter was the dominant and constant source of organic C for both mussels and clams, accounting for about 80% of the clam diet. Grey et al. (2004) studied a trout farm in Esthwaite Water (UK) and estimated that organic wastes from the farm constituted 45–50% of copepod diet, 62–68% of *Daphnia* diet, 73–89% of roach diet and 54–57% of chironomid diet. In the Mediterranean Sea, Vita et al. (2004) estimated that wild fish consumed 80% of the particulate organic matter that sank below fish cages while Phillips et al. (1985) reported that feed pellets constituted about 98% of the gut contents of wild fishes around a salmonid cage farm. The direct use of organic cage wastes by wild consumers such as fishes may also help to mitigate the environmental impacts of the cage operations (Shpigel and Blaylock, 1991; Shpigel et al., 1993), but may also lead to alteration of fish distributions and habitat relationships.

Studies have shown that fish species in Lake Malawi have evolved an astonishing diversity of feeding adaptations which enable the fish to exploit a wide range of food sources including phytoplankton, zooplankton, detritus, epilithic and epiphytic algae, macrophytes, mollusks, insects, benthic invertebrates, whole fish, fish scales, fish eggs and fish larvae (McKaye and Marsh, 1983). However, Duponchelle et al. (2005) analyzed gut contents and isotopic values of tissues of sandy shore fish species and their potential food sources in Lake Malawi and confirmed the large diet overlaps among the fish species previously reported by McKaye and Marsh (1983). They also observed that the diet overlaps among the fish species changed opportunistically with the availability of the food sources. Because of the low abundance of autochthonous food sources in the lake at less than 2 μg Chl*a* L^{-1} (Gondwe et al., 2008, 2011b; Guildford et al., 2000, 2007; Ngochera and Bootsma, 2011), food competition is likely a persistent selection pressure that would favor opportunistic feeding by fish species and other organisms. Consequently, it may be expected that the fish and other organisms in the vicinity of the cages might efficiently utilize the organic cage wastes as a novel source of energy for growth and reproduction. In order to appreciate the oligotrophic status of Lake Malawi, a comparison is hereby made with Lake Victoria where a mean chlorophyll a concentration of 10.6 μg L^{-1} in surface water has been reported for 2005–09 (Sitoki et al., 2010).

In this study $\delta^{13}C$ and $\delta^{15}N$ isotopic ratios were utilized to trace the uptake of cage-derived organic wastes into the planktonic and benthic food webs in the vicinity of an operational fish farm in the southeast arm of Lake Malawi. An organism's body reflects the isotopic ratios of the food source metabolized (Schroeder, 1983), and so significant shifts in isotopic signatures might be expected compared to control samples if organisms in the vicinity of the fish farm routinely utilize the cage-derived organic wastes in their diets (Dolenec et al., 2006) in preference to their native food resources. Because $\delta^{13}C$ and $\delta^{15}N$ values in an organism enrich systematically by 0–1‰ and 3–5‰ (mean 3.4‰), respectively, relative to the food source (Minagawa and Wada, 1984), $\delta^{13}C$ has been widely used to identify basal carbon resources to a food web while $\delta^{15}N$ has been used to determine relative trophic positions of organisms within a food web (Grey et al., 2001; Hecky and Hesslein, 1995). Similar shifts in stable isotope composition were expected in sediments underlying the fish farm due to a continuous rain of the cage-derived organic wastes in the form of unused feed pellets and fish feces from the cages.

2. Materials and methods

2.1. Study site

The cage aquaculture studied here was established in 2004 by Maldeco Aquaculture Ltd to farm *O. karongae* and *O. shiranus* fish species in the southeast arm of Lake Malawi (Fig. 1). Both fish species are endemic to the lake and the upper Shire River, the lake's only outlet which is near the cage farm. The fingerings were grown in cylindrical net cages (15 × 6 m diameter, depth) as mixed or unispecific stocks. In 2007 the number of deployed fish cages in the lake increased from 16 to 48 but due to scarcity of fingerlings only about half of the cages were stocked. Fingerlings were stocked at a mean size of 5 g. Fish were fed three pelleted diets, starter, grower and finisher, in that order from the day the fingerlings were stocked to harvest. Starter diet was supplied until the fish weighed 50–70 g, grower was supplied until the fish weighed 150–200 g while finisher was supplied until the fish reached a market size of ≥300 g (Maldeco Aquaculture Ltd, pers. comm.). The feed diets formulated principally from corn and soya meals on average contained 44.6% C, 5.8% N, 0.9% P and 5.2% H_2O (Gondwe et al., 2011a). Feed usage at the fish farm was about 33.4 tonnes $cage^{-1}$ which was converted into 12.9 tonnes of fresh fish $cage^{-1}$ $year^{-1}$ (Gondwe et al., 2011a). Target harvest per cage was 20 tonnes $year^{-1}$.

The fish farm was located in 14–24 m water depth about 1 km from shore with an inshore–offshore orientation generally perpendicular to the dominant wind and water current directions. Southeasterly and northeasterly persistent trade winds which dominate over much of the year result in northward and southward flowing currents alternating seasonally, roughly along the axis of the lake (Eccles, 1974). Water currents have been measured at 2.5 m off the bottom below the fish farm using a 2D-ACM Falmouth Scientific Inc. (FSI) acoustic current meter (accuracy of ± 2% of reading). On an annual basis, water flowed dominantly southward through the farm at a mean velocity of 9.3 cm s^{-1} (Gondwe et al., 2011b).

2.2. Sampling

Samples collected for this study included formulated fish feed diets (starter, grower and finisher), cultured fish, feces of cultured fish, cage-derived particulate organic matter (using sediment traps), periphytic algae growing on cage nets, phytoplankton, zooplankton, wild fish from the vicinity of the cages as well as benthic macroorganisms including bivalve mollusks, snails and earthworms.

Feed diets and cultured fish were donated by Maldeco Aquaculture Ltd. The feed diets were sampled in January, June, October and December 2007. Twenty seven samples of cultured fish ranging from 14.3 to 27.8 cm in total length (TL), weighing between 57.4 and 408.9 g (Table 2) were donated by Maldeco Aquaculture Ltd. All the cultured fish samples analyzed for stable isotopes were either on grower or finisher feed diets. The dorsal white muscles of all the fish samples were dissected for stable isotope analysis.

Feces from cultured fish were siphoned from the bottom of an aquarium where the cultured fish were held for 4 h. Particulate organic wastes which consisted of sedimenting feces, uneaten food as well as natural particulates falling from the cages were collected in base-weighted sediment traps suspended under the cages with ropes. A control station was identified about 1 km east of the fish farm where a set of 3 sediment traps was also deployed 6 times attached to a vertically stretched rope between a heavy anchor and a subsurface buoy. GPS coordinates were always recorded for later recovery of the traps. The traps were deployed at approximately the same depth as traps under the cages (6–7 m below surface). Due to interference from artisanal trawlers, only 3 of the 6 sediment trap deployments were successfully recovered from the control station. At the laboratory, trap samples were homogenized, subsampled, and