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Changes in the biomass of chambo in the southeast arm of Lake Malawi: A stock assessment of *Oreochromis* spp.

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ABSTRACT

Lake Malawi has one of the most diverse fish faunas in the world (500–650 species) and is a major source of protein for the people of Malawi. Chambo (*Oreochromis* spp.) is one of the most important food fishes; its abundance has declined sharply over the last twenty-years. Surveys by the Malawi Department of Fisheries have shown a decrease in chambo density in the southeast arm of the lake and the annual harvest has dropped substantially since 1985. We conducted a dynamic stock assessment of *Oreochromis* spp. which included all vessel and gear types and covered the entire southeast arm of Lake Malawi. Chambo biomass peaked in 1982 and then declined continuously through the early 2000s. The biomass is highly correlated with the mean lake height two years prior suggesting that recruitment may be linked to increased nutrient input, and spawning and nursery habitat associated with the flooding of low lying areas. The main driver of chambo biomass, however, was fishing pressure which was above the level that would achieve maximum sustainable yield during the entire time series. This study provides a baseline from which to measure changes due to future management actions or climate variations.

Introduction

Fish stocks around the world face dual challenges from fishing and climate change. Changes in precipitation, circulation patterns, and thermal shifts caused by periodic forcing in the coupled atmospheric-ocean system alter primary productivity, predator–prey dynamics, spawning and nursery grounds and internal metabolic activity (Mann and Lazier, 2004). Understanding how climate variation impacts fish stocks in concert with fishing is essential for proper management.

Lake Malawi, located in the African rift valley, has one of the most diverse fish faunas in the world (500–650 species) (Turner et al., 2001) and represents a major source of protein for the people of Malawi. Roughly 40% of all animal protein consumed in Malawi is derived from the lake (Bland and Donda, 1994). Since the onset of commercial trawling in 1968, there have been considerable changes in the composition of the fish community (Banda and Tomasson, 1997; Turner, 1995). Larger bodied demersals have been replaced by smaller pelagics and certain species have been extirpated (Turner et al., 1995). In particular there has been a decline in the catch of one of the most economically important fish, chambo (*Oreochromis* spp.) (Banda and Tomasson, 1997; Banda et al., 2005; Palsson et al., 1999; Weyl, 2001; Weyl et al., 2005; Weyl et al., 2010). Research surveys by the Department of Fisheries have shown a decrease in chambo density in the southeast arm of the lake (Kanyerere and Booth, 2001) and the average length of a landed fish has decreased (Palsson et al., 1999). During the same period the shoreline has seen an increase in the human population (>2.7% per annum), a decline in the ability to enforce fishing regulations, the conversion of forests to agricultural land, and large-scale variation in precipitation (Calder et al., 1995; Vollmer et al., 2005).

The name “chambo” encompasses three closely related species of endemic *Oreochromis* that have similar life history traits (Palsson et al., 1999). Chambo are maternal mouth brooding cichlids that use the nearshore environment as spawning and nursery areas. Females mate in shallow water nests built by males and then carry the fertilized eggs in their mouths for two weeks. After hatching the females remain in shallow water for several weeks where the fry develop and retreat into her mouth when threatened. Juveniles continue to develop in shallow water concentrated around macrophytes and rocky outcroppings. They scrape periphyton off rocks and submerged vegetation and expand their diet to include free-floating phytoplankton and detritus as adults. The majority of the chambo stock is concentrated in the southeast arm of Lake Malawi (SEA). This area is the most productive part of the lake and supports the main chambo fishery (FAO, 1993; Weyl et al., 2010). Their low fecundity and nearshore life history makes chambo highly susceptible to fishing pressure, changes in lake height and habitat destruction. Tweddle and Magasa (1989) found that chambo catch was related

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to lake height three years prior and that the productivity of all fish in the lake was related to primary productivity which is a function of the wind velocity and thermal structure of the water column. The lake height has varied over the last century with a peak in 1980 and a decline in the late 1980s through the 1990s (Calder et al., 1995; Vollmer et al., 2005).

The lake itself is over 700 m deep and shoals up to less than 50 m in the southeast arm. It is an oligotrophic system with a permanent anoxic layer below ~200 m. Strong southern winds during the dry winter months (May to September) combined with decreasing air temperatures reduce stratification causing nutrient upwelling. The increased nutrients enable high primary productivity rates which provide food for larger organisms (Bootsma and Hecky, 2003; Eccles, 1974).

High rainfall increases the height of the lake and can also result in increased nutrient input through runoff and river discharge (Hecky et al., 2003). Any changes therefore, in wind patterns, temperature or precipitation patterns could have major impacts on the level of primary productivity, and the amount of energy available to higher trophic levels. Lake Tanganyika, which has a similar limnological structure and is also located in the rift valley, has experienced a 20% drop in primary productivity due to increasing temperatures and decreasing wind velocities. The increased thermal stratification is believed to have reduced the nutrient supply to the base of the food web and is suggested as one of the major causes for the decline in the pelagic clupeid fishery (O'Reilly et al., 2003).

The aim of this study was to quantify the changes in chambo biomass, *Oreochromis* spp. in the southeast arm of Lake Malawi and determine if these changes were related to environmental drivers. We hypothesize that years with higher rainfall, greater wind strength or cooler temperatures would decrease stratification and increase nutrients through river runoff and upwelling. Greater nutrients would in turn provide more food and increase the production of chambo.

A considerable amount of work has been done on the fisheries of Lake Malawi (Weyl et al., 2010). However a single, non-equilibrium, estimate of the total biomass of chambo over the entire southeast arm that includes all the fishing sectors does not exist. This study provides a baseline and a method with which to measure future changes in the chambo population due to both anthropogenic and environmental factors. We developed a robust, statistical method for assessing the chambo stock in the southeast arm including all survey areas and all vessel and gear types. The method standardizes the vessel and gear types with a generalized linear model and fits a non-equilibrium or dynamic surplus production model with an objective function.

Methods

We conducted a dynamic stock assessment of chambo by fitting a Graham–Schaefer surplus production model to the catch and effort data in the SEA from 1976 to 2003 (ADMB-Project, 2009; Prager, 1994; Quinn and Deriso, 1999). We first standardized the catch and effort data from the multiple gears used in the chambo fishery with a two-part generalized linear model to produce a single catch-per-unit-effort (CPUE) index of relative abundance. The output of a surplus production model dynamically fit to an index of relative abundance (i.e. standardized CPUE) is an estimate of the total biomass of a stock (Quinn and Deriso, 1999). The model also produces an estimate of exploitation, the proportion of the biomass removed by fishing that is often termed the harvest rate. Reference points for catch, effort and harvest rate can also be obtained.

Surplus production models fit under an assumption of equilibrium assume the removals due to fishing in a given year, the catch or yield, exactly match the growth of the population in that year. The equilibrium assumption has been shown to be invalid leading to incorrect estimates of biomass and incorrect management advice (Hilborn and Walters, 1992). Models fit dynamically do not assume equilibrium and can provide good estimates of biomass and better management advice (Hilborn and Walters, 1992; Quinn and Deriso, 1999). They are often used when only catch and effort data are available. A surplus production model without environmental terms and a surplus production model with environmental terms were dynamically fit to the relative index of abundance. The environmental terms were selected based on regressions between the potential environmental drivers and the CPUE index. Parameter estimation can be difficult when surplus production models are fit to uninformative data such as time series that continuously decline (Hilborn and Walters, 1992). To improve parameter estimation, we fit a modified version of the highly stable surplus production model provided by the ADMB-Project (2009).

Lake Malawi is a long thin lake centered around 12° 00″ S and 034° 30″ E (Fig. 1). It is the fourth deepest lake in the world and third largest lake in Africa. The Malawi Department of Fisheries subdivided the lake into different areas or strata, which are then broken down into minor strata. The SEA is divided into three strata, which are subdivided into six minor strata.

The Malawi Department of Fisheries has collected catch and fishing effort data since 1976. Neither age structure nor length frequency data exist. The fishery in Lake Malawi is divided into two sectors, artisanal and mechanized. Both are commercial in nature; however the two differ in the level of investment and their vessel types. The artisanal fishery is generally open access and utilizes dugout canoes and plank boats while the mechanized fishery pays a license fee and typically utilizes larger vessels (trawlers and pair trawlers) (Banda and Tomasson, 1997). The two fisheries use a large number of boats and employ a wide variety of gear types (gill nets, seines, otter trawl, etc.).

The mechanized fishery catch and effort (days on the water) data are reported by the vessel owners to the Department of Fisheries as a requirement of the license. Prior to 1992, fisheries statistics for the artisanal sector were collected via a boat-based method. Once a year the Frame Survey counted the total number of boats, fisher folk and pieces of gear on the landing beaches of the six minor strata within the SEA. Based on the Frame Survey four representative beaches were then sampled once a month for catch by weight, number of fisher folk, number of boats and type, size and number of gears. The sample catch was scaled based on the ratio of boats sampled to the total number of boats in the minor strata from the Frame Survey. Effort was calculated as the number of boats or the number of gears. This method led to errors due to sampling, frequent paper-to-paper transcriptions and scaling factor calculations with pen and paper. There were also problems with the scaling factors because several boats often worked a single piece of gear and single boats often worked multiple gears.

In 1992 a new system was instituted with a stratified random sample design that sampled each gear type in proportion to the total number of gears in each minor stratum. Monthly sampling included the previous data, but the number of net pulls and gillnet sets were recorded to better calculate effort. The data sheets were entered onto computers and all scaling factors and calculations were performed on the computer. The new system has reduced transcription errors and resulted in more consistent estimates of catch and effort (FAO, 1993; Turner et al., 1992). After compiling all the information we corrected major errors in the raw data based on conversations with the Malawi Department of Fisheries and published articles (Tweddle et al., 1994). The data need to be used with caution, but do provide a complete 28 year time series.

Environmental data

Environmental data were compiled for the area around the southeast arm of Lake Malawi. Lake height data were compiled from monthly in situ gauge level records (1896–2000) (Calder et al., 1995; Vollmer et al., 2005) and daily satellite altimeter data (1992–2007). The altimetric lake level variations were available from the USDA Reservoir Database (http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/). The radar altimeter data were from the NASA/CNES Topex/Poseidon and Jason-1 satellite missions. Yearly lake height was calculated as the average of all measurements taken in a given year. Rainfall data were available from NOAA's climate prediction center (pers. comm. Eric