



INVESTIGATING ANTHROPOGENIC IMPACTS IN NIGERIAN COASTAL WATERS
USING ECOSYSTEM MODELING APPROACHES

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DEDICATION

This dissertation is dedicated to Jesus Christ my Lord and Savior – Who is Faithful and True (Rev 19:11).

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LIST OF ABBREVIATIONS

Ecopath with Ecosim.....	EwE
Fishing in Balance Index	FIB Index
Food and Agricultural Organization	FAO
Fin Cycling Index	FCI
Gulf of Guinea	GOG
Maximum Mean Length	MML
Marine Protected Area	MPA
Mixed Trophic Impacts	MTI
Maximum Sustainable Yield	MSY
Mean Trophic Level Index	MTLI
Nigerian Coastal Waters	NCW
Omnivory Index	OI
Trophic Level	TL
Total Number of Pathways	TNPW
Total System Throughput	TST

ABSTRACT

INVESTIGATING ANTHROPOGENIC IMPACTS IN NIGERIAN COASTAL WATERS USING ECOSYSTEM MODELING APPROACHES

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George Mason University, 2017

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Nigeria has two fishing subsectors in the inshore fishing area of the coast. Artisanal fisheries comprising of more than one million fishermen operating small fishing crafts and gears along an 853-km coastline in waters up to 40-meters deep, and about 250 industrial fish trawlers operating in deeper waters beyond the 5NM allocated to artisanal fisheries. Depletion of the target species - *Penaeus notialis* in deeper waters (50m) led to changes in target species (from *Penaeus notialis* to *Penaeus monodon*), and in the spatial attributes of the fisheries. This study investigates the hypothesis that ecosystem impacts increase as industrial fleets increase fishing in shallower nearshore waters. Impacts of the high fishing intensity and increased spatial overlap in fishing areas for the fishing subsectors in NCW (Nigerian coastal waters) need to be quantified from ecosystem fisheries perspectives. Important questions about fisheries impacts on energetic flows, the resulting food web structure, and spatial distribution of fisheries resources need to be

investigated and understood to improve information needed for fisheries management and policy in Nigeria. This research provided a holistic understanding of human impacts through fishing in an integrated framework. Ecopath with Ecosim (EwE), a mass balanced trophic model that accounts for fishing impacts on food webs was used to evaluate and inform how the ecosystem in Nigerian coastal waters is likely to have responded to changes in fishing and coastal management practices. Measures that reflect impacts of fishing in NCW such as the Mean Trophic Level and the Maximum Mean Length of Catch declined rapidly in the 1980s and these were accompanied by a geographical expansion of fisheries due to increasing Fishing in Balance Index during the same period. Network analysis in Ecopath showed increased ecosystem degradation in NCW between 1985 and 2000 as evidenced by increased homogenization, less energetic flows, reduced production and shorter cycles/higher recycling of organic matter. Spatial simulations in Ecospace suggest restricting trawling outside the first 5NM of the coastal waters will especially benefit large demersal predator species but biomass of other functional groups changed very little based on Ecospace simulations with this spatial management strategy. It is important to limit fishing effort in NCW ecosystem and to provide alternative means for self-support for coastal dwellers. This research is a first attempt to provide a fisheries ecosystem management model for Nigeria, and has contributed to fisheries ecology by furthering our understanding of the coastal food web and ecological responses especially in a highly perturbed ecosystem such as NCW.

1. GENERAL INTRODUCTION

Human activities are changing coastal ecosystems around the world and ecological consequences are sometimes unclear (Dunne et al. 2002; McCann 2007; Allesina & Pascal 2008). The most important human impacts in coastal waters include overharvesting of wild species (Roberts 1995; Libralato et al. 2002), pollution (Booths and Zeller 2005), eutrophication (De Mutsert et al. 2016), introduction of exotic species, and human induced climate change (Howell et al. 2012).

These stressors can act singly or in combination, causing shifting ecological baselines for emergent ecosystem properties like community structure, energy and material cycling, and food web properties (Libralato et al. 2002), which can reduce ecosystem productivity (Coll et al. 2008). The goal of this research is to investigate impacts of fishing in Nigerian coastal waters (NCW) by assessing fisheries data and by developing an ecosystem model to verify ecological outcomes in fisheries ecosystem of NCW during the intensification of shrimp production from 1985 to early 2000s.

Background

Environmental problems such as overfishing have ecosystem-wide impacts in Nigerian coastal waters (NCW - Figure 1.1). Overfishing is not limited in space or to a specific number of species, and impacts of fishing has increased in NCW because of growing human population and increasing industrialization of coastal fisheries.

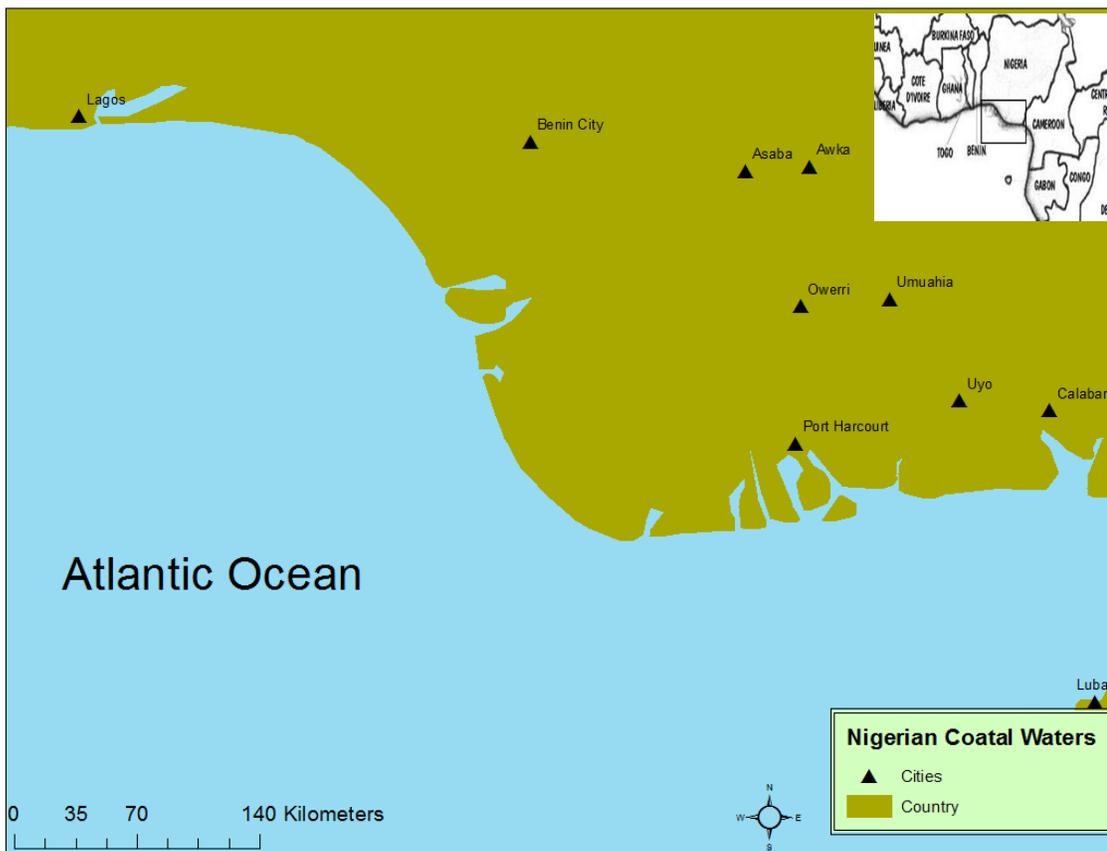


Figure 1.1. A map showing the coastal waters of Nigeria adjacent to the Atlantic Ocean.

Traditional approaches such as using single species modeling approaches (Moses 2000) and assessment of bycatch (Ambrose et al. 2004) to understanding ecological impacts of fishing in NCW has given only partial understanding, making it necessary to address coastal environmental problems from an ecosystem perspective (Ukwe et al. 2003). This has given rise to need for studies with broader ecosystem perspectives. Because Nigeria currently lacks an ecosystem model for the coastal ecosystem, this research project will contribute to on-going debate about anthropogenic impact in coastal ecosystems, by developing the first ecological food web model for assessing potential impacts of fishing in NCW.

Important contributions have been made to address human impacts in NCW, but these often lack ecosystem-wide perspectives within a framework that incorporates multispecies and multisector interactions (Moses 2000; Ogbona 2001; Cayford 1996; Sotolu 2011; Pegg and Zabbey 2013). This lack of ecosystem perspectives in current environmental research has been highlighted in several publications by scientists stressing the need for ecosystem approaches in Gulf of Guinea environmental and coastal research (Ukwe et al. 2003, Ukwe et al. 2006a, & Ukwe et al. 2006b).

Ecosystem fisheries models, such as Ecopath with Ecosim (EwE) are excellent tools for evaluating multispecies or multisector impacts of fisheries because ecosystem models can be adapted to provide scenario-based management information about tradeoffs managers encounter in administration of exploited coastal living resources. These models

enable the complex accounting of multiple species caught by multiple fisheries and fishing subsectors.

Furthermore, ecosystem approach to fisheries can be used to conceptualize the complex trophic interactions exhibited by coastal species spatially and through time. As such, the traditional approach to fisheries that focus on single species and lack trophic interactions and spatially explicit information about the ecosystem may result in imprecise/incomplete understanding of the ecosystem. This is because environmental information and trophic interactions are unaccounted for along with the catch attributes of fisheries operational in the ecosystem by such narrowly focused assessments.

Thus, ecosystem approaches have been encouraged and even mandated by a variety of voluntary and binding codes/conventions and instruments such as the FAO code for responsible fisheries established in 1995 (FAO TP 443; Plangayi 2007).

Theoretical/Conceptual Framework

Coastal ecosystems are complex systems, that are often subjected to multiple uses. Management of these important biomes requires a framework of information gathering and analysis of data for decision making and planning so that resources can be sustainably managed (FAO TP. 443).

The ecosystem approach to fisheries management provides such a framework for understanding the complex and integrated environmental problems in coastal ecosystems, and it is easier to elucidate the complex interactions exhibited within aquatic ecosystems better when using this approach than it would be when piecemeal approaches are implemented (FAO TP. 443).

The ecosystem approach to fisheries (EAF) is defined as an extension of conventional fisheries management recognizing more explicitly the interdependencies between human-wellbeing and ecosystem condition and the need to maintain ecosystem productivity for present and future generations. As an example, conserving the physical habitat, reducing pollution/degradations, minimizing waste, protecting endangered species, are all goals that can be set, evaluated from ecosystem perspectives, planned for, implemented, and enforced.

The most widely used ecosystem fisheries modeling suite is Ecopath with Ecosim, and it uses a mass balanced trophic dynamics approach and is relied upon by scientists as one of the best tools for evaluating impacts of fisheries and other environmental perturbations in ecosystems (Plangayi 2007). In this way, EwE provides information on how ecosystems will likely respond to anthropogenic impacts (Planganyi 2007).

Three main modules to the ecological modeling software are used in this research, which includes Ecopath (Polovina 1984), that estimates energy flows of biomass and their

utilization in a single snapshot of an entire modeled food web, Ecosim, that allows for temporal dynamic simulations (Walters 1997), and Ecospace, that makes it possible to model heterogeneous spatial behavior in exploited ecosystems (Walters et al. 1999).

Rationale

An ecosystem approach to fisheries is chosen for this research because it provides a relatively easy but powerful method to conceptualize entire ecosystems, and to understand impacts of multiple stressors on multiple compartments in each ecological system.

My dissertation project will be a first attempt to model and conceptualize the entire coastal ecosystem in Nigeria, in a framework that utilizes various ecosystem modeling approaches, including the marine trophic index approach, network analysis and spatially explicit ecosystem fisheries analysis. Although the modeling procedure only provides a simplified replica of the coastal food web, it is a step that represents progress in considerations of wider ecosystem impacts of fisheries anthropogenic disturbances in NCW.

Dissertation Overview

The overfishing problem highlighted in the introduction will be assessed in the various chapters with increasing complexity from an ecosystem perspective by incorporating fisheries data, food web dynamics, and spatial simulations to understand redistribution of fishing effort for analysis of impacts of fishing from different perspectives. The core of the dissertation document is three chapters devoted to analysis. I estimated fisheries catch metrics from Nigeria's fisheries data in chapter II, developed an ecosystem

model and carried out network analysis in Ecopath in chapter III, and investigated displacement of fishing effort from deeper waters into nearshore waters using Ecospace in chapter IV. These chapters are preceded by a general introduction, and summarized in a final general summary and conclusions.

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2. TRACKING IMPACTS OF FISHING IN NIGERIAN COASTAL WATERS USING FISHING DATA FROM 1950 TO 2010

Introduction

Gulf of Guinea (GOG) fisheries are in decline (Asiedu & Nunoo 2015; Lewerenz & Vorrath 2015; Kaitikiro & Macusi 2012), and fish are gradually losing their importance as a source of food security, employment, and means of income generation for millions of people who have few or no alternatives for self-support (Asiedu & Nunoo 2015).

The widely reported declines in GOG fisheries have been linked to open access policies, which are non-excludable fisheries characterized by rivalry and competition, since everyone utilizing the resource impacts each other while doing so (Gordon 1954 and Smith 1969). For artisanal fisheries across the sub-region, such policies have resulted in uncontrolled fishing effort, “race to fish,” and degraded ecosystems (Asiedu & Nunoo 2015; Lewerenz & Vorrath 2015; Kaitikiro 2012). In addition to the above-mentioned problems, inadequate environmental education, ill-equipped management institutions, and a lack of political will to address stock decline may be exacerbating an already bad situation (Asiedu & Nunoo 2015).

Some studies suggest declining fish stocks result from anthropogenic impacts (Pauly et al 1998; Pauly & Palomares 2005), while others report a combination of factors including changes in the natural environment, are responsible for the natural cycles of boom and bust observed in major fisheries globally (Sharpe & Hendry 2009; Caddy et al. 1998). It is often difficult to untangle the main cause of fisheries decline despite evidence

of decline in stocks as fishing effort increases (Pauly & Palomares 2005; Sharpe & Hendry 2009). Environmental trends may coincide with increasing fishing effort, making the task of deciphering the main cause of stock decline difficult (Sharpe and Hendry 2009).

Using a variety of biologically meaningful metrics for my dissertation research I investigated available fisheries data for Nigerian coastal waters (NCW) on the Sea Around Us (SAU) Project website for evidence of decline in the coastal fisheries to see if the local situation matches regional declines that have been reported in the literature (Asiedu & Nunoo 2015; Lewerenz & Vorrath 2015; Kaitikiro & Macusi 2012). For Nigeria, whose population is approximately 70% of the GOG regional population (World Bank 2015 estimates), understanding, addressing, and mitigating stock decline problems is essential to safeguard fish stock and maintain sustainable harvests.

Background

Fishing has been identified as a major cause of declining fish stocks in GOG fisheries, including in NCW (Boniface and Moses 2000; Nwafili and Gao 2007, Sotolu 2011; Kaitikiro & Macusi 2012; Asiedu & Nunoo 2015; Lewerenz & Vorrath 2015). Fishing data for NCW fisheries extends back to 1950. Although artisanal fishing has been practiced here for centuries and remains the more important contributor to coastal fisheries for the given period, industrial fisheries have gained ground in the last six decades and continue to contribute to local economies even in times of stock decline.

Using the available fishing data for NCW from the SAU Project, I investigated the ecological consequences of fishing during three periods of historical significance in NCW. The first period began in the 1950s when trawling in NCW was solely carried out by foreign fleets from Europe (Adetayo 1982). Beginning in the 1970s, Nigerian fisheries developed rapidly from a predominantly canoe-based, low technology fishing to a mixture of artisanal and industrial fisheries (Kaitikiro & Macusi 2012). During this period, artisanal fisheries became increasingly mechanized and motorized—giving rise to improved access to shelf-based coastal fish stocks that were previously inaccessible to traditional canoe-based fisheries. The result is a significant increase in the volume of fish landings, making Nigeria the top exporting country of fish products from West Africa to Europe during this period (Kaitikiro & Macusi 2012).

In the second period, intensification of shrimp capture occurred beginning around 1985 when indigenous fishermen, in partnership with foreign investors, exploited shrimp resources in NCW (Ogbona 2001). This period is the period of intense fishing in benthic habitats of 50-m depth along the 850-km coastline of Nigeria. Although total output in terms of fish landings increased (Figure 2.1), per-capital output in fish production simultaneously declined by approximately 50% between the 1980s and year 2000 (Nwafili & Gao 2007). This period coincides with the years of intensification in industrial shrimp exploitation in NCW (Ogbona 2001), decline in biomass of exploited species, and rapid growth in number of artisanal fishermen exploiting coastal resources in Gulf of Guinea waters adjacent to the Nigerian coast (Nwafili & Gao 2007).

A new era began in NCW around year 2000 due to the depletion of the most important commercial shrimp species in NCW - *Penaeus notialis* fishery (Ogbona 2001). This third period occurred at the turn of the century when fishing fleets operating in NCW either withdrew or switched to other fisheries. During this period, per-capita output in NCW fisheries declined by ~ 50%, and many more coastal dwellers depended on artisanal fisheries because of little or no alternative job opportunities (Nwafili & Gao 2007).

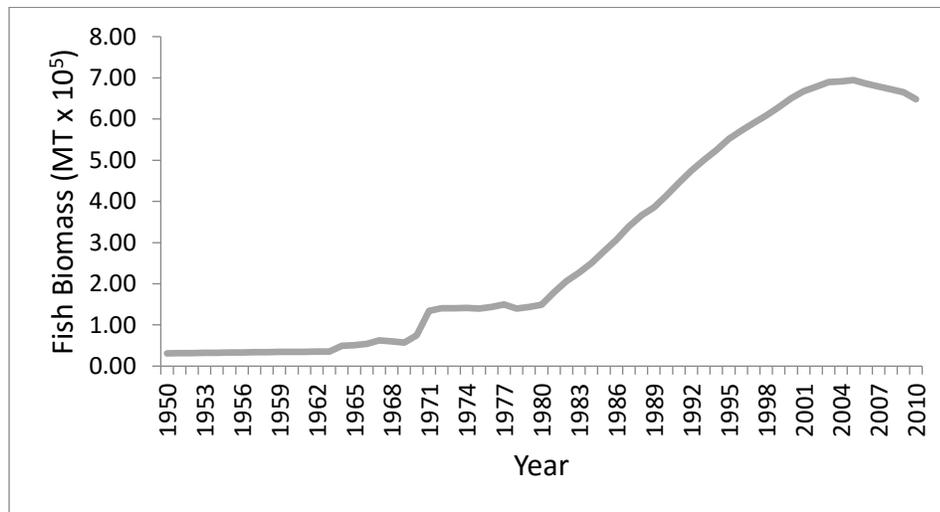


Figure 2.1. Total fish production in terms of landings from Nigerian coastal waters (1950–2010).

As evidenced by higher numbers of small-sized individuals and juveniles in landings (Ogbona 2001), impacts of artisanal fisheries in combination with industrial trawl shrimp fisheries in NCW are high, giving rise to the need for detailed evaluation of impacts particularly given the large population of artisanal fishermen (more than 1 million

fishermen) currently operating in the 850-km long coastal system, and more than 50% solely depend on coastal fisheries as means of self-support (Nwafili & Gao 2007). Before analysis of potential impacts of fishing (on biological metrics such as the mean maximum length of fish landing data) are given, a general description of coastal fishing subsectors will be provided.

Nigerian Fishing Subsectors

Two fishing subsectors operate in NCW, including an artisanal fishing subsector and an industrial fishing subsector. The artisanal fishing subsector operates mainly in the first 5 NM from the coastline (in coastal lagoons and in the creeks of the Niger Delta). Industrial fisheries grew rapidly from the mid-1980s, and has continued an upward trajectory until 2006 despite fish-stock depletion, and problems associated with crime on the high sea (Lewerenz & Vorrath 2015). The industrial fishing subsector mainly targeted *P. notialis* (pink shrimp) from the mid-1980s in coastal waters deeper than 18-m or in waters beyond 5 NM from the coast (Ogbona 2001; Nwafili and Gao 2007).

Artisanal Fisheries

The artisanal fisheries subsector is comprised of approximately 1,000,000 fishermen employing primitive and modern technologies to exploit fish resources along the coastline (Nwafili & Gao 2007). There are debates about the accuracy of these numbers, and attempts have been made to revise and update the number of artisanal fishermen and fish landings in NCW with more accurate information (Ssentago et al. 1983; Moses 2000; Nwafili & Gao 2007), but this is a difficult task given the remoteness of some of the fishing

settlements. Artisanal fishermen target a variety of taxa, including small pelagic fish like sardinellas and bonga shad. They also land benthic species such as croakers, tonguefishes, sea catfishes, and some species of sharks, rays and skates.

According to data available on Nigerian coastal fisheries (from SAU Project), the catch by the artisanal fishing subsector has been increasing since the end of the Nigerian civil war (1967-1970). Catches have increased gradually perhaps because of a growing population. The maximum catch of fish and invertebrates from NCW by the artisanal fishing subsector occurred in 2005 when 330,970.378 MT of fish were landed. The mean catch for the entire period (1950-2010) is 153,464.28 +/-108,421.63 (mean+/- SD).

Industrial Fisheries

The industrial fishing subsector consists of approximately 35 fishing companies whose ~250 fish trawlers are organized under the Nigerian Trawler Owners Association (NITOA). Fish/invertebrate landings from the industrial subsector remained lower than artisanal fish landings until the mid-1980s, when industrial fishing began to expand in NCW.

Commercial Landings from Nigerian Coastal Fisheries

The most important commercial species by landings are perch-like fishes, herring-like fishes, crustaceans (shrimp), flatfishes, sharks and rays (SAU Project – www.searoundus.org). Most of these species have average landings greater than or equal to 10,000 MT tons from the period 1950—2010 (Figure 2.2.). The maximum catch from Nigerian industrial fishing sector was landed in 2003 when 382,671.32 MT of fish and

crustaceans were landed. The mean catch for the entire period is 139,026.85 +/-152,190.21 (mean+/- SD).

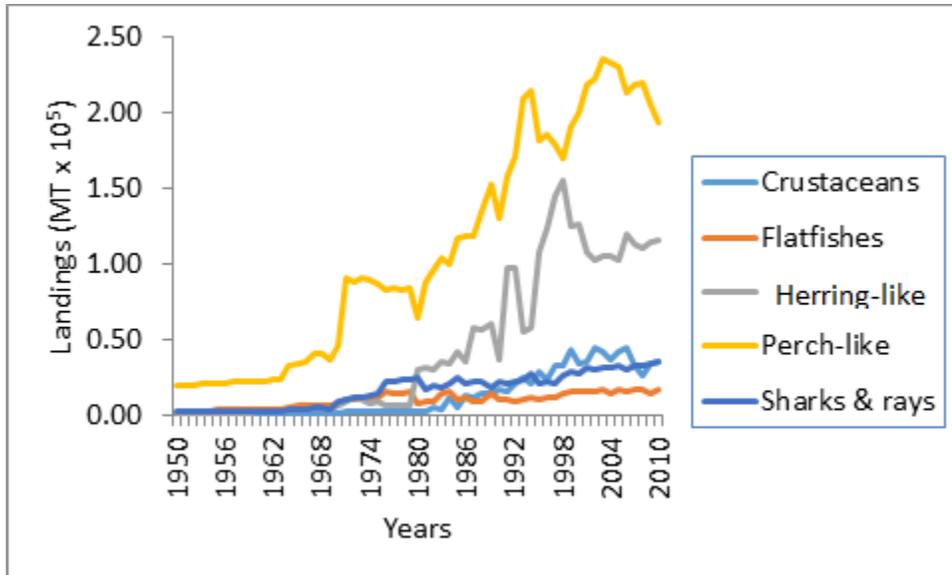


Figure 2.2. Fish landing from Nigerian coastal waters by commercial groups: crustaceans, flatfishes, herring-like fishes, perch-like fishes, sharks and rays (1950 – 2010).

Example of Overfishing in Nigerian Coastal Waters Using the *Penaeus notialis* Fishery

Fishing of lower trophic level (TL) shrimp species was a deliberate shift in fishing practice by industrial fishing fleets in NCW from the mid-1980s when an increasing number of companies registered to trawl in the exclusive economic zone (EEZ) switched from exploiting coastal finfish to shellfish (*Penaeus notialis* in particular). The change in target species was done for purely economic reasons as the average price of pink shrimp/kg in the 1990s was higher than the market price for most finfish species exploited in the

coastal waters of Nigeria (Pink shrimp ~\$12, catfish \$3.5, tilapia \$1.5 and small pelagic fishes \$0.5) (USAID 2002). Because of this economic incentive for targeting coastal shrimp stocks, the *P. notialis* fishery soon became overcapitalized and overfishing ensued (Ogbona 2001).

Unsustainable harvests of *P. notialis* by industrial trawlers not only affected the pink shrimp stocks, but other species as well (Ogbona 2001). As an example, the *P. monodon* stocks, which are exotic shallow-water brown shrimp in NCW, were harvested in sequences because of declining catch of *P. notialis* in deeper waters (up to 50 m) (Ogbona 2001). Consequently, shrimp fishing continued in NCW although the previously targeted species was beginning to show signs of biomass depletion (Figure 2.3.).

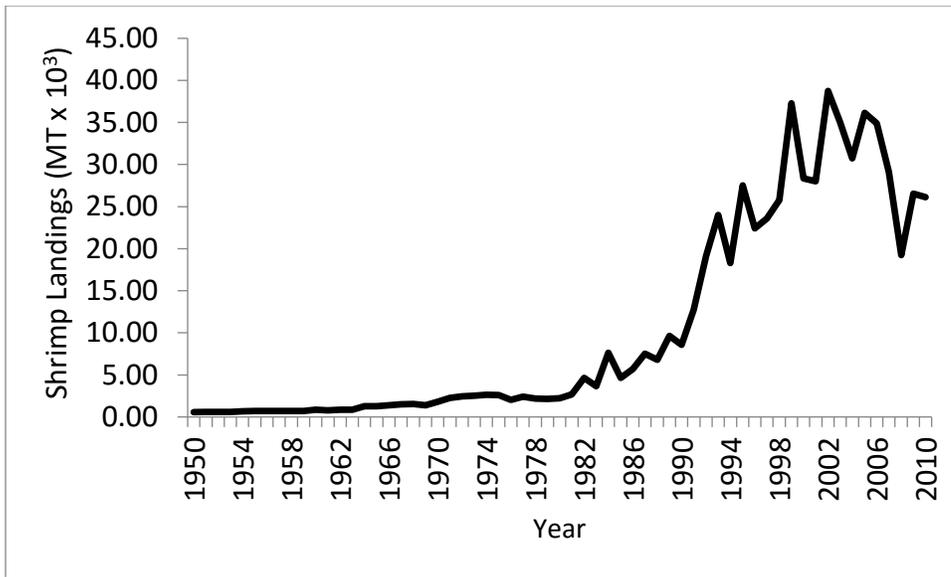


Figure 2.3. Shrimp (all species) landing from Nigerian coastal waters (1950–2010).

Because of the decline of the *P. notialis* fishery, fishermen also targeted *P. monodon*, an exotic species whose commercial value was comparatively less than *P. notialis*, and whose spatial distribution is closer to the coastline (unspecified depth but in presumably water depth less than 18 m) than the deeper waters where *P. notialis* was traditionally exploited by industrial fleets (Ogbona 2001).

This change in target species and fishing area eliminated the spatial distinction in fishing area between the fishing subsectors around year 2000, complicating interactions among fishermen, and resulting in concerns among scientists and managers that sensitive nearshore habitats that serve as nursery areas for important ecological and commercial species were being degraded by fishing impacts from trawl fisheries (Ogbona 2001).

During this period, coastal industrial fisheries accounted for about 40% of annual fish landings (2000 SAU Project). Increased fishing effort for *P. notialis* in waters beyond 5 NM employed trawl nets with smaller mesh sizes than the 60-mm mesh used for finfish. This method should catch most species encountered in the ecosystem, from small body-sized invertebrates like shrimps, to apex predators such as sharks. Data analysis for fishing trends may validate this assumption.

Investigating Potential Impacts of Fishing in Nigerian Coastal Waters

In exploited ecosystems, fishing mortality is often higher than natural mortality; it is strongly selective, and it targets high-value, late-maturing, large species and/or the adult cohort of exploited fish and invertebrate stocks (Swain et al. 2007). In this way, ecosystems can be depleted of higher TL, late maturing, fish with higher commercial value.

Two approaches are used in analyzing impacts of fishing in NCW to see whether there is a fishing down the foodweb in the coastal waters (where trophic levels are targeted by fishermen in sequence from higher trophic levels to lower trophic levels (Pauly et al. 1998)) and a reduction in average length of fish over the study period. The first approach investigates impacts of fishing in Nigerian coastal waters (NCW) on indicators of ecosystem health such as mean trophic level index of fisheries catch (MTLI) and the fishing in balance (FIB) index for fish landings data (Pauly et al. 1998; Bathal and Pauly 2008).

The second approach is a length/size-based approach used to verify impacts of exploitation in harvested fish stocks (Swain et al. 2007). Exploitation tends to diminish average size of harvested species due to size-selective harvest practices (de Roos et al. 2006; Swain et al. 2007; Sharpe & Hendry 2009). The maximum mean length (MML) of fish landed in NCW over the last 6 decades was analyzed, together with ecosystem indicators (MTL and FIB index), and these metrics compared among three historically significant periods based on data of fish landings in NCW from 1950-2010 (SAU Project).

MTL and FIB Index of Fisheries Catch in Nigerian Coastal Waters

Impacts of fisheries in coastal landscapes go beyond the mortality imposed on target species—affecting entire food webs (Pauly et al. 2000). Populations parameters such as abundance and size structure are relatively stable (even static) for unexploited stocks (De Roos et al. 2006). Year-to-year fixed dynamics is expected for unharvested fish stocks (Sharpe & Hendry 2009). Fishing alters such stability, resulting in impacts on both exploited resources and the habitat from which they are extracted.

The MTL and FIB Index are biological metrics that provide information about fishing intensity in an ecosystem (Pauly et al. 2000; Bathal & Pauly 2008). The FIB index is considered a good accompanying indices along with the MTLI, and as indicated by Pauly et al. (2000), unbiased evaluation of impacts of fishing should consider deliberate attempts to fish at lower trophic levels. Using the FIB index in combination with MTLI, may help

safeguard against such bias because moving down TL should provide more of the ecosystem production to fisheries in unperturbed systems (www.fishingdown.org).

Larger fish and higher trophic levels (TL) are targeted earlier in the progression of fishing ecosystems because these species have higher economic value; although some species such as shell fishes with lower TL if commercially present can provide economic incentive to fish at lower TL rather than target higher TL species; (Pauly et al. 1998; Christensen 2015). These higher TL species are also more vulnerable to the impacts of fishing and are quickly depleted from ecosystems because they are slow growing, late maturing species. In addition, they are theoretically less abundant than lower trophic-level forage species because of efficiency of energy transfer (Jennings et al. 1999; Pauly et al. 2000). Once higher value, slow growing species are depleted to points of economic extinctions, fisheries target the next accessible high value species and, in this way, reduces average TL (MTL) by depleting higher TL species to lower TL species in sequence (Pauly et al. 1998; Pauly and Palomares 2005).

In their 1998 paper, Pauly et al. described the phenomenon of sequential depletion from higher to lower TL species as fishing down marine food webs. There, they provided evidence that landings from fishing data over a 45-year period show a global decline in mean trophic level of marine fisheries catch from TL 3.3 to less than TL 3.1. They recognized trophic level for organisms in exploited ecosystems as functional entities—rather than as category designating concept—and used non-integer values estimated from

diet information of ecosystem entities which is presumably a more accurate method than the older integer-based system. They also showed that plots of MTL against catch revealed abrupt phase shifts (backward bending plots of MTL against catch), which were interpreted as evidence of changes in underlying ecosystem food web structures because transfer of production from lower TL up the food web becomes impaired.

Questions have been raised about the accuracy and adequacy of Pauly et al.'s (1998) interpretation of global trends in MTL of fish landings (see Caddy et al. 1998, Essington et al. 2006, Branch et al. 2010) and alternative explanations were given in support of these trends as observed in data (Caddy et al. 1998; Essington et al. 2006). These authors questioned whether MTLI should be used as a measure of ecosystem health and suggested more accurate indices for measuring ecosystem health status should be developed. Despite this debate, I have chosen MTLI as a measure to evaluate ecosystem status in NCW because there is need for scientific information about what is happening in the ecosystem and the MTLI may provide a first step to explore this.

Although in certain situations the MTL index (MTLI) may track ecosystem MTL imprecisely (Branch et al. 2010), there are several advantages of using MTLI for analysis of marine food web structure. It is an easy index to calculate, and the data for estimating MTLI is readily available on the SAU Project website for all marine areas globally. Furthermore, MTLI as an index for evaluating biodiversity in exploited ecosystems was adopted by the convention of Biological Diversity to measure global biodiversity and has

become the most widely used indicator for measuring fishing impacts on ecosystem biodiversity (Branch et al. 2010).

Despite criticism leveled against the MTLI approach, better methods are not currently available to assess the condition of ecosystems from widely available fishing data, so the MTL and FIB index approach have been adopted in this study to be used in combination for analyzing impacts of fishing in Nigerian coastal waters.

The FIB index is a good supplement for MTLI analysis (Christensen 2015). Moving down the food web to catch lower trophic level species may be deliberate since biological production increased by a factor of 10 for each TL below the current one being fished (Christensen 2015). Environmental change, economic situation and the need to create new opportunities for species utilization may drive fishing industries to catch increasing amounts of abundant lower TL species (Essington et al. 2006). As such, fair evaluation of impacts of fishing should consider deliberate attempts to fish at lower trophic levels with biological metrics such as the FIB Index. When FIB Index increases over time with exploitation, fisheries are expanding over a wider range of TLs (Bathal & Pauly 2008).

An increase in FIB index often accompany spatial expansion of fisheries (Bathal & Pauly 2008). For Nigerian coastal waters where there was a shift in fishing area by industrial fisheries from deeper waters to near shore waters, investigating the FIB index may clarify fishing impacts on the coastal food web. Spatial contraction from deeper waters

into nearer shore waters in Nigeria may be a reverse expansion and one of the aims of this research will be to analyze available data to verify evidence of such spatial contractions in fishing area in FIB index for fishing data from NCW 1950 -2010.

Mean Maximum Length of Fisheries Catch in Nigerian Coastal Waters

An evolutionary consequence of fishing is the reduction in MML of fish caught over time. This occurs because of: (1) reduction in MTL such that small, short-generation time, forage species sequentially replace large, slow-growing and long-lived species over the fishing history in an exploited ecosystem (Pauly et al. 1998), and (2) reduction in average size (length) of individual for species subjected to fishing because fishing gear (nets) tends to select for large mature individuals first (Fenberg 2008).

Fishing alters marine ecosystems through size reduction in exploited populations (de Roos et al. 2006; Fenberg 2008). Selective removal of organisms with different growth rates can impact fisheries in very specific ways. Fishing can drive life history in exploited stocks through density-dependent plastic changes that are due to accelerated growth at low stock sizes (De Roos et al. 2006), and many fisheries tend to select for reduced age and size at maturity (Sharpe & Hendry 2009). Sharp and Hendry (2009) observed strong negative effects on size as fishing mortality increased.

There is a direct correspondence between TL and size for most species (Pauly et al. 1998), and reduction in aggregate size should co-occur with sequential reduction in MTL

(Pauly et al 1998). Furthermore, there are several reports in the scientific literature of size reductions induced by exploitation in wild marine populations (Swain et al. 2007; Fenberg 2008; Sharpe & Hendry 2009; De Roos et al. 2006).

It is important to track size changes in population dynamics of harvested stocks because biological attributes that impact stock productivity such as fecundity and survival are closely related to organism sizes (Conover et al. 2009; De Roos et al. 2006). Fishers target the largest individuals, and in some fisheries, they do so because of size restrictions or gear specific for certain age and size brackets (Conover et al. 2009; Sharpe & Hendry 2009). Sharpe and Hendry (2009) tested the hypothesis that size selective harvesting of wild fish populations impacts size trends across a wide variety of fish stocks, and found increasing fishing mortality has strong negative effects on length at 50% maturity with stocks experiencing the highest exploitation rates approaching smaller sizes at 50% maturity.

There are arguments that diminishing size at maturity is driven mainly by selective fishing because harvest tends to select for early maturation (De Roos et al. 2006), although it may be difficult in some cases to disentangle impacts of environment or genetics on size distribution in harvested populations. Halting selective fishing does not guarantee that other sources of natural selection in the environment (e.g. pathogens, predators and competitors) will sufficiently reverse the selection process (Conover et al. 2009).

The Need for Sustainable Fisheries with Ecosystem Perspectives in Coastal Nigeria

Important lessons on marine stewardship can be learned by comparing the state of the ecosystem in an impacted scenario to baseline data from 1950 and to the pre-shrimp exploitation era before 1985. It is important to adopt sustainable fisheries with ecosystem perspectives in NCW. Where negative impacts of fishing are detected, fish stocks will need to be rebuilt to maintain viable populations while accommodating human uses within the framework of ecosystem-based fisheries management (Howell et al 2012; FAO TP 443).

Gulf of Guinea fisheries are declining due to uncontrolled fishing and open access fishing policies (Asiedu & Nunoo 2015; Lewerenz & Vorrath 2015; Kaitikiro & Macusi 2012). This study investigates the hypothesis that measures reflecting impacts of fishing, such as MTL, FIB index and MML of fish/invertebrate landings in NCW over the last 60+ years differ significantly among three periods (1950–1959, 1980–1989, & 1995–2005) with varying fishing intensities. Fishing intensity information is compared among these periods to see if trends in aggregate catch characteristics reflect trends in fishing intensity through the recent fishing history of NCW.

Methods

Measures that indicate fishing intensity in the ecosystem of NCW such as MTL, FIB index, and the MML of catch data was used as yardstick for comparing the state of the ecosystem in three historically important fishing periods in recent history. Fisheries data obtained from the SAU Project was analyzed for measures that reflect impacts of

intensification of fishing through time. The slopes of the MTL index, FIB index and MML for these distinct periods were calculated to compare rates for each fishing period. Except for 1950, fishing periods are bounded by fishing information 5 – 10 years before and after the year in question (1950, 1985, and year 2000). ANOVA was used to determine whether significant differences in biological metrics occur among the three periods for which data were available (1950, 1985, and year 2000). Statistical significance was tested at alpha level of 0.05.

Impacts of fishing were estimated using the weighted MTL index of catch (Pauly et al. 1998), the mean maximum length of catch (MML), and the FIB index (Bathyal & Pauly 2008). The data used in analysis were obtained from the SAU Project.

Fishing impacts as determined by changes in MTL index of catch and/or the FIB index reflect the trajectory of fishing history in an ecosystem by shedding light on the composition of the food web. A reduction in MTL of catch typically reflects loss of higher trophic level species (Pauly et al. 1998) or/and addition of lower trophic level to catch statistics (Essington et al. 2006). Declines in MTL of catch can result from deliberate targeting of lower trophic-level species by fisheries such as in NCW where shrimps were targeted from the mid-1980s.

The Mean Trophic Level of the catch per year t is estimated using equation 1.1:

$$MTL_t = \frac{\sum i(Y_{it} * TL_i)}{\sum i Y_{it}} \text{----- Eq. 1.1}$$

Where Y_{it} is the sum of the catch of species or group i in year t and TL_i is the trophic level of species i . The MTLI is the time series of MTL_t 's calculated for each year in the period of interest.

Fish in Balance index in any year t is estimated using equation 1.2:

$$FIB_t = \log_{10}\left(Y_t * \left(\frac{1}{TE}\right)^{MTL_t}\right) - \log_{10}\left(Y_o * \left(\frac{1}{TE}\right)^{MTL_o}\right) \text{ --- Eq. 1.2}$$

Where, Y_o and MTL_o are realized catches and trophic level in the initial year respectively, Y_t = reported catch in year t , MTL_t = the mean trophic level of the catch at year t , & TE = Transfer efficiency.

The impacts of fishing on MML will be investigated for NCW using available data from the SAU Project. The maximum average size of fishes are estimated for year and compared among three periods with different fishing intensity.

Results

The most prominent features observed through analysis of fishing data for coastal Nigeria were an overall decline in MTLI and MML, and an increase in FIB index over the period.

Analysis of Mean Trophic Level for Landings from Nigerian Coastal Waters (1950 - 2010)

The average values for the MTL was significantly different for the 3 periods in question (ANOVA: $P = 8.92e-14$). Post Hoc test (Least significant difference) revealed that average of the MTLI for period 1 (1950 - 1959) was different from period 2 (1980-

1989) and 3 (1995-2005), and the average period 2 MTLI was different from period 3 (Figure 2.4). The general trends in the fishing landings data are a slight initial increase in MTLI followed by declining MTLI on average. A slight increase in MTLI beginning in 1998 tapered off in 2003, and since then the MTLI began to decline again. Data showed that for the first 20 years in the fishery, MTLI increased slightly by 0.07 from 1950 (3.69) to 1969 (3.76) when the highest MTL was recorded for landings from NCW. Hereafter, a cyclical pattern of rise and fall in MTLI is observed, but this cycle showed a steady decline in MTLI from 3.75 beginning in the late 1970s to MTL of 3.35 in the early 1990s. The lowest MTL is recorded in 1998 when MTL dipped to 3.29.

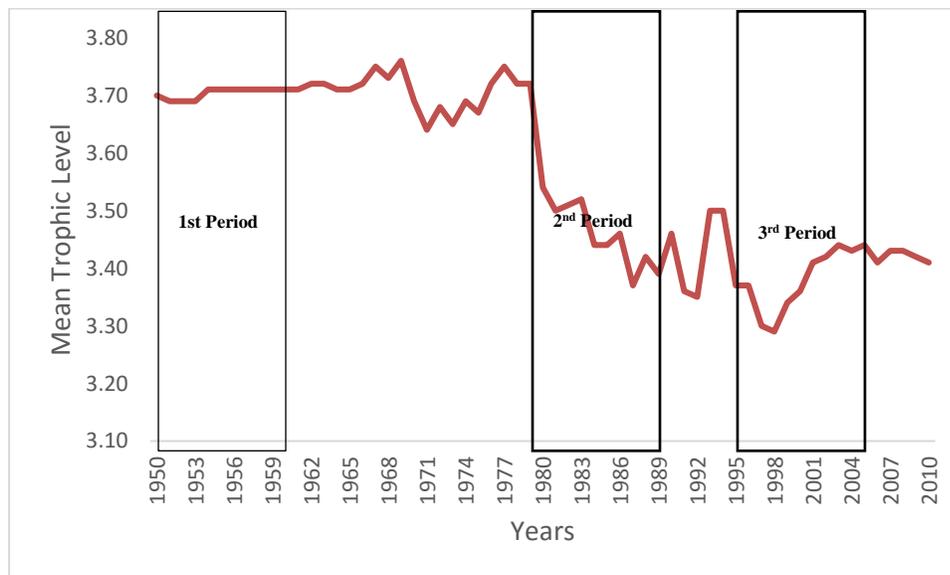


Figure 2.4. Time series of MTLI for NCW for the years 1950 – 2010

The trajectories of the MTLI in the three periods show differing trends, with an initial gentle rise in MTLI in the 1950s (1950 – 1959), when the slope of the MTLI curve was 0.0024 and peak MTL 3.71 (Figure 2.5). This peak showed a 0.01 rise from baseline MTL in 1950.

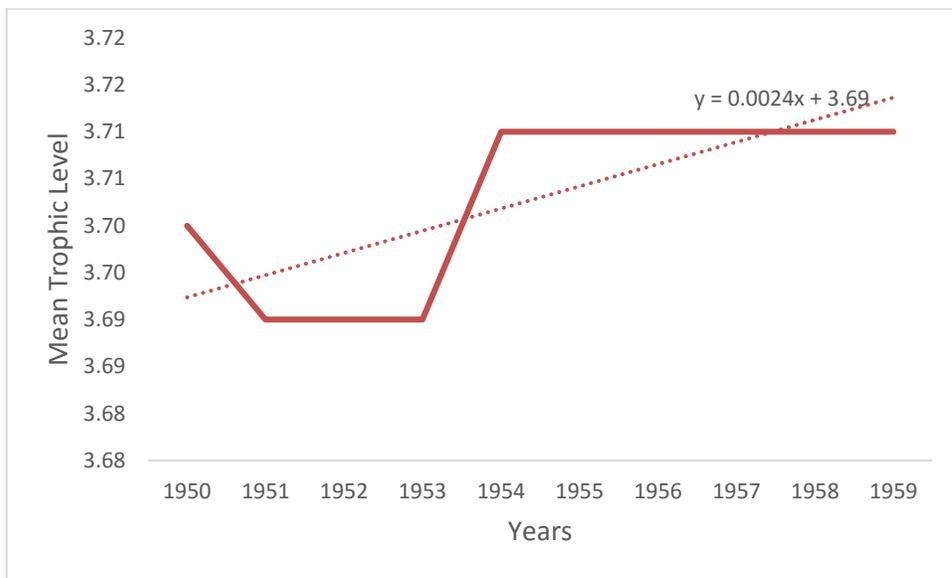


Figure 2.5. Time series of MTL for NCW for the years 1950 – 1959 with trendline and equation for the line

In the second period, which is between 1980 and 1989, the slope of the MTLI curve declined more intensely by one order of magnitude than the positive slope observed in the 1950s (-0.0169 vs. 0.0024). These are the years for which MTLI in NCW declined the most based on available data. In 1980, the MTL was highest for this period (3.54) and a significant contrast to 1989’s value of MTL of 3.39 (Figure 2.6).

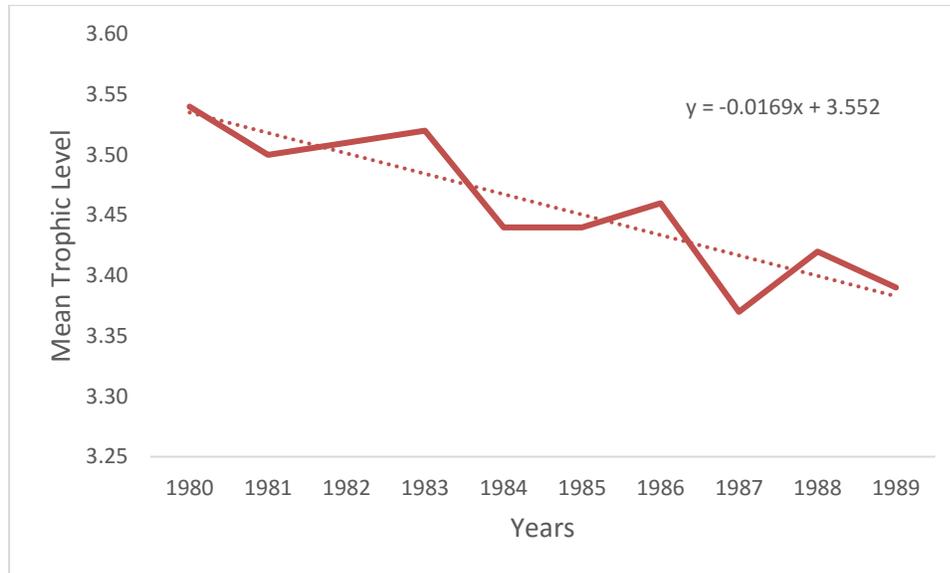


Figure 2.6. Time series of MTL for NCW for NCW for the years 1980–1990 with trendline and equation for the line

The third period in the time series (1995–2005), a period of general rise in MTL (Fig 2.6). The lowest MTL in the time series (3.29) was recorded for this period in 1998. Compared with the initial rise in MTLI for the 1950s, the rise in MTLI for this period was more pronounced with the same order of magnitude but in the opposite direction as the slope for MTLI for the 1980s MTLI (Figure 2.7). This period appears to be a period of slight increase in MTLI, and peak MTL for this period returns MTL to 3.44 (2005), the same value of MTL observed 20 years earlier in 1985 when shrimp trawling intensified.

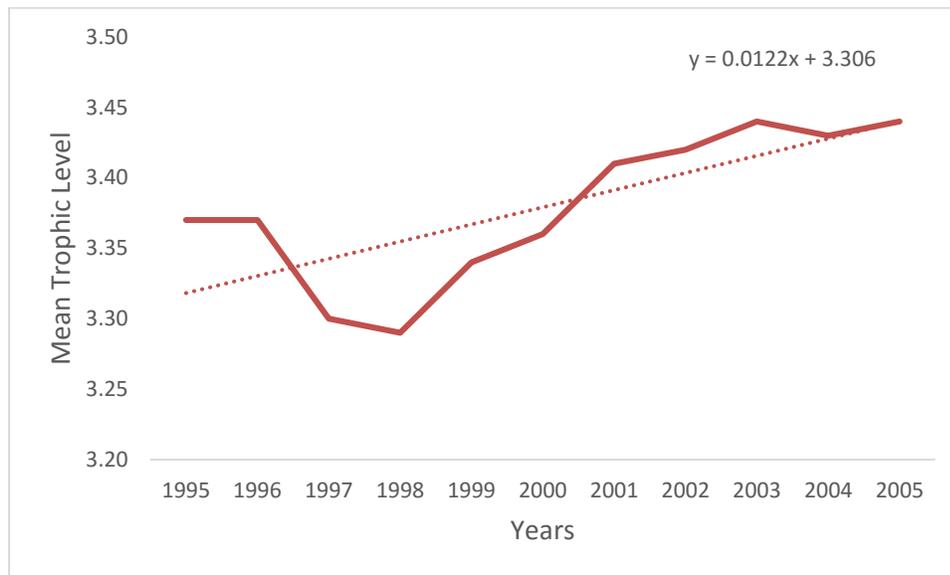


Figure 2.7 Time series of MTL for NCW for the years 1995 – 2005 with trendline and equation for the line

Analysis of FIB Index for Landings from NCW (1950-2010)

The general trend in the fishing landings data was an increasing FIB index on average, but data showed that for the first 13 years (1950–1963) in the fishery, FIB index increased slightly from -0.01 in 1951 to 0.24 in 1963 (Figure 2.8). From 1963 to 1977, the FIB index rose precipitously from 0.24 (1963) to 1.75 (1977). There was a small dip in FIB index from 1977 to 1981, when the FIB index reduced from 1.75 to 1.28. Thereafter, steady rise in FIB index was observed in time series data from the early 1980s to the mid-1990s when FIB index rose from 1.28 (1980) to 2.06 (1994). From here, a small dip in FIB index back to the 1977 level of 1.75 FIB index was counteracted by rising FIB index that peaked in 2005 at a FIB index of 2.21.

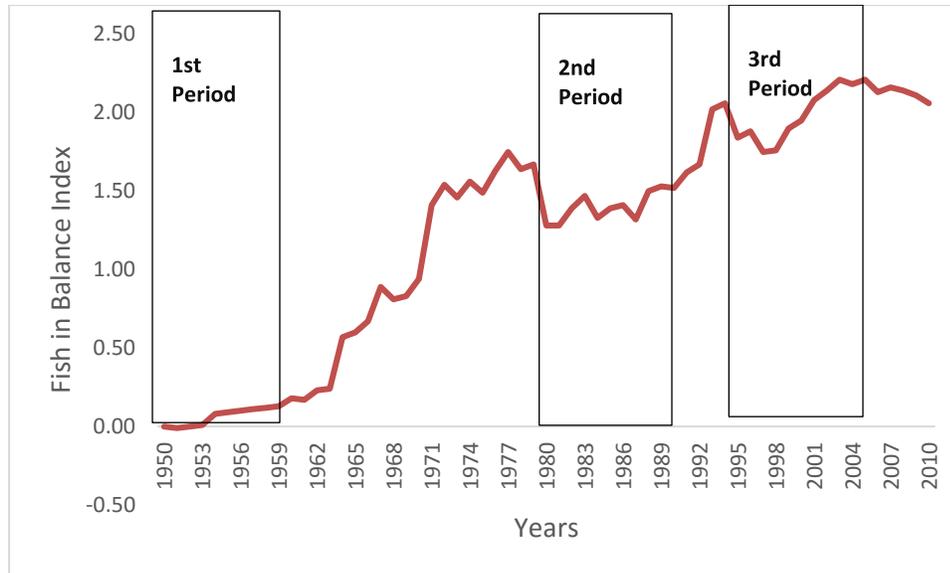


Figure 2.8 Time series of the FIB Index for NCW for the years 1950–2010

Difference in average FIB index calculated was significantly different for the three periods in question (ANOVA: $P = 1.75e-21$). Post Hoc test (Least significant difference) revealed that average FIB index for period 1 (1950 - 1959) was different from period 2 (1980-1989) and 3 (1995-2005), and the average FIB index for period 2 was different from period 3. During the earliest fishing period for the time series, FIB index gradually increased with a gentle slope (0.0176). The negative index observed in 1951 (-0.01) may be the result of the initial decline in MTL below the value of MTL observed in the baseline year – 1950 (Figure 2.9). FIB index peaked for this period in 1959 was at 0.13. The initial

steep trajectory for the FIB index between 1953 and 1954 is offset by a much gentler slope from 1954 (FIB index 0.01) to 1959 (Fib index 0.08).

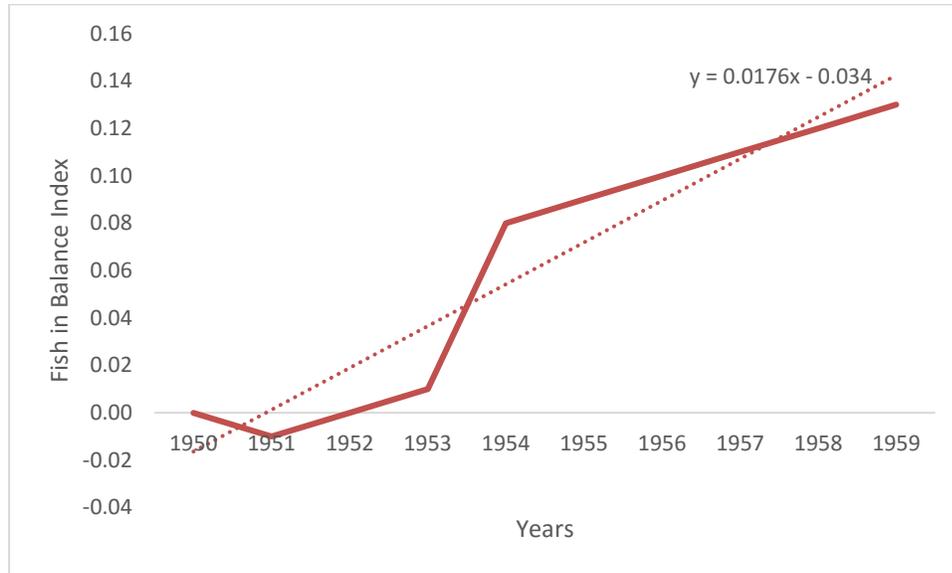


Figure 2.9 Time series of FIB Index for NCW for the years 1950 – 1959 with trendline and equation for the line

A cyclical pattern of rise and fall in FIB index can be observed in the 1980s (Figure 2.10). This pattern in the data had an increasing rate over the period. During this period, FIB index peaked in 1989 with value of 1.53. Lowest observed values for FIB indices were for 1980 and 1981 at FIB indices of 1.28 and the general slope for the FIB index curve is a little steeper than for the initial period of fishing history at 0.021 (1980) versus 0.0176 rate of increase for the FIB indices observed in the 1950s.

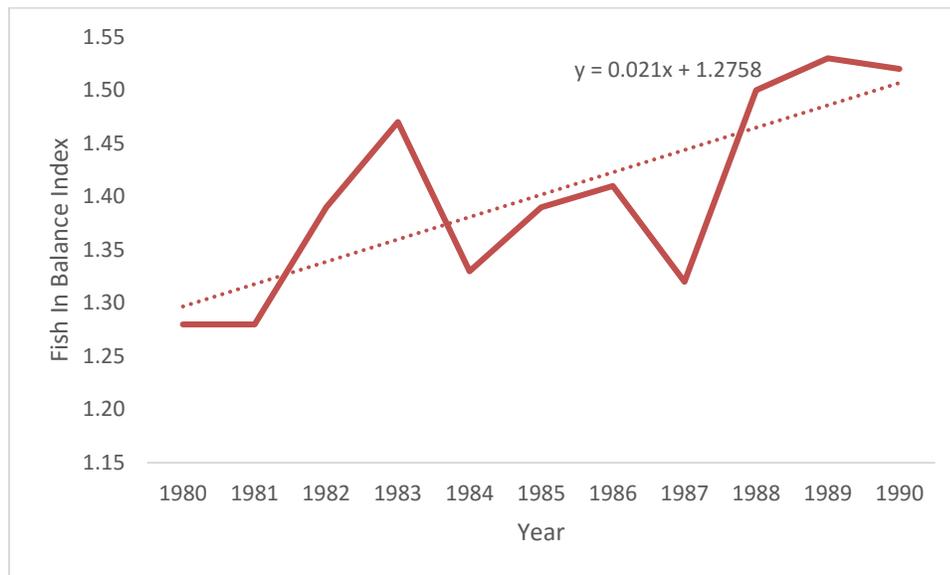


Figure 2.10 Time series of the FIB Index for NCW for the years 1980–1990 with trendline and equation for the line

The highest rate in increase of FIB index is observed in the third period (Figure 2.11). Here, FIB index peaks in two years (2003 & 2005) at the same value of 2.21. The lowest value is recorded for 1997 at a FIB index of 1.75. The rate of increase in FIB index for 1995-2005 (0.0488) is higher than the rates for the 1950s (0.0176) and the mid-70s – mid 80s (0.021).

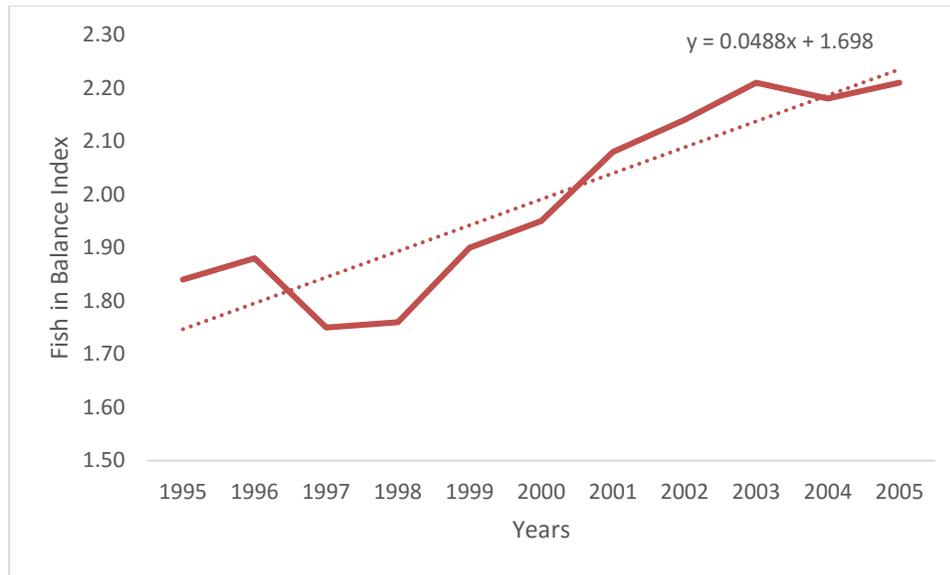


Figure 2.11 Time series of FIB Index for NCW for the years 1995 – 2005 with trendline and equation for the line

Analysis of Mean Maximum Length for Landings from NCW (1950 – 2010)

Between 1950 and 1980 MML increased from 74.8 (1950) cm to 91.8cm (1980). Consequently, average size of landings initially increases for landings in NCW (Figure 2.12). Continuous reduction in MML with intermittent local peaks of 76.4 in 1985, 73.8 in 1998, and 72.7 in 1994, showed a declining trend with pulse increase in MML that were not sustained over the time series. The lowest value for MML was observed in 1997 at 60.6 cm, but small increases in MML were realized between 1997 and 2010 when MML increased in landings data from 60.6 cm to 64.5 cm.

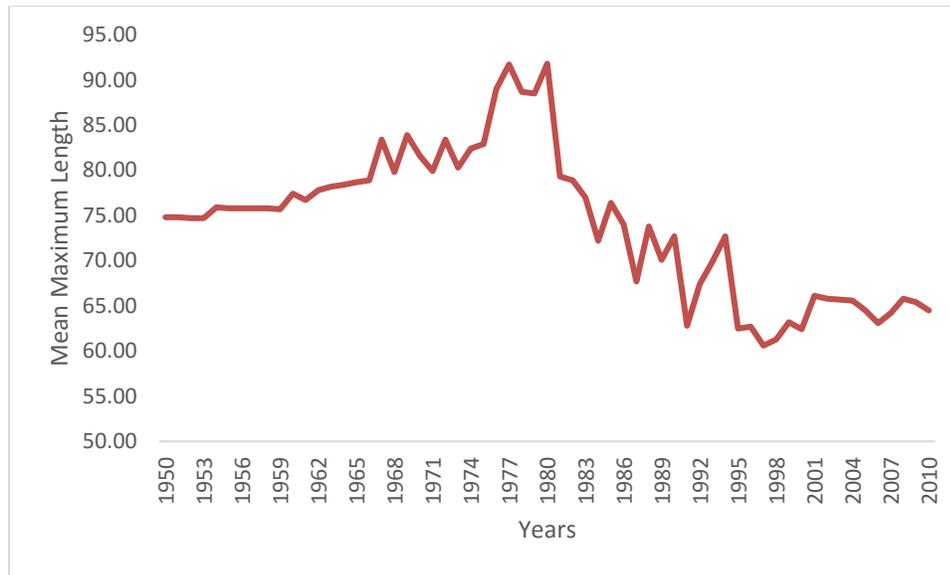


Figure 2.12 Time series of MML for NCW for the years 1950 – 2010

The MML was significantly different for the 3 periods in question (ANOVA: $P = 1.17e-07$). Post Hoc test (least significant difference) revealed that MML for period 1 (1950 - 1959) was different from period 2 (1980-1989) and 3 (1995-2005) and MML for period 2 was different from period 3. The average size of landing increased in the first period between 1950-1959 as MML of landing data shows (Figure 2.13). The slight dip in MML in 1953 was quickly offset by rising MML in 1954 of 1.2cm. From 1954 -1959, MML was reduced very slightly by 0.02cm. There is a general positive trend in the rate of the MML curve with a slope of 0.14 The highest MML was in 1954, with average length of 75.9cm and the lowest was in 1953 with MML of 74.7cm.

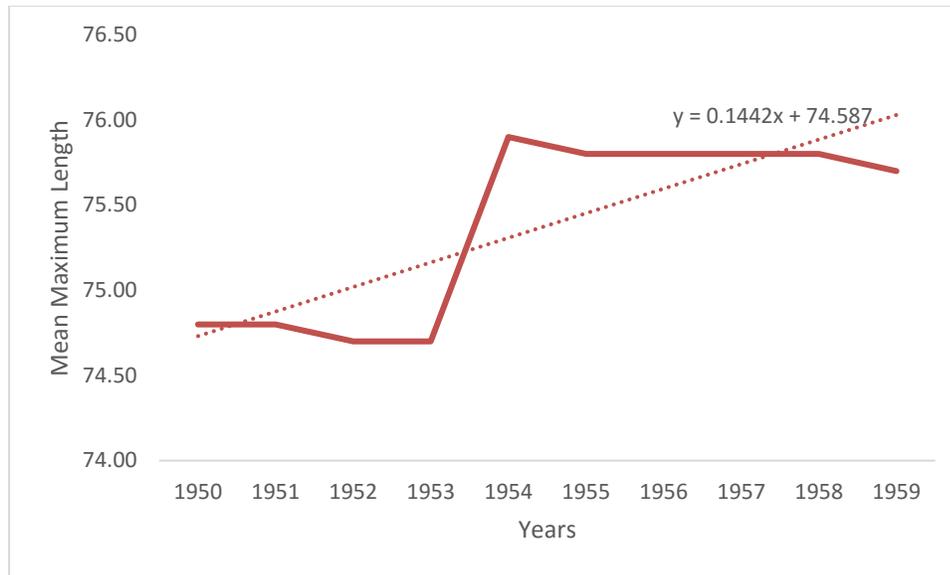


Figure 2.13 Time series of MML for NCW for the years 1950–1959 with trendline and equation for the line

In the decade between 1980 and 1990, the MML of landings time series for NCW declined with a negative slope at a rate of -1.4945 (Figure 2.14). Almost a stepwise pattern of reduction in MML is observed in the data. The highest MML value for this period is 1980 (91.8 cm) and the lowest value is 1987 (67.7cm).

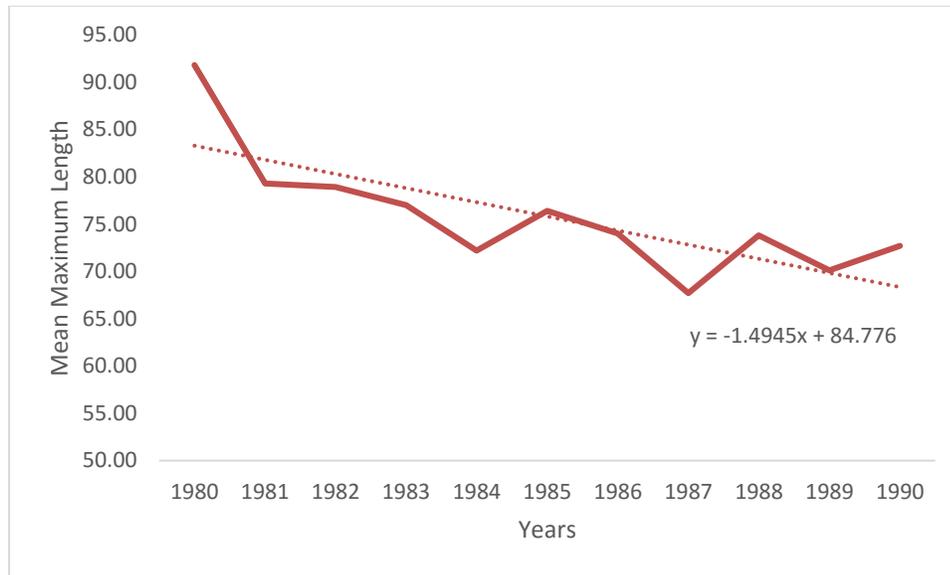


Figure 2.14 Time series of MML for NCW for the years 1980–1989 with trendline and equation for the line

A trend reversal is observed in MML for 1995–2005 (Figure 2.15). A positive and increasing slope with a rate of 0.4436 is observed from the data. The initial decrease in MML from 62.7 cm in 1996 to 60.6 cm in 1997 was offset by increases in 1999 to 63.2 cm, and in 2001 to 66.1 cm. There were small reductions in average length in year 2000 (62.4 cm) and 2004 (65.6 cm) and 2005 (64.5 cm).

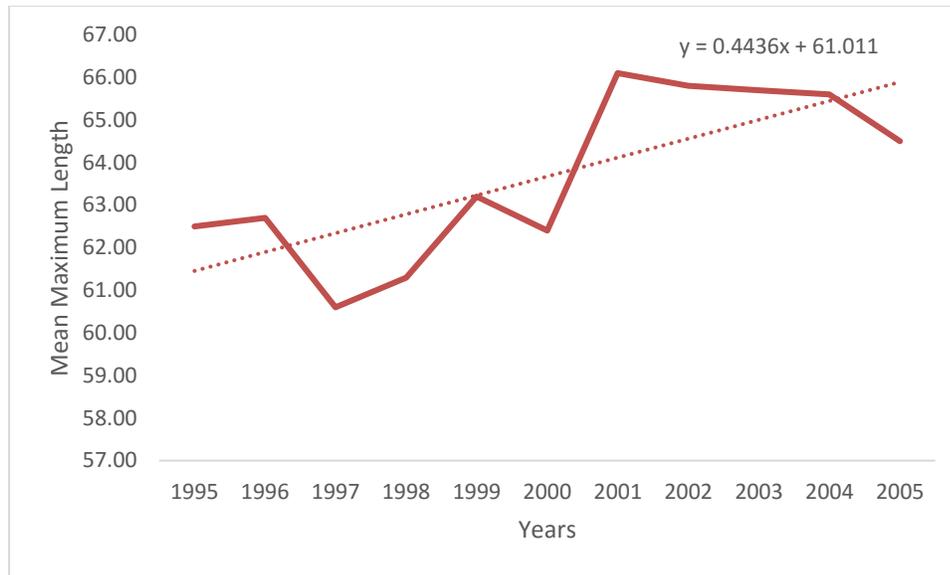


Figure 2.15 Time series of MML for NCW for the years 1995–2005 with trendline and equation for the line

Plots of MTL versus catch shows the highest catches were landed for MTL between 3.29 and 3.44 (intermediate to low trophic levels, as can be expected from ecological theory). The backward bending pattern may be evidence of a phase shift that suggests structural changes in marine food webs (Figure 2.16).

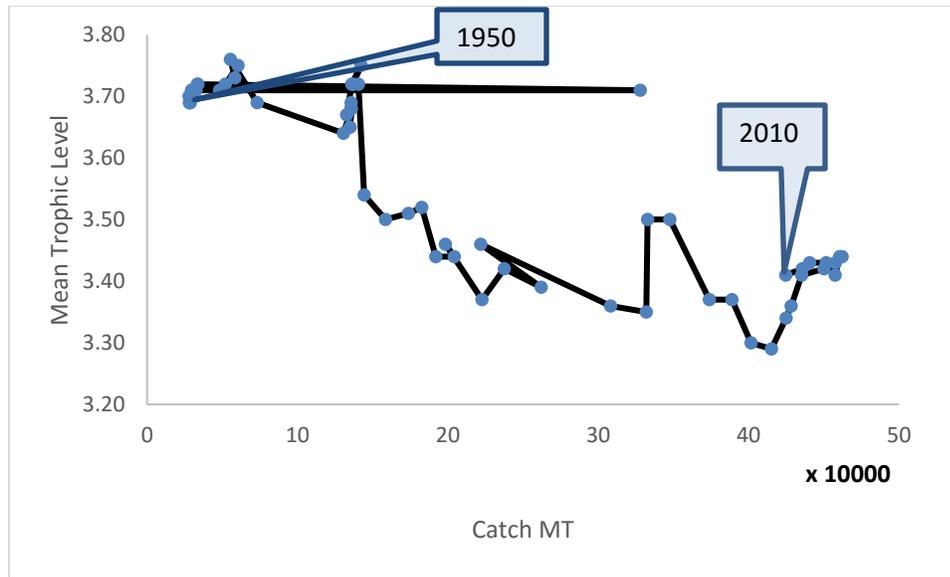


Figure 2.16 Plots of MTL against catch for NCW for the years 1950–2010

Discussion

Evidence from data support the hypothesis that biological metrics that reflect impacts of fishing such as the average MTLI, FIB index & MML of fisheries catch for three periods investigated (1950–1959, 1980–1989, and 1995–2005) were significantly different from each other. In the first period (1950–1959), fishing in NCW was mostly carried out by artisanal fishermen with low technology and vessels that are limited to the shallower areas in the coast. Industrial fisheries began to grow in the 1980s due to increasing investment in coastal shrimping. By the third period (1995–2005), more than 200 trawler boats were involved in coastal fishing and the fishing industry had become overcapitalized.

Over the last six decades, the coastal fisheries in Nigeria expanded considerably. These expansions are illustrated in the data by sharp increases in FIB index mid-way through the 1960s and in the mid-1980s. Period one (1950–1959) was characterized by a relatively flat MTLI while period two (1980–1989) had declining MTLI. The increase in MTLI for period three (1995–2005) may be a sign of overfishing (and not recovery of higher TL species) especially because over the 15-year period between 1985 and 2000, the number of shrimp trawler boats more than quadrupled and the number of artisanal fishermen more than doubled. This led to further expansion in the fisheries and previously inaccessible stocks in the EEZ with perhaps higher TL were now being fished in addition to the inshore fish resources that were previously targeted. The decline in MML, particularly beginning in 1980, is a sign that most apex predators were fished out during the last three decades and NCW may be structurally different now than it was before the ramping up of fishing effort by industrial trawlers in the mid-1980s.

During the first period, (1950–1959), industrial fishing contributed approximately 4.6% to fish landing data. In the second period, industrial fisheries contributed more at 18.11% of landing and mainly targeted abundant pink shrimp resources in inshore waters, along the Niger Delta eastward to Calabar. In the third period, industrial fisheries contributed more than 40% of landings, though the shrimp fishing industry was becoming overcapitalized, and some trawlers changed their target from pink shrimp (*P. notialis*) to brown shrimp (*P. monodon*) (Ogbona 2001).

In the artisanal fishing subsector, an increasing number of people began to depend on artisanal fishing during this period 3 (Nwafili and Gao 2007). As artisanal fishing became more important as a means for both income and food production for coastal communities, industrial fishing concurrently increased landings; placing more pressure on the coastal resource base. Consequently, per-capital landing declined, although catch increased marginally from the 1980s to 2000s (while catch almost doubled, the population of fishers more than tripled for this period; Nwafili & Gao 2007).

Mean Trophic Level of Catch

As was the case with global data (Pauly et al. 1998), an initial plateau in MTL is observed for the time series data for NCW. This plateau was interpreted as resulting from insufficiently detailed fishing data (Pauly et al. 1998). Local data was initially flat but increased very slightly from 1950–1970. The initial increase in MTLI may be due to the landings that comprise a significant amount of high TL species such as Lutjanidae with TL 4.02 (9.3% of total catch in 1950); Sphyraena with TL 4.4 (9.9% of total catch in 1950); Carangidae with TL 4.05 (11.3% of total catch in 1950); and Sciaenidae with TL 3.79 (13.3% of total catch in 1950).

In 1971 the first major decline in MTLI data from 3.76 to 3.64 occurred, perhaps because of increasing fishing effort due to a return to normal commercial and industrial activities post Nigerian civil war (1967–1970). Furthermore, contributions of higher TL species such as sharks declined from 4.45% to 3.72%, and more mullets (with TL 2.53, and contribution to catch of 2.37%, in contrast to 1.74% in the 1950s) were landed.

Although contributions of Sciaenidae and Sphyraena increased to 19.20% and 10.62% respectively, these were not enough to prevent the drop in MTLI. The increasing landing of species broadly designated as miscellaneous from the 1970s onward may explain some of the decline in MTLI. This might have masked underlying trophic structure, and skewed it in ways that complicate observable patterns. Because detailed taxonomic information for the miscellaneous mix is not available it is not possible to draw reliable inference from these data.

The MTL climbed back from 3.64 in 1971 to 3.75 in 1977, but steadily declined thereafter (throughout the 1980s) to a point of 3.35 in 1992. The year 1998 featured the lowest MTL on record of 3.29, and MTLI gradually rose to 3.41 in 2010. The general decline in MTLI from the 1980s into the 21st century may be due to a variety of reasons, including the higher contribution of crustaceans with low TL to landings data from 1.74% in 1950 to 5.46% in year 2000. During this period, apex predators, such as sharks, increased in catch very slightly, perhaps because of increased mechanization in fisheries operations in NCW during these years. By the year 2000, the contribution of sharks in landings had declined from 6.66% of landings data in 1985 to 1.68% in year 2000, presumably because sharks and other apex predators had become scarce in the ecosystem as compared to earlier years due to increasing exploitation.

The backward bending trend in the plot of MTL data against catch reported by Pauly et al. (1998) for global fisheries data was also observed in NCW ecosystem fisheries

data. This most likely occurred because upward transfer of production was impaired as impacts of fishing become increasingly pronounced in the coastal ecosystem (Pauly et al. 1998). Pauly et al. (2000) discussed several ways in which this trend can reverse: First, MTL versus catch trends may reverse because of large and increasing unreported catches. Second, the large quantities of discards in global fisheries could have accounted for backward bending trends observed in global fisheries. Third, the quality of data used, methodology adopted, and or assumptions made could be flawed.

For Nigerian coastal waters, the open access nature of artisanal fisheries makes it difficult to accurately account for fish landing. Furthermore, unreported catch statistics has changed very significantly over the years. In the 1950s, approximately one third of landings were unreported but landings at that time were comparatively small. Reporting of landings greatly improved in the 1960s up until the 1980s, but from 1981 onward reporting standards became increasingly relaxed, and many unreported catches from NCW were observed every year since 1981. This situation became more difficult in the 21st century as many more fishers who do not report to local fishing authorities have taken to artisanal fishing for self-support. In 2005, approximately half of all fishes landed from NCW was not reported (272, 000 MT as opposed to 285, 100 MT that was reported). In a sense, we can assume industrial fishing is reported, while artisanal fishing is largely unreported.

Lewerenz & Vorrath (2015) reported illegal fishing is a major problem in GOG fisheries and linked this to fish decline across the entire region. It is unclear how much

illegal fishing is contributing to decline in MTLI or the apparent distortions in the plots of MTLI versus catch, nevertheless it is important to address the problem of large unreported and illegal catches since these degrade the marine ecosystem and cause substantial economic loss to the state and to coastal communities that depend on fish resources for food and income. Addressing this will require more resources be devoted to monitoring, surveillance, and enforcement (Lewerenz & Vorrath 2015).

While large quantities of discards in global fisheries could have accounted for backward bending trends observed in global fisheries, in NCW discards are comparatively very low. As an example, in 2013 only 3% of landings were discarded. Most fish are landed and utilized in Nigeria for either human consumption or for other industrial purposes. As an example, small sized fishes are sold in local markets for human consumption or used for preparation of condiments (Ogbona 2001). Because of this, it is unlikely that discards or unreported landing are the reasons for the backward bending trends in plots of MTL against catch observed for Nigerian fisheries landings from 1950–2010.

Pauly et al. (1998), in response to Caddy et al. (1998), acknowledge inherent data quality problems in global fisheries data which was indicated as the third reason for the unusual distortions in plots of MTL versus catch. Similarly, in NCW data, problems arise from the large amounts of unreported landings particularly from the 1980s. Furthermore, there are taxonomic resolution problems in landings data. As can be seen for example in 2004 when 148, 600 MT (27% of observed data) was designated as miscellaneous species

as opposed to 406, 540 MT of the landings data that were resolved into clear categories. Various data quality problems for NCW fisheries should be addressed for proper management of the coastal fisheries.

The sequential depletion of high TL, long-lived and economically more valuable species intensified in NCW from 1978–1992, because these years have the steepest decline in MTLI. Midway through this period, the deliberate targeting of lower-TL shrimps continued to keep MTLI at low levels beginning in 1985 and continuing into the 2000s.

This fishing hypothesis appears to be the most relevant explanation for observed trends in MTLI for NCW and is corroborated by the taxonomic contribution of various fish groups to the landings data during the three periods, which may explain in part the trends in decline observed. Alternative explanations can be explored for NCW, because it appears a variety of factors contributed to the observed changes in MTLI data, including (and may not be limited to), a changing environment, economic conditions, and other social considerations.

As an example, the sequential additions of lower trophic levels to fisheries catch predicated by boom and bust outcomes in GOG sardinella fisheries is one possible such environmentally mediated reason for change in landings data, which can explain the observed trends in fish landings from an environmental perspective. Furthermore, the

deliberate attempt to increase high-value lower TL crustaceans in landings data might further explain the observed declines in trends in MTLI and FIB Index.

Other hypotheses used to explain trend in MTLI in the literature include aquaculture (Caddy et al. 1998), environment, eutrophication (Caddy et al. 1998), taxonomic resolution of catch data (Caddy et al. 1998), change in fishing practice, economic considerations (Christensen 2015) and deliberate targeting of lower-trophic level species (Essington et al. 2006; De Mutsert et al. 2008).

Fishing in Balance Index

Bathal and Pauly (2008) showed that expansion in coastal fisheries is positively correlated with FIB index. They recorded a four-fold increase in FIB index for coastal fisheries in India between 1970 and 2000. Over the same period in NCW, FIB index only increased ~2 folds from 0.94 (1970) to 1.95 (2000). An increase in FIB index was interpreted by Bathal and Pauly (2008) as expansion of Indian coastal fisheries. Similarly, the increase in NCW FIB index is a sign that coastal fisheries have expanded over the years, perhaps to meet growing demand for fisheries products. In the earliest period (1950s), the FIB index gradually increased in NCW. This slow growth in FIB index (1950-1963) was followed by a precipitous rise in FIB Index from a value of 0.24 in 1963 to 0.89 in 1967. Between these periods, catch almost doubled for all species landed and overall catch grew from 41,300 MT (1963) to 69,300 MT (1967). This was the first period of sharp expansion in the coastal fisheries of Nigeria.

A second steep rise in FIB index was observed in 1972 when FIB index increased to 1.54 and 3000 MT of sardinella were landed from coastal waters for this year (the 1970s was the first-time sardines appeared in fish-landing times series for NCW). Throughout the 1950s and 1960s the sardinella fishery was nonexistent, but in 1970 1000 MT of sardinella was landed. Sardine fisheries was maintained for five years until 1974, when only 100 MT of sardines were landed. Hereafter, sardines disappeared from coastal landings until 1986. Nwafili and Gao (2007) reported that the appearance and disappearance of sardines in landings data from NCW was environmentally mediated.

An important feature in the sardinella fishery of NCW was its fluctuation over the time interval. The sharpest decline in MTL observed in data for coastal fisheries occurred from 1979–1992. Midway through this period sardines became increasingly observed in catch, especially from 1986. Between 1986 and 1992, MTL decreased from 3.46–3.35. The slight increase of MTLI back to 3.5 in 1993–1994 was quickly offset by a steeper decline in MTL until the lowest MTL was attained in 1998 at 3.29. With trophic level of 2.77, sardines are low trophic-level species; however, despite increased landings of sardines, MTLI from 1998 to 2010 has gradually increased to the level it was before increasing intensification of shrimping in NCW began in 1985.

For the most part, the FIB index showed continuous expansion for fisheries dataset in NCW through the periods examined (1950s, 1980s and 2000s). The FIB index curve

was generally steeper in the 1980s than it was in the 1950s, but a higher rate of increase in the FIB index was observed in the third period (1995–2005).

The slope of FIB Index time series for NCW was most pronounced in the 2000s with a slope of 0.049, as compared to 0.018 in the 1950s, and 0.021 in the 1980s. The FIB index peaked in 2003 and 2005, but contracted slightly thereafter from 2.21 to 2.06. This shows that the fisheries expanded most in the 21st century. This expansion may be linked to the increased mechanization in the fisheries beginning from the 1970s and increasing into the 21st century. The main drivers for such expansion were identified as government subsidies (Nwafili & Gao 2007), economic incentives (Ogbona 2001) and a growing population (Kaitikro & Macusi 2012).

Mean Maximum Length of Catch

Because important population parameters, such as survival and reproduction, are size dependent, it is necessary to monitor and manage exploited species for size (Conver et al. 2009). In NCW, a gradual increase in MML for fish landing was initially observed in the data. From the 1950s to the 1980s, MML increased from 74.8–91.8 cm. Such a rise in MML could be the result of increased landings of higher TL species, such as sharks and barracudas in the 1950s to the 1970s.

From the 1980s, however, MML of coastal fisheries in Nigeria began to decline precipitously. A steady decline in mean size began to be noticeable in data as MML declined from 91.8 – 64.5 cm between the 1980s and 2010. Several mechanisms can be

used to explain the initial rise and subsequent decline in the aggregate size of fisheries landed in NCW for these two distinct periods. Three such mechanisms are described.

First, density dependent plastic response may be one reason for the observed decline in mean size of harvested species (Sharpe & Hendry 2009; de Roos et al. 2006). Accelerated growth rates in exploited species may be due to a release of intra-specific competition, making it possible for surviving fishes to grow faster when stock abundances are lower. In this situation, there are more resources available for individual surviving fishes for both somatic and gonadal growth, and reproductive size and age may be attained earlier. If this situation persists, genetic changes may occur in the fisheries. This mechanism may explain the initial increase in MML in landings data from 74.8–91.8cm NCW may be explained by such plastic response to initial fishing on the coastal fish stocks.

The next phase of general decline in average size of landings can be attributed to size-selective fishing, which might have induced reduction in average size of landings from NCW. Evolutionary theory predicts size-selective reduction in average size as harvest increase in most fish stocks (Sharpe & Hendry 2009). Harvesters deliberately target larger specimens of fish, either for economic reasons or to comply with fishing policies that have size restrictions on fish that can be landed. In Nigeria where fishing regulation impose size limits based on mesh sizes in gears deployed, such selective fishing can result in targeting the largest and fastest growing fishes in each growing cohort. This can result in life history changes and ultimately diminished sizes in the given fisheries.

Overall reduction in MTLI may be another reason for the reduction in MML over the study period. There is a correlation between size and MTL (Pauly et al. 1998). In this case, sequential reduction in MTL (if it occurs) will lead to average length reductions. Mean size reductions observed in the dataset may reflect the deliberate attempt to fish for lower trophic-level shrimps beginning in the mid-1980s or the increased landings of sardinella in the early 1970s and in the mid-1980s to the present.

Conclusions

The status of fisheries in NCW was analyzed using three methods that suggest impacts of fishing are high. The local situation in Nigerian coastal fisheries mirrors the reported regional declines. Uncontrolled fishing in NCW has given rise to higher landings in recent years, but coastal production is declining as evidenced by the need for expansion in coastal fisheries and the decline in MML and MTL. Declines in abundance, MTLI, and the expansion in Nigerian coastal fisheries as indicated by rising FIB index may be sign of declining production. However, as observed in the fisheries, environmental mediation is evident from the cycle of boom and bust in sardinella fisheries and expansion associated with FIB index growth may be because of new fishing areas. Moreover, MTL/MML may decline because of deliberate addition of lower TL species to target species, as is the case in the coastal fisheries in 1980 to 1990s when sardinella and crustaceans increased in landings data. Despite these concerns, data analyses corroborate the hypothesis that increased fishing in NCW correlates with reduction in MTL and MML, and growth of FIB index.

Data show Nigeria's abundant coastal resources are on a decline from analyzing 60 years of fishing data. Measures of fishing intensity (MTL, MML, FIB Index) reveal that NCW fishing impacts are considerably high. Although economic and ecological factors may partly explain patterns in NCW fisheries, the focus of this research is on impacts of fishing. Future studies should incorporate these additional variables in analysis.

The final MTL and MML (2010) of the fisheries generally declined from initial values in 1950. This means that on average lower trophic-level species and small-sized fishes have dominated fish landings in the 21st century. The FIB index of the fisheries has continued to expand at an increasing rate for the most part, meaning that the fisheries are perhaps expanding to meet increasing demand for fisheries products.

All biological metrics investigated in this study for the coastal fisheries of Nigeria were significantly different for the three periods from which measurements were considered (1950s, 1980s and 2000s). Difference does not imply a harmful scenario, although the evidence of difference coupled with decline in fish abundance, TL and average size may signal an impending crisis that require immediate attention.

An important trend in the most recent fishing period is the apparent slight recovery in MTLI and MML for coastal fisheries although these slight increases in MTL and MML may have resulted from a reduction in landings contribution of lower TL species such as

P. notialis. Conover et al. (2009) have shown evidence of slow recovery from diminishing average size induced by size-selective fishing. They noted that full recovery from 5 generations of intense fishing may take 12 generations. It is important to track population changes such as size reduction in harvested populations so that exploited coastal stocks can be well managed and the recovery process aided by adequate adjustments in given fisheries after impacts are identified (De Roos et al. 2006).

In NCW, the contribution of industrial fishing has increased over the time series from 4% to 40% of total landings. It is harder to control artisanal fishing due to the number of unknown participant in this fishery, but the federal government can control industrial fisheries and curtail fishing effort to conserve coastal resources, reverse decline in MTL and average size, and limit expansion when it is reasonable to do so. Expansion in global fisheries is inevitable because of increasing technology, subsidies that aid distant waters fisheries, and growing populations. These factors are important to coastal fisheries in Nigeria. There are also new opportunities to utilize fisheries products in areas ranging from food processing to aquaculture ((Pauly et al. 1998; Pauly & Palomares 2005). Nevertheless, it is important to think and act sustainably even when current demand for fisheries products incentivize wasteful and unsustainable exploitation.

The growth of the shrimp fishery in coastal Nigeria is well documented (Ogbona 2001). As low trophic-level species, increasing landings should contribute to lowering the average TL of landings. The expansion of the *P. notialis* fishery throughout the 1980s and

1990s led to the inevitable decline of the fishery at the turn of the century and major changes in fishing characteristics of nearshore waters in NCW. As the fishing industry, increasingly landed *P. monodon* in place of *P. notialis*, trawlers encroached nearer and nearer to shallower waters designated as fishing grounds for artisanal fishers, leading to conflicts and increasing environmental concerns that trawl nets were degrading nearshore habitats that are regarded as sensitive nursery grounds for important commercial fisheries (Ogbona 2001). Potential impacts of the spatial displacement of fishing effort from waters 50-m deep into water less than 18-m deep has not been fully researched. Future research should focus on answering questions that relate to possible impacts of spatial change in fishing area on nearshore fish and invertebrate communities.

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3. A COMPARATIVE NETWORK ANALYSIS FOR NIGERIAN COASTAL WATERS USING TWO ECOPATH MODELS DEVELOPED FOR 1985 AND 2000

Introduction

Human pressures in NCW have increased significantly in the last 3 decades. During this period, Nigeria's population more than doubled from ~ 84 million in 1985 to ~ 182 million in 2015 (World Bank). Nwafili and Gao (2007) estimated that approximately 1% of this population is involved in fishing. Therefore, during this period, the number of artisanal fishermen more than doubled from ~ 308,746 (1982) to ~ 666,320 fishermen (2000) (Ssentango et al. 1986; Nwafili & Gao 2007), but the increase in number of fishermen resulted only in minimal growth in fish landings, suggesting coastal fisheries in Nigeria have reached full utilization of the coastal fish resources. Currently more than 1 million fishermen, are exacting fishing effort along the 853-km coastline and in the Niger Delta region (Figure 3.1). However, ecological consequences of such intense fishing effort are unclear, and have yet to be examined from an ecosystem perspective.

In 1985, industrial trawlers began targeting high-value pink shrimps (*Peneus notialis*) to export into international markets. This led to higher shrimp production, and a growing number of trawler boats switched from fishing finfish species to fishing in the *P. notialis* fishery (Ogbona 2001). At that time, shrimpers increased from 40 trawlers in 1985 to 173 shrimper-trawlers in year 2000 (Nwafili & Gao 2007).

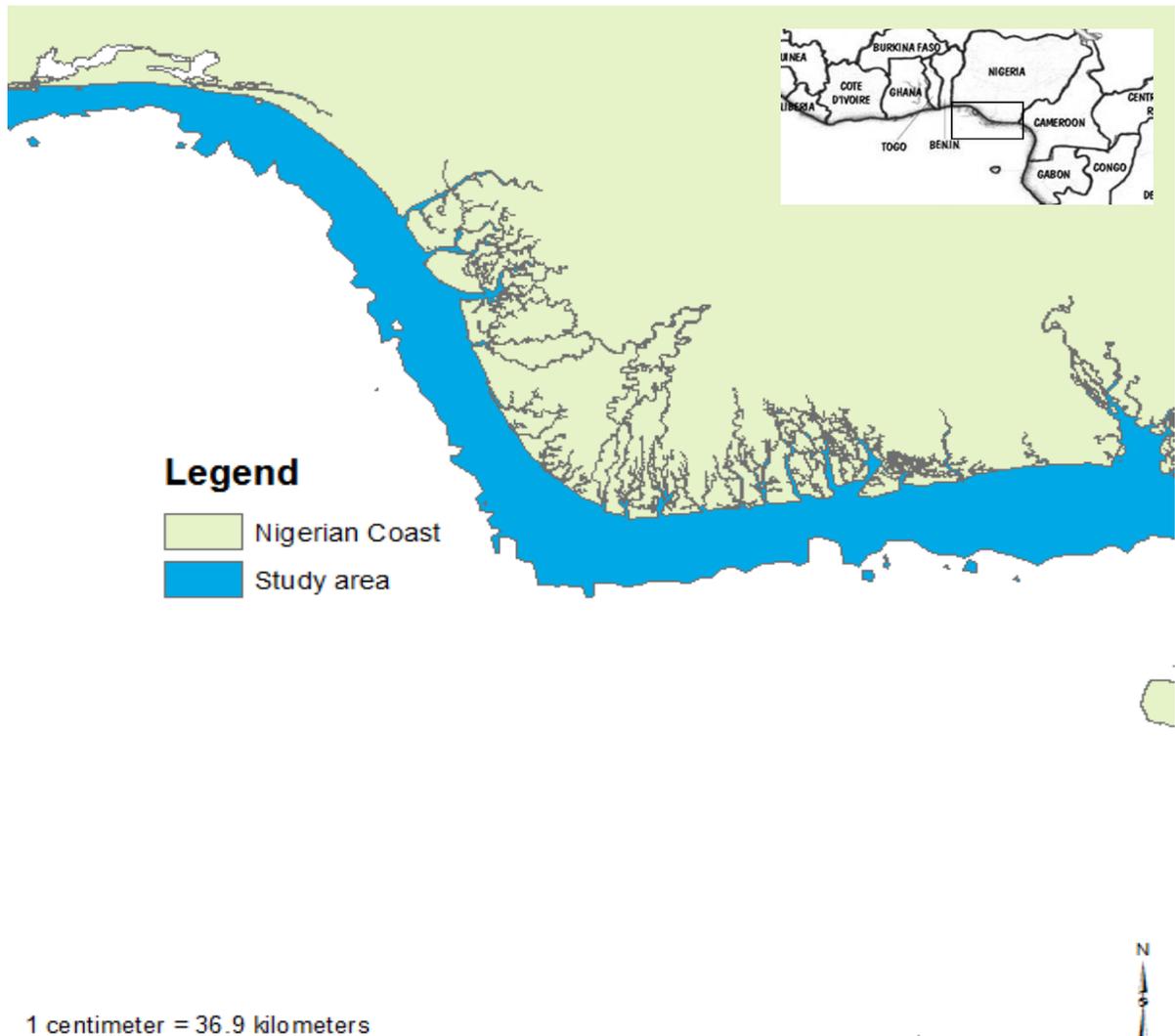


Figure 3.1 Map of Nigeria showing its geographical location in relation to adjacent territories and the Atlantic Ocean.

Shrimp resources were exploited from Lagos West ground in the western coast, to the Niger Delta (midway along the Nigerian coast), and as far east as Calabar, where the wider continental shelf supports a better shrimp fishery than in the narrower shelf of the western coast (Ogbona 2001; Amire 2003). On average, fishermen spent 25–45 days at sea and made 3–5 trips each season (Ogbona 2001).

Prior to the 1980s, shrimp was mainly considered by-catch (Adetayo 1982), but around 1985 the *P. notialis* (pink shrimp) stock was subjected to increasing exploitation, and by the year 2000 the pink shrimp biomass had become depleted. In response to this, other shrimp species, such as *P. monodon* were targeted in addition to pink shrimp to augment catch (Ogbona 2001). At this point, many trawler operators began to fish in shallower waters where they could exploit brown shrimp, which aggregate in these shallower areas of inshore waters (Ogbona 2001). Scientists and managers have described this fishing tactic as potentially more ecologically damaging in NCW (Ogbona 2001).

Fishing changes the trophic structure of aquatic food webs. For this study, food web properties are categorized into measures that reflect impacts of fishing, energy flows within the ecosystem, and structural complexity. The goal of this study was to verify the hypothesis that increased fishing effort in NCW, particularly during the shrimping years of the mid-1980s to the early 2000s, led to ecosystem-wide changes in these emergent ecosystem properties including trophic structure, productivity, and cycles and pathways in the coastal food web.

Ecosystem structure was compared in EwE using measures of connectance, total number of pathways (TNPW), mean trophic path length, fraction of top predator taxa, fraction of basal taxa, maximum trophic level, diversity and omnivory index. Connectance is the measure of interaction richness (Dunne 2002), whereas omnivory index shows how

feeding interactions are distributed among the trophic levels in each model (Libralato et al. 2002).

Ecosystem productivity is based on energy flow, which determines properties such as total system biomass (the biomass of the entire community minus detritus and primary producers), the ratio of primary production to total production, and total system throughput (TST), which sums all flows in a system and reflects the ecological size of the system (Heymans et al. 2014).

This study contributes the first ecological model of a food web network representing trophic interactions for the Nigerian coastal ecosystem for the purpose of assessing the structural components of the coastal food web, to aid in understanding trophic links. The models developed was used to identify how main drivers of impacts like fishing induce changes in the coastal ecosystems.

To achieve this objective, two Ecopath models were developed in EwE 6.5. 14040.0 to assess fishing impacts. The first model represents the state of the Nigerian coastal ecosystem before intensification of shrimping effort in 1985, and the second is a snapshot of the coastal ecosystem after the pink shrimp fishery began to decline in year 2000.

Impacts of Fishing in Nigerian Coastal Waters

Chapter 2 showed that fishing expanded in NCW over the past six decades and that measures that reflect impacts of fishing such as the mean trophic level index (MTLI) and maximum mean length (MML) of fisheries catch have declined over the study period, especially in the early 1980s. Although, by itself, this is useful information, when this knowledge is combined with ecosystem approaches, it can improve understanding of the impacts of fishing in the Nigerian coastal ecosystem.

The major fishing subsectors operating in NCWs have been described (see chapter 1). Although many of the fishermen exploiting coastal resources are part-time fishermen, more than 50% work full-time as fishermen and have little or no alternative income sources (Ogbona 2001; EJF 2003). Each artisanal fisherman has a small impact, but when combined, aggregate impacts can be great. Such additive effects have reduced per-capita output by half in recent decades (Nwafili & Gao 2007).

Reliable predictions of the ecological consequences of fisheries decline is necessary for proper planning and management of coastal resource harvests to limit resource depletion and regenerate depleted fish stocks (Herthaus et al. 2008). A mathematical model of the Nigerian coastal food web is used to provide quantitative assessments and ecological information that can be used for more efficient management of coastal resources. By developing a virtual presentation of trophic interactions that incorporates fishing

information, a clearer understanding of fishing impacts on the coastal food web of Nigeria can be gained and fishing impacts may be better described.

Fishing can have ecosystem-wide impacts (Robert 1995; Pauly et al. 1998; Swain et al. 2007; Coll et al 2008; Kaitikiro & Macusi 2012; Asiedu & Nunoo, Lewerenz & Vorrath 2015). In Nigeria, most exploited species in the ecosystem are targeted in combination with associated organisms, therefore entire fish communities should be considered in assessment of impacts of fishing. Fishing contributes to biodiversity loss (Robert 1995; Worm et al. 2006), it reduces abundance of important functional and commercial groups within an ecosystem, and it causes structural shifts in ecological communities (Roberts 1995). Other impacts of fishing include the reduction in mean trophic level due to loss of top predatory species (Pauly et al. 1998).

In natural systems, organisms are involved in an intricate network of trophic interactions that are collectively referred to as the food web. These dense networks of interactions provide the structure on which ecosystems are built and support the function and services that they provide (McCann 2007; Farnsworth et al. 2012).

The feeding relationships among the structural components of the ecosystem facilitate transfer of matter and energy between the living and nonliving components of the environment (Myster 2001). Fishing even at low intensities can potentially alter the food web structure, the interactions among food web components, and the flow of matter and energy (Roberts 1995; Libralato et al. 2002; Coll et al. 2008).

Roberts (1995) indicated that tropical ecosystems may be unsuitable for large-scale extraction enterprises because they are characterized by close balance between production and consumption. Given current and projected future demands for the limited fish resources in NCW, human impacts may very well tip the balance of nature in the coming years, resulting in overfished, depleted and collapsed coastal fisheries that cease to provide ecosystem services such as provision of food (Roberts 1995; Nwafili and Gao 2007).

Nigeria's population more than doubled in the last 30 years and may double again in the next 30 years. Such rapid growth in population will result in higher demand for fish and other coastal resources. The already intense fishing may intensify further, and this will increase pressure on already strained coastal fish resources. In view of this, it is important to explore conservation and management strategies for long-term fisheries sustainability in NCW.

Predicting Impacts of Fishing in Nigerian Coastal Waters Using an Ecosystem Approach to Fisheries

Fisheries regulations, such as the FAO code of conduct for Responsible Fisheries in 1995, emphasize the need for wider ecosystem considerations in fisheries management (Planganyi 2007; FAO Technical paper 443). Nigerian fisheries science and regulation now needs a more holistic approach that considers multiple species and wider environmental issues.

A multispecies model was developed to inform the management of coastal fish stocks in Nigeria. This approach highlights broader ecosystem effects of coastal fishing in Nigeria. Linking the NCW food web and fisheries, will provide important insights and improve management by providing information that will aide in making better decisions to ameliorate fishing impacts.

The most popular multispecies approach is Ecopath with Ecosim (EwE). EwE's ability to address largescale ecosystem issues is well documented (Plangayi 2007). Over the past three decades, the development and evolution of ecological models has been significant, and EwE has contributed significantly to understanding of coastal and oceanic ecosystems during this time (Pinnegar et al. 2005; Plangayi 2007). EwE has 3 main modules—Ecopath (Food web), Ecosim (time dynamics) and Ecospace (spatio-temporal dynamics). Ecopath is the structural module in EwE, which quantifies the network of flows constructed from biomass, production, and consumption in an ecosystem (Pauly et al. 2000). It represents a snapshot of trophic flows and biomass of an ecosystem. It solves systems of linear equations to describes the energy budget for ecosystems.

For this research, two Ecopath models were developed to describe the main structural features of the Nigerian coastal food web in two snap-shots—one for 1985 and the other for year 2000. These two years were chosen because they represent two distinct levels of fishing impacts in Nigerian coastal waters, including a high level of fishing intensity before shrimping intensified in the mid-1980s (1985), and very high fishing

intensity (2000), when the number of fishing trawlers grew from 40 (1985) to ~200 (2000) and the number of artisanal fishermen expanded from ~ 300,000 to more than 650,000.

It would be most appropriate to compare multiple years in each given period to clearly portray the impacts of fishing in NCW, but a significant amount of work and effort goes into developing each model, so I have chosen to develop two, one that represent the year shrimp intensification began (1985) and another model for the year when pink shrimp fishery declined to the point where fishermen needed to switch to another shrimp fishery to augment their shrimp catch (2000). These two years are representative years - one the year of inception of industrialization and the other the year of expansion to another species of shrimp. Outputs of network analysis for two Ecopath models developed will be compared.

Hypotheses

This chapter investigates the hypothesis that increased fishing intensity altered ecosystem emergent properties by changing the food web structure as measured by food web properties in the ecosystem. Fishing impacts are expected to increase from 1985 to 2000 as measured by lower MTL of catch for year 2000 (See equation 2.1 and explanation of MTLI on page 18 of Chapter II).

Mixed trophic impact was used to assess the impacts of fishing on functional groups and the impacts of the various fisheries on one another. It shows the impacts of all functional groups and all fishing subsectors on all compartments in the model. Impacts can

be either positive, negative, or neutral. The number of positive, negative, and neutral impacts will be compared between the 1985 and 2000 Ecopath models.

Objectives

The goals of this study are: (1) to achieve a first description of the ecosystem structure in NCW using mass-balanced ecosystem modeling approach, (2) to use the models developed to assess fishing intensification impacts in NCW during two stages in the development of the shrimp fishery with the first during the early stages of the shrimping era in 1985 and the second 15 years later in 2000 after depletion of the *P. notialis* fishery; and (3) Compared model outputs for NCW with other modeled ecosystems (Catalan Sea in Southern Europe, and the Caribbean Sea in the Americas; Coll et al. 2008) to see how NCW compare to published modeling outputs from these ecosystems in a medium (1985) and high (2000) exploitation regime. I especially focused on the year 2000 when the *P. notialis* fishery became overfished and compared model outcomes to baseline pre-shrimping model outputs for 1985.

Methods

Food Web Construction and Model Parameterization

Two Ecopath models were developed for NCW: one that represents 1985, and one that represents 2000. Energy flows, ecosystem structure (complexity), MTL of catch, and mixed trophic impacts were estimated using inbuilt algorithms and tools within the EwE software (Version 6.5. 14040.0).

Ecopath was first described by Polovina (1984), who built an ecosystem model of coral reefs in the French Frigate Shoal in Northwest Hawaiian Islands. The Ecopath model has since been taken up by scientists at the University of British Columbia, modified into a mass-balanced models and complemented with a temporal component (Ecosim), and a spatial component (Ecospace. www.ecopath.org). The current version of Ecopath was used to develop the NCW Ecopath models. The main input parameters are biomass estimates, consumption and mortality estimates for functional groups, and fishing information for exploited species. Fishing data and biological information for all functional groups were obtained from published literature (Ogbona 2001; Agbaje & Falaye 2007; Amire 2003), FishBase and the Sea Around Us Project (SAU). The basic equation (Equation 3.4) provides quantified network of flows derived from production, consumption, and biomasses of functional groups:

$$Bi\left(\frac{P}{B}\right)_i EE_i = Y_i + \sum_{j=1}^n B_j \left(\frac{Q}{B}\right)_j DC_{ji} \text{ -----Equation. 3.4}$$

Where B_i is biomass, $\left(\frac{P}{B}\right)_i$ is the production per biomass ratio (mortality); EE_i is the ecotrophic efficiency (fraction of production utilized or exported from the system); Y_i is fisheries yield; B_j is the predator biomass j ; $\left(\frac{Q}{B}\right)_j$ is the consumption biomass ratio for group j ; and DC_{ji} is the fraction of prey i in diet of predator j (Sanchez et al. 2002; Walters and Martell 2004).

The sum of flows in EwE (TST) is calculated as (Heymans et al. 2014):

$$TST = \sum_{i=1, j=1}^n Tij \text{-----Equation 3.1}$$

Where Tij is the flow between any two compartments and includes respiration and export flow.

Measures of energy flow were evaluated using mean transfer efficiency, (a property that represents the geometric mean of transfer efficiencies from trophic level II to IV), and the Finn's cycling index, which is a comparative estimate of recycling that shows measures of stress and structural differences between models (Heymans et al. 2014). Finn's cycling index is calculated as:

$$FCI = \frac{TST_c}{TST} \text{----- Equation 3.3}$$

Where TST_c is the total flow that is recycled and TST is the total system throughput.

The omnivory index is calculated as:

$$OI_i = \sum_{j=1}^n (TL_j - (TL_i - 1))^2 \cdot DC_{ij} \text{----- Equation 3.2}$$

Where TL_j and TL_i are trophic level of predator j and prey i respectively, and DC_{ij} is the proportion of prey I in the diet of predator j.

Structurally, the models developed (1985 & 2000) for this research were similar. There were ten fish groups, one marine mammal group, one bird group, two invertebrate groups, two primary producers, one zooplankton, and one detritus. Groups were presumed to have similar metabolism between the periods since habitat conditions should be similar

(Libralato et al. 2002) during the given period, with perhaps the exception of fishing intensity.

Fisheries Data

Data from the SAU Project website (www.seararoundus.org) was used to estimate fisheries catch and biomass of modeled fish groups. This information varies for years and species based on the catch history from available time series.

Group biomasses were estimated from catch data in conjunction with catch per unit of effort (CPUE) data obtained from published literature (Ogbona 2001; Agbaje and Falaye 2007; Amire 2003). Estimates of biomass were made using surplus production models in R (version 3.2.2) and Microsoft Excel (version 2016). Surplus production models are simple logistic models with rate processes such as recruitment, mortality, and growth pooled into one simple production function that can be used to measure rate processes and estimate population parameters such as biomass, exploitation rates, and MSY (maximum sustainable yield) (Walters & Martell 2004). The main input parameters for production models used were catch/landings data, and CPUE time series for the period modeled. The code used for production modeling is given in Appendix 1.

Mortality and consumption rates for all modeled groups were estimated from the life history tools for species in Fishbase (www.fishbase.org) and presented in the results section (Tables 3.5 and 3.6). The life history tool provides information about important

modeling parameters for EwE such as natural mortality (P/B), and food consumption (Q/P).

Fisheries landings for 1985 and 2000 are also presented (See Table 3.1 and Table 3.2).

Table 3.1 Fisheries landings in the year 1985 for the Nigerian ecopath model

<i>Group name</i>	<i>Trawlers (t/km²/year)</i>	<i>Seiners (t/km²/year)</i>	<i>Artisanal (t/km²/year)</i>
<i>Large Benthopelagic Rays</i>	0.0358103	0.03581	0.182354
<i>Large Demersal Large Pelagic</i>	0.009905	0.0091	0.0395
<i>Flat Fishes</i>	0.1182051	0	0
<i>Reef Fishes</i>	0	0.04677	0.085148
<i>Medium Pelagic</i>	0.04629	0	0.1137
<i>Medium Demersal Croaker</i>	0.670212	0	1.045
<i>Juvenile Croaker</i>	0	0.07912347	0.379022
<i>Adult Croaker</i>	0.665	0	1.452
<i>Miscellaneous Species</i>			
<i>Small Pelagic</i>	0.05171232	0	0.1712136
<i>Small Demersal Shad</i>	0.2108	0	0.445
<i>Juvenile Shad</i>	1.38E-06	3.82E-06	5.14E-05
<i>Adult Shad</i>	0	0.03543	0.08119
<i>Other Shrimp</i>	0.11697	0	0.237
<i>Adult Pink Shrimp</i>			
<i>Juvenile Pink Shrimp</i>	0	0.2388	0.5208
<i>Pink Shrimp</i>	0	0.0811592	0.123472
<i>Sum</i>	0.0002	0	0.005153
	0.0357123	0	0.071298
	0.0571385	0	0.14357
	2.017957	0.5261965	5.095472

Information used in estimation of fisheries landings was obtained from the SAU website based on fish landing information for 1985 (table 3.1) and for 2000 (Table 3.2) (www.searoundus.org).

Table 3.2 Fisheries landings in the year 2000 for the Nigerian ecopath model.

<i>Group name</i>	<i>Trawlers (t/km²/year)</i>	<i>Seiners (t/km²/year)</i>	<i>Artisanal (t/km²/year)</i>
<i>Large Benthopelagic Rays</i>	0.03533	0.02533	0.101604
<i>Large Demersal</i>	0.04956	0.05157	0.1268
<i>Large Pelagic</i>	0.07152019	0	0.1005415
<i>Flat Fishes</i>	0	0.0612094	0.04681231
<i>Reef Fishes</i>	0.0895	0	0.07135
<i>Medium Pelagic</i>	0.14511	0	0.307696
<i>Medium Demersal</i>	0	0.1042346	0.3156789
<i>Croaker</i>	0.6092546	0	1.402916
<i>Juvenile Croaker</i>	0.0681235	0	0.1234575
<i>Adult Croaker</i>	0.2583013	0	0.32818
<i>Miscellaneous Species</i>	0.02574	0.025444	0.0816224
<i>Small Pelagic</i>	0	1.1265	1.3906
<i>Small Demersal</i>	0.09161	0	0.14243
<i>Adult Shad</i>			
<i>Juvenile Shad</i>	0.1489	0	0.22434
<i>Shad</i>	0.05992	0	0.071495
<i>Other Shrimp</i>	0.23	0	0.29
<i>Pink Shrimp</i>			
<i>Juvenile Pink Shrimp</i>	0.001	0	0.008
<i>Pink Shrimp</i>	0.01	0	0.01
<i>Sum</i>	1.89387	1.394288	5.143524

Diet Data

For group diet (Table 3.3 and Table 3.4), initial values were obtained from the Guinea Bissau preliminary EwE model (Amorin et al. 2003) because Guinea Bissau is a closely related ecosystem in the Gulf of Guinea. Furthermore, information on diet from Fishbase and Sealifebase was used to modify diet among functional groups to obtain mass balance.

Table 3.3 Diet matrix for Nigerian coastal ecosystem (1985 model).

Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9	Column10	Column11	Column12	Column13	Column14	Column15	Column16	Column17	Column18	Column19	Column20	Column21	Column22	Column23
	Prey \ predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	Cetaceans	0	0	0.194328	0	0	0.001486	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Shore Birds	0	0	0.292119	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Large Benthopelagics	1.52E-05	0	0	0.000132	0.000628	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Rays	0.000526	0	0.004663	0	0.019121	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Large Demersal	0	0	0.000499	1.77E-06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Large Pelagic	0	0	0.000561	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Flat Fishes	0	0	0.326081	0.005752	0.000471	0	0	0	0	0	0	8.50E-05	0.000859	0	0	0	0	0	0	0	0
8	Reef Fishes	0	0	8.05E-09	1.72E-09	0	0	0	0	0	0	0	0	1.77E-07	0	0	0	0	0	0	0	0
9	Medium Pelagics	0	0.026771	0.000131	0	0	7.48E-08	0	0	0	0	0	7.50E-09	0	0	0	0	0	0	0	0	0
10	Medium Demersals	0	0	0.000536	0	0.000493	0	0	0	0	0	0	9.60E-05	0	0	0	0	0	0	0	0	0
11	Croaker1	0	0	3.23E-08	1.80E-08	0	0	0	1.60E-07	0	0	0	6.79E-07	0	0	0	0	0	0	0	0	0
12	Croaker	0	0	0.12068	0.004866	0.834574	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Miscellaneous Species	0	0	0.000386	0.000603	0.06269	5.60E-05	0.002193	0.001294	7.58E-05	0.001288	0.003727	0.00026	0	0.002305	4.71E-05	0	0	0.070555	0.070555	0.049628	0
14	Small Pelagics	0	0.071845	0	0	0	0.015454	0	0	0.041803	0	0	0	0	0	0	0	0	0	0	0	0
15	Small Demersals	0	0	0.014325	0.009324	0.017053	0	0.000154	0.000834	0	0	0	0.00072	0.000944	0	0	0	0	0	0	0	0
16	Shad1	0	0.013426	0	0	0	0.150556	0	0	0.005704	0	0	0	0.004993	0	0	0	0	0	0	0	0
17	Shad	1.63E-05	0.062377	0.045691	0	0	0.003767	0	0	0.000383	0	0	0	0.000711	0	0	0	0	0	0	0	0
18	Other Shrimp	0	0	0	0.004535	0.010268	0	0.00873	0.006672	0	0	0.007999	0.00896	0.000859	0.010082	0.007531	0	0	0	0	0	0
19	Pink Shrimp1	0	0	0	0.000297	0.003425	0	0.002641	0.001298	0	0	0	0.001273	5.39E-06	0.079015	0	0	0	0	0	0	0
20	Pink Shrimp	0	0	0	0.004751	0.051279	0	0.041492	0.041776	0	0	0	0.039528	8.34E-07	0.041052	0.002687	0	0	0	0	0	0
21	Zooplankton	0.47342	0.728199	0	0.041564	0	0.579272	0	0	0.408598	0	0	0	0.30431	0.502199	0.579804	0.3	0.5	0	0	0	0
22	Phytoplankton	0.526022	0	0	0	0	0	0	0	0.873873	0.445266	0	0.648101	0.365347	0	0.7	0.5	0	0	0	0	0.8
23	Aquatic Macrophytes	0	0	0	0	0	0	0	0	0	0	0	0	0.034912	0	0	0	0	0	0	0	0.1
24	Detritus	0	0	0	0.928173	0	0.24941	0.94479	0.948126	0.543436	0.124839	0.543008	0.949077	0.004306	0	0.40993	0	0	0.929445	0.929445	0.950372	0.1
25	Import	0	0.097383	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	Sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
27	(1- Sum)	0	0	0	0	5.96E-08	5.96E-08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.4 Diet matrix for Nigerian coastal ecosystem (Year 2000 model).

Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9	Column10	Column11	Column12	Column13	Column14	Column15	Column16	Column17	Column18	Column19	Column20	Column21	Column22	Column23	
	Prey \ predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
1	Marine Mammals	0	0	0.185581	0	0	0.001464	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
2	Shore Birds	0	0	0.278969	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
3	Large Benthopelagics	1.52E-05	0	0	0.000131	0.000608	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
4	Rays	0.000526	0	0.004453	0	0.02113	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
5	Large Demersal	0	0	3.75E-08	1.80E-08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
6	Large Pelagic	0	0	8.54E-06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
7	Flat Fishes	0	0	0.311403	0.005527	0.00052	0	0	0	0	0	0	8.76E-05	0.000882	0	0	0	0	0	0	0	0	
8	Reef Fishes	0	0	0.005725	0.000129	0	0	0	0	0	0	0	0	1.81E-06	0	0	0	0	0	0	0	0	
9	Medium Pelagics	0	0.024934	0.000133	0	0	0.000238	0	0	0	0	0	7.54E-05	0	0	0	0	0	0	0	0	0	
10	Medium Demersals	0	0	0.000537	0	0.000493	0	0	0	0	0	0	9.60E-05	0	0	0	0	0	0	0	0	0	
11	Croaker1	0	0	8.12E-05	8.74E-06	0	0	0	8.57E-06	0	0	0	8.65E-06	0	0	0	0	0	0	0	0	0	
12	Croaker	0	0	0.084677	0.003194	0.615468	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
13	Miscellaneous Species	0	0	0.057783	0.046596	0.324958	0.00085	0.009949	0.002584	0.001293	0.014484	0.016657	0.003915	0	0.044625	0.001374	0	0	0.142926	0.142926	0.142926	0	
14	Small Pelagic	0	0.07944	0	0	0	0.025479	0	0	0.061111	0	0	0	0	0	0	0	0	0	0	0	0	
15	Small Demersals	0	0	0.00771	0.007267	0.015817	0	0.000557	0.003329	0	0	0	0.000812	0.003856	0	0	0	0	0	0	0	0	
16	Shad1	0	0.01293	0	0	0	0.148294	0	0	0.005562	0	0	0	0.005127	0	0	0	0	0	0	0	0	
17	Shad	0.000163	0.087603	0.062938	0	0	0.007446	0	0	0.003669	0	0	0	0.004828	0	0	0	0	0	0	0	0	
18	Other Shrimp	0	0	0	0.005429	0.020704	0	0.016789	0.01582	0	0	0.01631	0.016657	0.002074	0.016696	0.01472	0	0	0	0	0	0	
19	Pink Shrimp1	0	0	0	2.85E-06	1.04E-05	0	4.65E-05	2.31E-06	0	0	0	2.35E-06	5.54E-06	2.33E-05	0	0	0	0	0	0	0	
20	Pink Shrimp	0	0	0	3.99E-06	0.000291	0	2.05E-05	1.98E-06	0	0	0	1.76E-05	8.57E-06	2.33E-05	4.92E-06	0	0	0	0	0	0	
21	Zooplankton	0.473351	0.701307	0	0.039934	0	0.570568	0	0	0.398439	0	0	0	0.312473	0.49111	0.576387	0.3	0.5	0	0	0	0	
22	Phytoplankton	0.525945	0	0	0	0	0	0	0	0	0.862326	0.435696	0	0.665487	0.447522	0	0.7	0.5	0	0	0	0.833333	
23	Aquatic Macrophytes	0	0	0	0	0	0	0	0	0	0	0	0	0.000837	0	0	0	0	0	0	0	0	0.166667
24	Detritus	0	0	0	0.891778	0	0.245662	0.972638	0.978254	0.529925	0.12319	0.531337	0.978328	0.004421	0	0.407514	0	0	0.857074	0.857074	0.857074	0	
25	Import	0	0.093786	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
26	Sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
27	(1- Sum)	0	5.96E-08	0	0	5.96E-08	0	0	0	0	0	0	0	1.19E-07	0	0	0	0	0	0	0	0	

Mass-Balance

Mass-balance was achieved by setting values for biomass, consumption/biomass, and production/biomass for all groups to parameterize the model and ecotrophic efficiency was estimated internally within the model. The balanced model also require diet (Tables 3.3 & 3.4) and fishing (Tables 3.1 & 3.2) information. The input parameters for the NCW EwE model are given (Tables 3.5 & 3.6). With these, Ecopath estimates a possible picture of how energy and biomasses are utilized within the ecosystem (Christensen and Walters 2004).

Food Web Properties

Quantitative assessments of food web properties were done in this study by following methods of Libralato et al. (2002), Coll et al. (2008), and Heymans et al. (2014). Ecosystem properties (structure, productivity, cycles and flow, consumption and respiration, mixed trophic impacts, and fishery catch) were quantified and compared using the EwE network analysis for the models developed for 1985 and year 2000. Comparing the state of the ecosystem using model information for these two years made it possible to evaluate ecosystem status, structure, and function for NCW in middle level (1985) and high (2000) fishing intensity years during recent fishing history based on data collected for coastal fisheries (1950–2010) on the SAU project website.

Results

Twenty-two functional groups were included in each EwE model developed for this project (Table 3.5 & 3.6). The 1985 model parameters are given in **Error! Reference source not found.** below. **Error! Reference source not found.** contains basic estimates for year 2000 model.

Table 3.5 Basic estimates from the NCW EwE model showing groups, trophic levels (TL), biomass per habitat area, consumption per biomass, production per biomass (P/B) and the ecotrophic efficiencies (EE) for groups. Estimations from other models¹, parameters from Fishbase/Sealifebase², Ecopath derived parameters³. This model represents the ecosystem as it was in 1985.

Group name	TL	Biomass in Area (t/km²)	Q/B (/year)	Z or P/B (/year)	EE
Marine Mammals	2.474 ³	18.25 ³	9.00 ²	0.05 ²	0.65 ³
Shore Birds	3.11 ³	1.65 ³	30.00 ²	5.40 ²	0.10 ³
Benthopelagic Sharks	3.47 ³	0.71 ¹	4.30 ²	0.39 ²	0.94 ³
Medium Rays	2.08 ³	0.82 ¹	6.10 ²	0.39 ²	0.62 ³
Flatfishes	2.06 ³	1.37 ¹	7.90 ²	0.93 ²	0.969 ³
Adult Bonga Shad	2.31 ³	1.75 ¹	11.40 ²	2.50 ³	0.80 ³
Juvenile Shad	2.45 ³	0.92 ³	26.46 ³	3.00 ³	0.84 ³
Medium Pelagic	2.50 ³	12.52 ¹	3.10 ²	0.23 ²	0.63 ³
Large Pelagic	2.81 ³	0.43 ¹	3.60 ²	0.37 ²	0.84 ³
Adult Croakers	2.06 ³	4.20 ¹	6.90 ²	0.73 ³	0.90 ³
Juvenile Croakers	2.01 ³	0.13 ³	23.19 ³	1.70 ³	0.98 ³
Medium Reef fishes	2.06 ³	3.30 ¹	6.10 ²	0.52 ²	1.00 ³
Small Demersal	2.59 ³	0.45 ¹	19.25 ²	1.65 ²	0.82 ³
Large Demersal	3.08 ³	0.52 ¹	4.01 ²	0.24 ²	0.97 ³
Brown Shrimp	2.09 ³	0.61 ¹	27.38 ²	6.95 ²	0.27 ³

Adult Pink Shrimps	2.07 ³	0.71 ¹	27.38 ²	4.95 ³	0.58 ³
Juvenile Pink Shrimp	2.09 ³	1.59 ³	72.72 ³	7.00 ³	0.74 ³
Miscellaneous Species	2.32 ³	9.50 ¹	9.11 ²	0.90 ²	0.86 ³
Zooplankton	2.00 ³	12.00 ¹	84.87 ³	35.00 ²	0.48 ³
Aquatic Macrophytes	1.00 ³	15.74 ¹	-	7.00 ²	0.95 ³
Phytoplankton	1.00 ³	22.87 ¹	-	240.00 ²	0.19 ³
Detritus	1.00 ³	10.00 ¹	-	-	0.06 ³

Table 3.6 Basic estimates from the NCW EwE model showing groups, trophic levels (TL), biomass per habitat area, consumption per biomass, production per biomass (P/B) and the ecotrophic efficiencies (EE) for groups. Estimations from other models¹, parameters from Fishbase/Sealifebase², Ecopath derived parameters³. This model represents the ecosystem as it was in 2000.

Group name	TL	Biomass in Area (t/km2)	Q/B (/year)	Z or P/B (/year)	EE
Marine Mammals	2.47 ³	13.93 ³	9.00 ²	0.05 ²	0.60 ³
Shore Birds	3.11 ³	1.15 ³	30.00 ²	5.40 ²	0.10 ³
Benthopelagic Sharks	3.49 ³	0.47 ¹	4.30 ²	0.39 ²	0.91 ³
Medium Rays	2.07 ³	1.01 ¹	6.10 ²	0.39 ²	0.90 ³
Flatfishes	2.03 ³	1.18 ¹	7.90 ²	0.93 ²	0.81 ³
Adult Bonga Shad	2.50 ³	1.43 ¹	11.40 ²	2.50 ³	0.96 ³
Juvenile Shad	2.30 ³	0.75 ³	26.46 ³	3.00 ³	0.63 ³
Medium Pelagics	2.51 ³	7.93 ¹	3.10 ²	0.23 ²	0.68 ³
Large Pelagic	2.82 ³	0.349 ¹	3.60 ²	0.37 ²	0.84 ³
Adult Croakers	2.03 ³	3.49 ¹	6.90 ²	0.73 ³	0.99 ³
Juvenile Croakers	2.04 ³	0.11 ³	23.19 ³	1.70 ³	0.99 ³
Medium Reef fishes	2.03 ³	0.90 ¹	6.10 ²	0.52 ²	1.00 ³
Small Demersal	2.60 ³	0.68 ¹	26.50 ²	1.11 ²	0.93 ³

Large Demersal	3.14 ³	0.74 ¹	4.01 ²	0.24 ²	0.98 ³
Brown Shrimp	2.19 ³	0.44 ¹	27.38 ²	6.95 ²	1.00 ³
Adult Pink Shrimps	2.19 ³	0.23 ¹	27.38 ²	4.95 ³	0.65 ³
Juvenile Pink Shrimp	2.19 ³	0.103 ³	72.72 ³	7.00 ³	0.49 ³
Miscellaneous Species	2.336 ³	4.50 ¹	9.10 ²	0.90 ²	0.96 ³
Zooplankton	2.00 ³	12.00 ¹	84.87 ²	35.00 ²	0.36 ³
Aquatic Macrophytes	1.00 ³	24.74 ¹	-	7.00 ²	0.98 ³
Phytoplankton	1.00 ³	22.87 ¹	-	240.00 ²	0.19 ³
Detritus	1.00 ³	10.00 ¹	-	-	0.02 ³

Emergent properties measured for the two ecosystem models showed differences in important parameters that measure ecosystem health. Structurally, the two modeled food webs appear similar, although there are slight differences (Figure 3.2 & 3.3). After parameterization, a visual appraisal of the two flow diagrams (one for 1985 and the other for 2000) shows slight structural differences including pink shrimp biomass decreasing by more than 50% of 1985 biomass in the 2000 model, and the trophic level of zooplankton had changed. In addition, the distance between primary producers (phytoplankton and aquatic macrophytes), and detritus shrunk in 2000 compared to 1985.

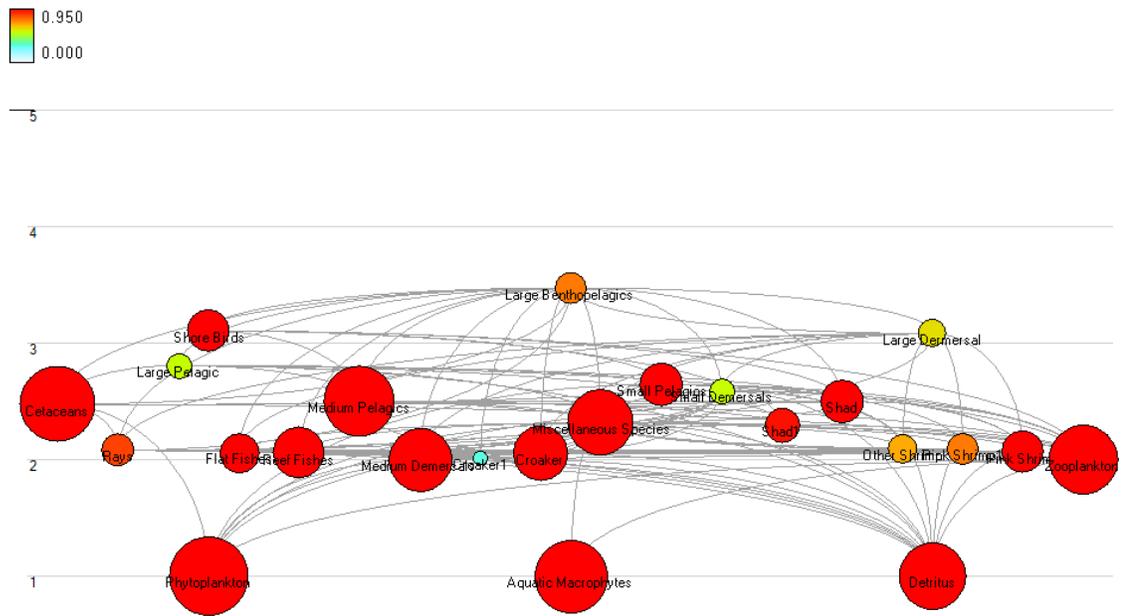


Figure 3.2 Ecopath with Ecosim food web model for Nigerian coastal waters (1985). The y-axis reflects the trophic level. Cool colors (blue) indicate lower biomass and warm colors (red) indicate higher biomass in model area. Larger circles indicate higher biomass than smaller circles.

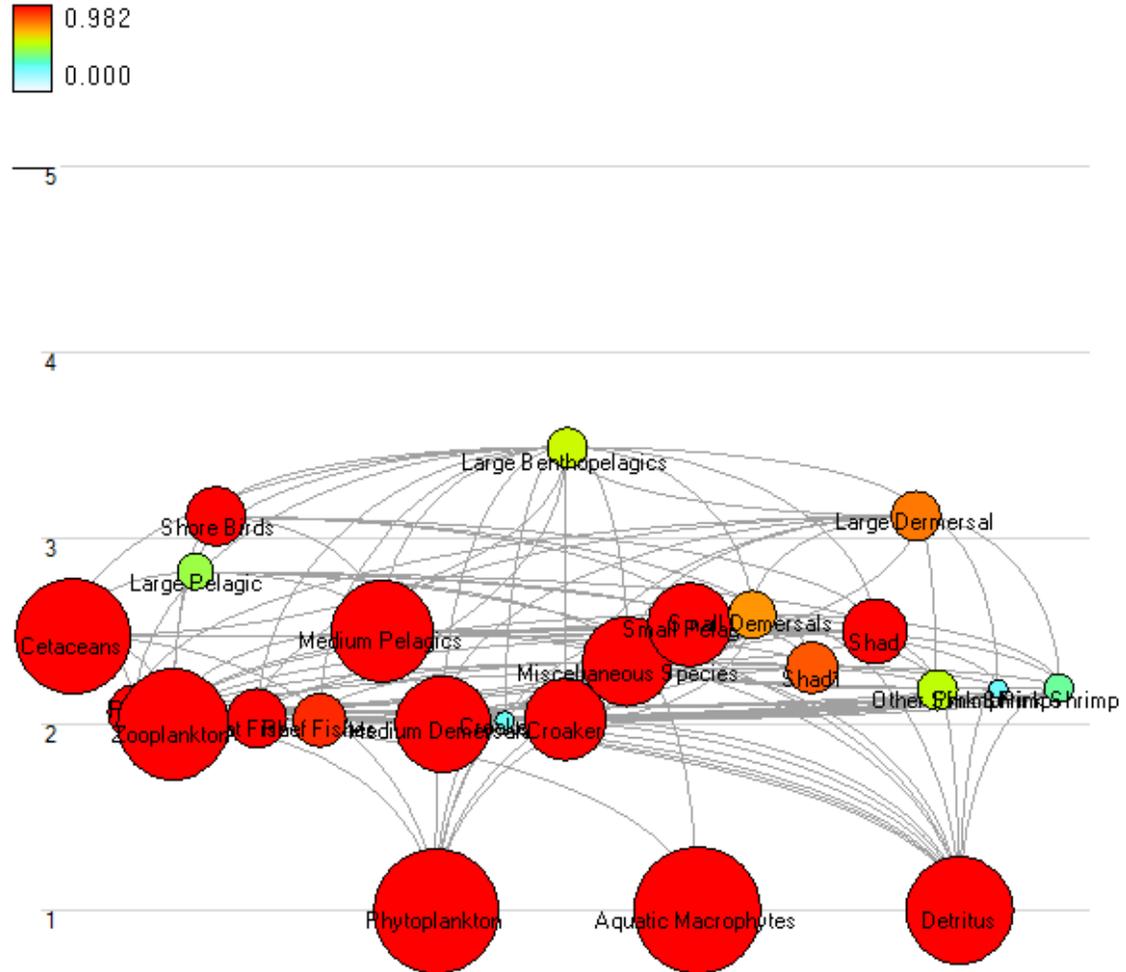


Figure 3.3 Ecopath with Ecosim food web model for Nigerian coastal waters (year 2000). The y-axis reflects the trophic level. Cool colors (blue) indicate lower biomass and warm colors (red) indicate higher biomass in model area. Larger circles indicate higher biomass than smaller circles.

Structural complexity

The NCW ecosystem became less complex over the course of the study period (1985–2000) with modeling results (Table 3.7) showing declines in several important

parameters, that including the total number of pathways declining from 43,842 to 33,072; mean length of pathways declining from 8.94 to 8.84; fraction of top predator taxa declining from 3.94E-05% to 2.38E-05%; Shannon diversity index declining from 2.456 to 2.14; and connectance declining from 0.241 to 0.239 between 1985 and 2000. During the same period, some model parameters increased, including: maximum trophic level increased from 3.474 to 3.493, omnivory index increased from 0.134 (1985) to 0.147 (2000), and the fraction of basal taxa increased from 37.55% (1985) to 43.56% (2000).

Productivity and Energy Flows

The NCW ecosystem was less productive over the course of the study period. With values of TST declining from 12325 (1985) to 12150 (2000). The biomass/production ratio was higher in 1985 (0.0097) than it was in 2000 (0.009). Ecosystem cycles and flows changed considerably during the study period. Transfer efficiency increased from 6.104 (1985) to 7.901 (2000) between 1985 and year 2000, whereas Finn's cycling index decreased from 0.884 (1985) to 0.149 (year 2000) during the same period.

Fisheries

Measures of fisheries were generally higher in year 2000 than in 1985. Fisheries total catch increased from 7.64 t/km²/year in 1985 to 8.16 t/km²/year in 2000. The MTL of catch also increased from 2.21(1985) to 2.31 (2000).

Table 3.7 Results of network analysis for NCW for two models developed for 1985 and year 2000 showing measures that reflect ecosystems complexity, productivity, cycles and flows, consumption/respiration and fisheries take

<i>Ecosystem Structure</i>	<i>Parameter</i>	<i>1985</i>	<i>2000</i>	<i>Units</i>	<i>Expected Direction</i>
1	Total number of pathways	43842	33072		Lower
2	Omnivory Index	0.133548	0.147		Lower
3	Mean length of pathways	8.938	8.838		Lower
4	Fraction of top predator taxa	3.94E-05	2.37882E-05	%	Lower
5	Fraction of basal taxa	37.553	43.560	%	Higher
6	Maximum trophic level	3.474	3.493		Lower
7	Shannon diversity index	2.456329	2.14		Lower
8	Connectance	0.24053	0.239		Lower
<i>Ecosystem Productivity</i>					
1	Total system throughput	12325.04	12171.210	t/km ² /year	Lower
2	Biomass /production ratio	0.009691	0.009		Lower
<i>Cycles & Flows</i>					
1	Transfer efficiency	6.104	7.288	%	Lower
2	Cycling index (Finn's)	0.884	0.185	% of throughput	Shorter
<i>Consumption/Respiration</i>					
1	Sum of all consumption	1693.752	1469.081	t/km ² /year	Higher
2	Sum of all exports	4730.667	4950.289	t/km ² /year	Higher
3	Sum of all respiratory flows	873.1274	714.951	t/km ² /year	Higher
4	Sum of all flows into detritus	5027.49	5036.893	t/km ² /year	Higher
<i>Fishery</i>					
1	Total catch	7.639626	8.162	t/km ² /year	Lower
2	Mean trophic level of catch	2.212446	2.314		Lower

Mixed Trophic Impacts

In 1985, 6.17% of impacts from fisheries were positive (proportion of blue cells in the red box of Figure 3.4), which suggests the major fisheries have positive impacts on some components of the NCW food web, perhaps through indirect means such as trophic mediation that remove predators and provide more prey for certain compartments in the coastal food web, 50.62% were negative (number of red cells in Figure 3.4) and 43.21% were neutral (proportion of white cells in Figure 3.4). In 2000, 7.41% of impacts from fisheries were positive, 50.62% were negative and 41.98% were neutral (Figure 3.5). The general observation from MTI is that the impacts of fishing in NCW is mostly negative.

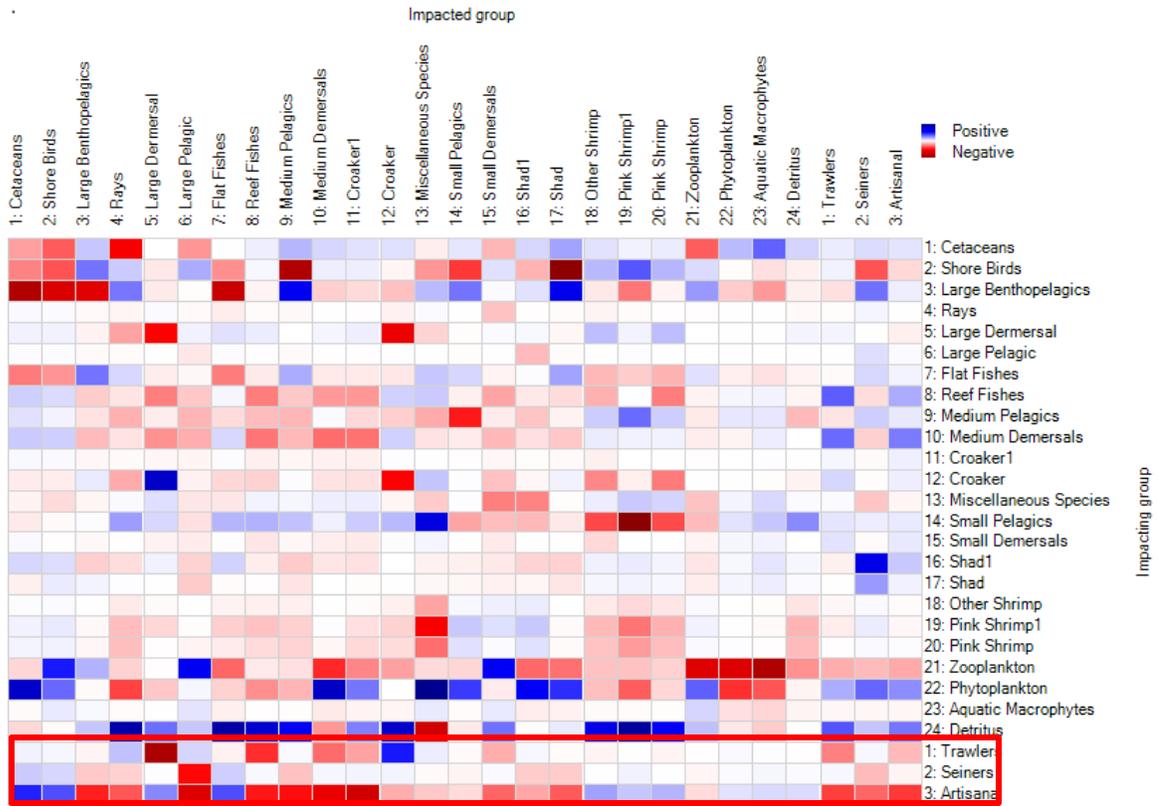


Figure 3.4 Mixed trophic impact for 1985 model showing impacts of all components of the models (including fisheries and functional groups) on one another.

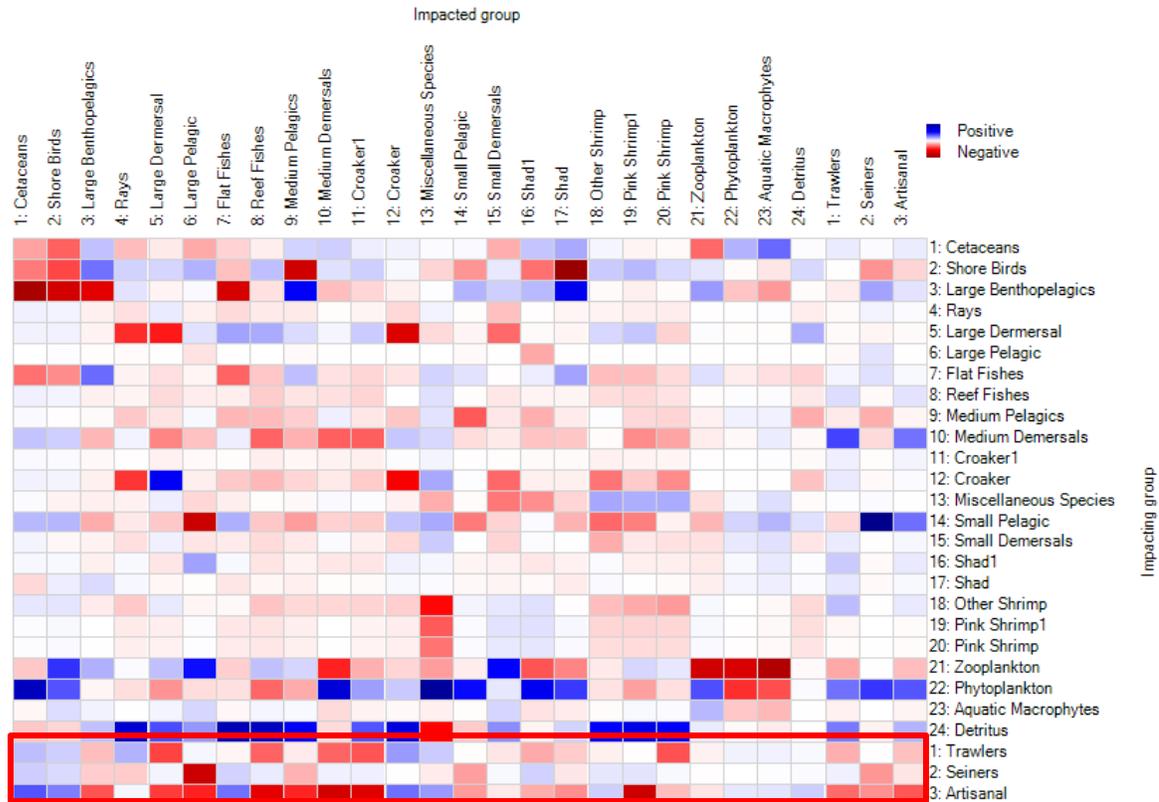


Figure 3.5 Mixed trophic impact for year 2000 model showing impacts of all components of the models (including fisheries and functional groups) on one another.

Discussion and Conclusions

Model results (comparing the 1985 and 2000 EwE models) showed that the Nigerian coastal ecosystem was more degraded in year 2000 than in 1985 due to lower total system throughput, lower mean length of pathways, shorter cycles, faster recycling, and more energy being stored in detritus. Ecological indicators were compared among three ecosystems including NCW (based on the two EwE models parameterized for NCW for 1985 and 2000), the Catalan Sea in Southern Europe, and the Caribbean Sea in the Americas (based on information derived from Coll et al. (2008)).

In terms of structure, the NCW models showed a slight shift in structural complexity. The fraction of predators estimated for NCW in the 1980s–37.55% was less than predicted for Catalan Sea (in 1990) of 70% and the Caribbean Sea (of 60%). This is perhaps an indication that compared to the latter ecosystems, NCW contained more intermediate TL species that had both predators and prey and/or top predators that had prey and relatively few or no predators. The former assumption appears more plausible given the fact that fraction of top predators predicted for NCW in 1985 and 2000 were very low at 3.94E-05 and 2.37882E-05 respectively. By the year 2000, the fraction of basal TL species increased from 37.55% to 43.56%, an indication of increasing loss of higher trophic levels, and increasing homogenization and degradation in NCW between 1985 and 2000.

Model results for productivity and flows showed that TST was slightly lower for NCW in 2000 than in 1985 (Table 3.8). These values were higher than estimates for Catalan Sea, a system described by Coll et al. (2008) as degraded, but lower than the value of TST for the Caribbean Sea. Further comparison with the US continental shelf TST showed the estimation for US continental shelf is closer to the estimate for NCW than it is to the Catalan or Caribbean Seas.

Table 3.8 Model outputs for NCW compare to published EwE outputs for Catalan Sea, Caribbean Sea and US continental shelf

<i>Emergent property</i>	<i>NCW 1985</i>	<i>NCW 2000</i>	<i>Catalan Sea</i>	<i>Caribbean Sea</i>	<i>USA Shelf</i>
<i>TST t/km²/year</i>	12325.04	12171.21	3845	23673.49	11210.32
<i>TE %</i>	6.10	7.29	10.00	12.90	-

The productive waters of the Nigerian coastal ecosystem stems from its adjacency to the Niger Delta that supplies nutrient rich waters coming from upstream in the Niger and Benue Rivers through its many tributaries into the Gulf of Guinea (Ajayi & Talabi 1984). The hypothesis that TST will be lower for NCW in a more perturbed ecosystem due to increased fishing was supported by observed data. A reduction in TST is regarded as attenuation of productive capacity, (Libralato et al. 2002; Coll et al. 2008) although it is not certain if amount of reduction observed for NCW in 2000 is biologically significant. Coll et al. (2008) indicated that system productivity for both the Adriatic Sea and Catalan Sea improved between the 1970s and 1990 although these ecosystems were considered degraded, conversely, NCW ecosystem became less productive between the study period (1985 and 2000), which may have resulted from increased exploitation of living marine resources.

TE was also expected to be lower and this was supported by data obtained from network analysis. The TE (transfer efficiency) calculated for NCW is less than the theoretical estimate of 10% (Christensen 2015), despite the increase in estimated TE value from 6.104% in 1985 to 7.288% in 2000. The Caribbean Sea had an estimated value of 12.90% and Catalan Sea 10%, values that were both higher than the values of TE recorded for NCW.

The hypothesis that model results for MTI (mixed trophic index) analysis will show higher impacts on ecosystem components in the 2000 model compared to the 1985 model was not supported. Overall negative ecosystem impacts of fishing were similar in 2000 (50.62%) and 1985 (50.62%), as evidenced by the comparison of the MTI assessment. Although similar, the distribution of negative impacts among the compartments were slightly dissimilar due to expansion of impacts for the 2000 model compared to 1985 model. As an example, in 1985 impacts of fisheries on shrimps were either positive or neutral depending on the subsector considered, but in 2000, artisanal fisheries and industrial trawl fisheries had negative impacts on pink shrimps and juvenile pink shrimps, because of increasing fishing effort on these species by fishermen throughout the late 1980s, and into the 1990s.

Due to the increase in concentration of fishing on pink shrimps during the 1990s, it appears that fishing impacts in NCW were expanded or shifted from one set of compartment to another, especially from higher TL finfish to lower TL invertebrates.

Nevertheless, overall impacts predicted were similar between the two years in question, whereas per-capita impact increased for some groups like shrimps in 2000 compared to 1985.

Positive impact estimated from the 2000 (7.41%) MTI model analysis was slightly greater than 1985 (6.17%). The positive impacts predicted were mainly due to impacts of fisheries on unfished groups such as cetacean, shorebirds, lightly exploited groups like other shrimps, and three commercially exploited groups: flatfishes, croakers and miscellaneous species. These impacts might have resulted from indirect interactions between modeled species mediated by fisheries.

The greatest intensities of impacts in 1985 occurred with large/medium pelagic and demersal functional groups, indicating the disproportionate impacts of fisheries on higher TL and ground fish species for that year. This pattern is similar in the 2000 MTI result except that low TL juvenile pink shrimps was highly negatively impacted by artisanal fisheries. Artisanal fisheries were impacting juvenile pink shrimps more, perhaps because of the increase in fishing effort in that fishing subsector due to the > 150% increase in the number of participants operating in the artisanal fisheries in coastal water of Nigeria in year 2000 when compared to 1985. Such higher impacts that remove or negatively affect biomass of juvenile pink shrimps can potentially result in growth overfishing, in which juveniles of a species are harvested too early for them to contribute optimally to the commercial fisheries that is exploiting them.

In addition, transfer efficiency, MTL of catch, and fishery catch were higher in the 2000 Ecopath model than the 1985 Ecopath model. The study prediction that MTL would be lower and that fisheries landings would be lower in 1985 was unsupported from modeling outputs. Although the general trend was one of increasing ecosystem degradation in NCW, fisheries landings almost doubled in 2000 (517,000 MT) compared to 1985 (255,600 MT). Increased landings were due in part to higher production of small pelagic species (Amire 2003, Nwafili & Gao 2007), and also because there was an increase in number of fishermen exploiting fisheries in NCW in 2000 compared to 1985 (Nwafili & Gao 2007).

One alternative explanation for the higher MTL in a more degraded ecosystem as observed in the 2000 model is the resolution of taxonomic data. Examination of fisheries landings data shows the taxonomic resolution of species for more than 44% of fisheries data for year 2000 had broad categorization (miscellaneous species) as compared to the 1985 data which was 32.7%. This lack of specificity in taxonomic data was reported by Pauly et al. (1998) as a factor that confounded results and interpretation, since higher taxonomic resolution has been shown to better clarify attenuation of MTLI. If broader categorizations are resolved into appropriate taxonomic categories, the reason for the MTL reduction in the 2000 fishery may be more clearly revealed in this study.

Higher fisheries catch in 2000 may have occurred because of the resurgence in sardinella fisheries when 94,000 MT of sardinella was landed compared to 1985, when sardinella was unavailable in the fisheries catch data. Sardinella availability in NCW has been connected to environmental changes (Amire 2003; Nwafili & Gao 2007). Consequently, the higher landings despite increased ecosystem degradation may have resulted from environmental changes that enhance sardinella fisheries rather than management efforts to rebuild fish stocks.

The increased landings by new entrants to the coastal artisanal fisheries and the increasing availability of sardinella might have further obscured decreasing ecosystem productivity. This would portray a more productive ecosystem when the system was in fact less productive in 2000 compared to 1985. This can be seen in supporting ecosystem indicators of production such as the TST and biomass/production ratio, which were lower in the 2000 EwE model than in 1985 EwE model, probably because the increase in small pelagic species was not enough to offset decreasing production in all other declining ecosystem components.

The increased availability of sardinella may have induced further capitalization in the coastal fisheries resulting in more investments in gears and fishing vessels to take advantage of the boom in sardinella fisheries. The growing number of artisanal fishermen entering the fisheries in 2000 because of Nigeria's rapidly growing population would have enjoyed the ability to access abundant coastal sardinella stock for that year. The higher

number of fishermen exploiting resources may have also made higher catch and landings possible.

Other ecological indicators assessed showed increasing impacts in Nigerian coastal ecosystem, which likely resulted from higher fishing effort. These indicators include: increased homogenization of the food web, as evidenced by lower Shannon diversity index and lower connectance; less energy flowing through the system, as shown by lower number of pathways and lower mean path lengths. In addition to these, there was also lower biomass/production ratio, higher sum of all exports, higher sum of all flows into detritus; shorter cycles, and faster recycling of organic matter, as shown by lower Finn's cycling index.

Overfishing may be an important reason for coastal degradation in NCW. During the period between 1985 and 2000, overfishing was intensified because the number of fishermen participating in coastal fisheries more than doubled, with a 152% increase in number of artisanal fishermen between 1985 and 2000 (Nwafili and Gao 2007). Although the number of fishermen more than doubled, these fishermen could only increase the amount of fish landed from the coastal waters by ~70%, perhaps because the ecosystem had reached its optimum fish production capacity beyond which marginal production with additional fishing effort is negligible. The hypothesis of increased ecosystem impacts following the mid-1980s intensification of fishing effort in NCW is therefore supported by data from model outputs along with evidence from the literature.

There were modeling challenges in this project, especially in regards to the quantity and quality of the data available for the system studied. On occasion, there were contradictions in available fisheries data obtained from literature, and detailed diet data required for parameterization was lacking. Nevertheless, most data needs were addressed using freely available databases (SAU project, Fishbase and Sealifebase).

Conclusions

Two models were parameterized and mass-balanced for NCW to provide comprehensive, tractable pictures of the NCW ecosystem structure, biodiversity, and species interaction for two distinct times in recent fishing history (Dune et al. 2002). Developing these models to show fishery changes before and after impact have made quantitative cross-comparison of ecosystem emergent factors possible. It is now possible to see the impacts of 20 years of intense fishing in the *P. notialis* fisheries in NCW by comparing the model for 1985 which represents the ecosystem at the inception of the fisheries with the model for 2000 which represent the overfished ecosystem.

The models revealed an expansion of fisheries impacts from higher and medium TL ecosystem components to low TL shrimps between 1985 and 2000. Impacts observed were fishing-sector dependent. Artisanal fisheries are by far the most important driver of impacts in NCW for the two years modeled, but benthic trawlers grew in importance as they exerted more impacts in 2000 compared to 1985. The most intense impacts were associated with long-lived, large benthic and pelagic species, and reef fishes. As shrimp

exploitation intensified between the mid-1980s and early 2000s, impacts of benthic trawl fishing was extended to sharks, shads, and shrimps, which previously were not impacted by this fishing subsector in the 1985 model.

The increase MTL observed in 2000 may be the result of spatial expansion in the fishery that allowed previously unfished areas in the 1980s to be accessed by artisanal fishermen due to increased vessel motorization. This increase in MTL in 2000 matches trends observed in MTLI for NCW (In Chapter II), which suggests the NCW EwE replicates/reproduce patterns observed in the fisheries even though the model in its current form is yet to be calibrated with time-series data. This is good because effective models ought to match known characteristic of the ecosystem they represent (Pauly et al. 2000).

Higher predictions of fisheries catch in 2000 compared to 1985 is most likely associated with sardinella resurgence, which is temperature mediated (Amire 2003; Nwafili & Gao 2007). Because the productivity of these species naturally fluctuates, these fluctuations have resulted in inconsistent landings for fisheries that correlate with environmental conditions.

Another possible cause of increased landings is the increase in fishing capacity/access to presumably more pristine deeper shelf waters for artisanal fishermen who traditionally only fished in nearshore water within the first 18-meters depth. Increasing motorization and number of fishermen (Nwafili and Gao 2007) resulted in higher landing

by ~70% in 2000 compared to 1985. Thus, the increased catch is a result of increase exploitation and higher fishing capacity in 2000 compared to 1985.

Ecosystems are dynamic and complex systems. Therefore, depictions of food webs for two separate years alone may only present a partial picture of ecosystem outcomes. It is necessary to continue data collection and field observations that can be used to map more accurately the dynamics of ecosystem components, and the fisheries that operate in the NCW ecosystem (Cohen et al. 1990).

Human pressures on coastal resources in NCW have increased significantly in the last three decades. Over the 15-year period considered in this study, ecosystem structure was simplified, productivity and ecosystem cycling reduced, and fisheries landings increased. Increasing landings may have resulted from higher fishing effort and consequently higher human impacts for NCW during the year 2000. Over-exploitation resulting from increase extraction tied to population growth in West Africa and Nigeria may intensify in the coming years. Proper planning and alternative means for livelihoods/sustenance in coastal fishing communities should be considered.

Over the last 30 years, EwE has matured as a tool for describing ecosystems, analyzing impacts of fishing, and understanding policy gaming and ecological studies. By using EwE to provide a first description of NCW ecosystem and analyzing fishing impacts

in EwE's network analysis toolset, outcomes for NCW have been briefly outlined using comparison of model outputs.

Further studies (described in Chapter 4), will focus on spatio-temporal analysis of the fisheries to gain better understanding of fishing impacts and possible means to ameliorate anthropogenic impacts in NCW. Other future studies using the NCW ecosystem models described in this study can also incorporate other agents of ecological disturbance (e.g. climate change, pollution). Such additional studies and data collection to improve the model inputs will greatly strengthen the value of model predictions and put Nigeria and Gulf of Guinea coastal fisheries on sustainable trajectories.

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4. USING SPATIO-TEMPORAL MODELING TO INVESTIGATE POSSIBLE IMPACTS OF HISTORICAL REDISTRIBUTION OF FISHING IN NIGERIAN COASTAL WATERS

Introduction

Marine resources and the fisheries that depend on them are unevenly distributed spatially (Romagnoni et al. 2015)—a factor unaccounted for in the non-spatial fisheries assessment of Nigerian coastal waters (NCW) presented in chapters II and III.

In this chapter, an ecosystem model of NCW was developed in Ecospace, the spatial component of Ecopath with Ecosim (EwE), to investigate whether spatial redistribution of fishing effort (from waters up to 50-meter-deep into waters less than 18 meters deep) by industrial shrimp trawlers operating in NCW in the period between 1985 to 2004 will increase impacts of fishing on nearshore waters that serve as living habitats and important nursery areas in NCW.

Shrimping grounds in NCW stretch from 5° 0° E to 8° 30° E, extending up to 80-m depths from the shoreline (Ajayi and Adetayo 1982). Overcapitalization of the coastal shrimp fisheries during the 1990s led to depletion of the main target species, pink shrimp (*Peneus notialis*; Ogbona 2001). This species historically accounted for more than 90% of decapod landings and was exploited in deeper inshore areas (up to approximately 50-m deep) (Ajayi and Adetayo 1982).

After overfishing and depletion of the *P. notialis* stocks, some shrimp trawlers encroached into shallower nearshore waters less than 18-m deep in search of alternative shrimp species (*Parapanaeopsis atlantica*, *Peneus monodon* and *Nematopalaemon hastatus*) that occupy shallower nearshore waters in NCW than *P. notialis*. The ecological and economic consequences of this fishing tactic that violated fishing regulations in the late 1990s and early 2000s is yet to be investigated from a spatial context.

The Sea Fisheries (Fishing) Regulation and the Sea Fisheries (Licensing) Regulation of 1992 contain provisions that guide and control industrial marine fisheries in Nigeria. Item No. 4 of these regulations prescribed the “Delimitation of 5 NM non-trawling zone which places restrictions on trawling in sea water area covering 7898.78 km² of the Nigerian continental shelf essentially to protect the nursery ground from indiscriminate fishing. It is also to protect the artisanal fishermen who operate within the zone, as well as to reduce conflict between them and trawler operators” (Ogbona 2001).

When spatially explicit administrative (fishing) rules are inadequately enforced, conservation and management of marine resources may be jeopardized. It is imperative to investigate possible ecological consequences of such occurrence. One approach to quantifying impacts is to compare alternative policies for use and management/conservation of oceanic resources (Halpern et al. 2008). This approach is used to better understand ecosystem impacts on fisheries in a spatial context. In this study, I quantified impacts of alternative spatial management strategies in coastal shrimp fisheries

on fished groups in NCW. I used an ecosystem model developed in EWE 6.5 for all analyses in this project.

Background

The inshore fishing area in NCW covers 36,472 km² and is divided spatially into two distinct sections with the first 5 NM from the shoreline reserved for artisanal fishermen, but both artisanal fisheries and industrial fisheries target resources in waters from the 18-m to 40-m contour (Amire 2003). In these waters, industrial trawlers ranging from 10 to 23-m-long (Ajayi and Talabi 1984) concentrate fishing effort on *P. notialis*, while artisanal fisheries target a variety of species (including shad, sardinella, estuarine prawn, swimming crabs, crayfish, etc.) in water <40-m deep (Amire 2003).

In the late 1990s some shrimpers ignored the spatial regulations designed to separate the two-major fishing sub-sectors, to maintain undiminished shrimp catch after the depletion of the *P. notialis* fishery (around year 2000), by targeting shrimp species occupying shallower habitats of the continental shelf (Ogbona 2001). The main species targeted was the exotic brown shrimp (*P. monodon*), a species that occupies spatially distinct shallower oceanic habitats than the depleted *P. notialis* stocks previously targeted in deeper waters up to 50-m depth.

The redistribution of fishing effort into shallower areas (<18-m depth) may mean that fishing effort from the two fishing subsectors became more concentrated in time and

space—in potentially more sensitive habitats that serve as nursery areas for a variety of ecologically and commercially important fish and invertebrate stocks (Ogbona 2001). In addition to this, by deploying trawl nets aimed at targeting shallow-water shrimps, industrial shrimping trawlers increased bycatch of artisanal target species and juveniles of other commercial species that use this area as nursery grounds.

Although fishing effort was comparable on average from the late 1990s to the early 2000s, concentrating this higher amount of fishing effort in a smaller area may accelerate nearshore habitat degradation and depletion of coastal fish stocks from the nearshore strip of operation area. This is a concern because the area is recognized as nursery habitats and potential source habitat for other fishing grounds in deeper areas of the continental shelf (Ogbona 2001).

By continuing to fish in the non-trawl area, trawlers may precipitate ecological loss through recruitment failure, which will lead to economic and social problems for coastal fisheries in Nigeria. As an example, conflicts have been reported by Ogbona (2001) because of increased competition among fishermen arising from trawlers fishing in the nearshore 5NM non-trawl zone. While fishing here, some trawlers tow away nets set in shallow areas and ram into other valuable objects utilized by artisanal fisheries (Ogbona 2001).

From a management standpoint, it is desirable to minimize conflicts among fishermen, which was one of the reasons the spatial regulation was put in place. Separating fishing areas ensures only minimal overlap in operation areas for the main fishing sub-sectors (artisanal and industrial fisheries) in NCW. Such administrative tools, though simple, guarantees less competition for resources between industrial fishermen and their artisanal counterparts.

In addition, managers and scientists have expressed concern that accelerated degradation of nearshore coastal habitats in Nigeria would result when such spatial administrative tools are violated/ignored by industrial fishing boats (Ogbona 2001). Moreover, most fish stocks in Nigerian coastal waters use the nutrient rich waters of the Niger Delta as nursery area, and nearshore coastal waters are likely used as nursery areas too (Ogbona 2001).

Illegal trawling in potentially sensitive habitats may have led to increased bycatch of juveniles of commercial fish species, which can result in growth overfishing if juveniles are caught in the nursery areas before they can grow, migrate into deeper waters, and recruit into the coastal industrial fisheries (Ogbona 2001). Such fishing strategy will, in the end, limit overall fisheries production for coastal fisheries altogether.

Distribution of fish resources informs the behavior and decision-making process for fishermen. Spatial allocation of fishing effort should mirror patterns of exploited marine

species distribution (Aburto et al. 2009). There is limited information on community composition and the spatial distribution of commercial fish stocks in Nigeria (Amire 2003), making it necessary to verify community distribution through surveys and spatial mapping (Walters et al. 1999). Such information will improve coastal planning and fisheries management for coastal fisheries in Nigeria, but because such detailed survey maps are difficult to obtain, an alternative approach may be to use spatial modeling to understand spatial distribution of marine resources and the fisheries that depend on them. It matters to fisheries where fish are geographically located, because fishermen concentrate fishing effort there (Jennings et al. 1999; Ramagnoni et al. 2015). Since it costs money, time, and effort to access fishing grounds, fishermen carefully consider cost and benefits of fishing at any given location (Aburto et al. 2009), and guide their decisions by how much profit can be made per expenditure.

This chapter aims to predict impacts of spatial redistribution of fishing effort from deeper inshore waters ~ 50-m depth to nearshore waters < 18-m depth in Nigerian coastal waters. Impacts will be predicted using Ecospace, the spatial module of the Ecopath with Ecosim (EwE) modeling tool (www.ecopath.org), to understand how biomass, catch rates, and spatial distribution of fishing effort change under alternative spatial management approaches. By integrating spatial dynamics and trophic interactions in an ecosystem food-web model, important insights in coastal ecosystem processes within the inshore fishing area of NCW can be gained (Romagnoni et al. 2015).

I investigate the hypothesis that displacement of fishing effort by shrimp trawlers from the 50-m isobath into the 5 NM nearshore area reserved for artisanal fisheries led to increased impacts on commercially exploited fish and invertebrates through reduction in fish and invertebrate biomass and a decline in catch rates, along with changes in spatial distribution of fishing effort.

Research Approach/Design

An ecosystem approach to fisheries was used to analyze impacts of spatial redistribution of fishing effort in NCW by combining food web and spatial dynamics of functional groups within a single framework (Christensen et al. 2015). Spatial structure of the fisheries and the impact of spatial displacement of fishing effort on marine fish and invertebrate biomass and fisheries catch rates are simulated in the spatial component of EWE – Ecospace, to shed light on spatial patterns and improve understanding of impacts of fishing in nearshore tropical waters in the Nigerian coastal ecosystem.

Methods

Study Area

Nigeria's inshore fishing area (Figure 4.1) extends approximately over 36,000 km², but only 30% of this area is trawlable. The western portion of the continental shelf extends only 15 km off Lagos, whereas the shallow part of the continental shelf reaches 80 km off Cross River in the east. The narrowness of the continental shelf limits fish abundance and areas where trawlers can operate (Amire 2003).

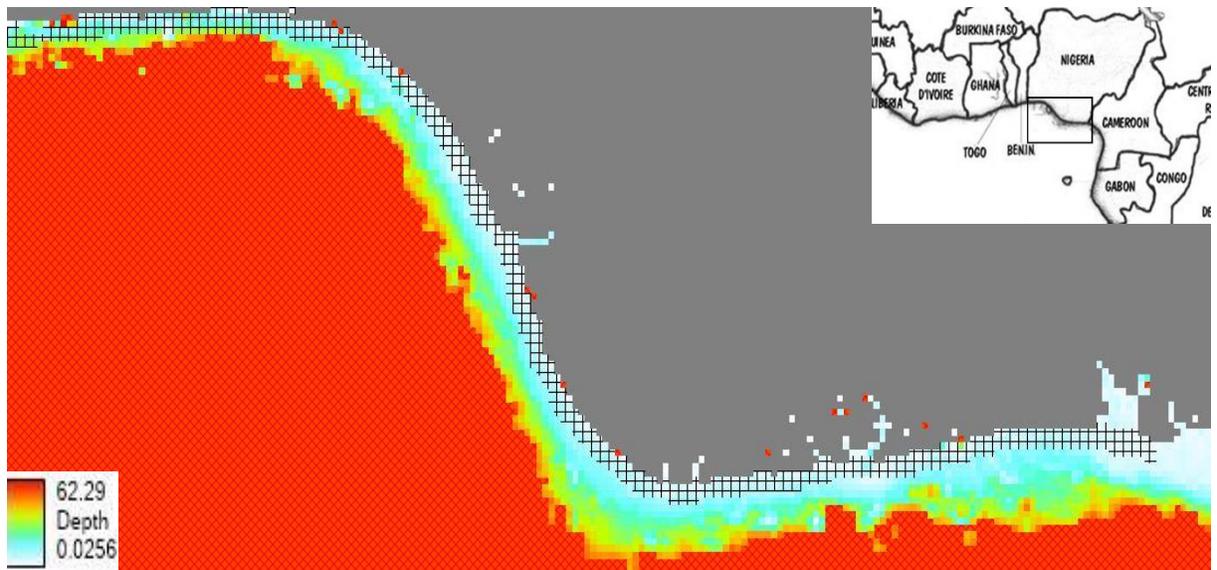


Figure 4.1 Coastal map of Nigeria showing the study area with the first 5 nautical miles depicted as MPA to prevent fishing in this narrow strip within the Ecospace model developed for Nigerian coastal waters. The red hatched area indicates the area excluded from the model area, where trawling is not possible.

Model Parameterization and Calibration in Ecopath and Ecosim

Twenty-two functional groups were parameterized to represent average situation in NCW in 1985—the year shrimp exploitation started to expand. The mass-balanced model was parameterized using equation 3.4 (see chapter III on page 68). Biological parameters for the NCW were obtained from Fishbase, while fishery data came from the Sea Around Us (SAU) Project and from published fisheries literature (Ogbona 2001; Agbaje & Falaye 2007; Amire 2003). Estimates of pink shrimp biomass and fisheries catch data were used to calibrate the model dynamically to evaluate predictive capability of the model in Ecosim where biomass dynamic is expressed as:

$$\frac{dB_i}{dt} = g_i \sum_{j=1}^n Q_{ji} (B_j(t), B_i(t)) - \sum_{j=1}^n Q_{ij} (B_i(t), B_j(t)) + I_i - (M0_i(t) + F_i(t) + e_i)B_i(t) \text{----- Equation 4. 1}$$

Where $B_i(t)$ is the biomass of i at time t , g_i is the growth efficiency, I_i is the immigration rate; $M0_i$ is the natural mortality, $F_i(t)$ is the fishing mortality, e_i is the emigration rate, Q_{ji} represents the consumption due to predation on i by predator j , the term Q_{ij} represent the consumption due to predation on group j by predator i (Christensen & Walters 2004).

Functional groups were modeled in two states—as either vulnerable or invulnerable to predation base on the Foraging Arena Theory (Walters and Martell 2004). Transfer rates between the two fractions determined vulnerable biomass at each time instance which is calculated in Ecosim using the dynamic time-dependent equation for interactions between prey i and predator j (Plaganyi E. 2007).

$$\frac{d(N_i - V_{ij})}{dt} = -v_{ij}(N_i - V_{ij}) + v'_{ij} - V_{ij} \text{-----Equation 4.2}$$

Where vulnerable prey dynamics was represented as V_{ij} , and dynamics of invulnerable prey as $N_i - V_{ij}$.

In Ecosim the fit-to-time series tool was used to determine vulnerabilities that produced the best fit of model predictions to landings data for all exploited species and biomass data for *P. notialis*.

The model fit was performed using the sum of squares formula:

$$SS = \sum_i^{nts} (\sum_i^{nobs} w_i \log(\frac{o_{it}}{p_{it}})^2) \text{ ----- Equation 4.3}$$

Where SS is sum of squares, *nts* is the number of time series loaded, *nobs_s* is the number of observations in time series *i*, and *o_{it}* is the observed value in time series *i* at time step *t* (De Mutsert et al. 2016).

In the anomaly search routine, temperature time series was utilized as a forcing function for obtaining a better fit of model to data to obtain further reductions in the sum of square errors. Reasonable fits were obtained for most groups in the model based on Equation 4.3.

Ecospace

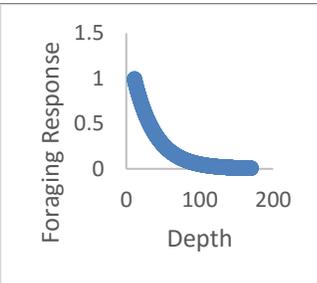
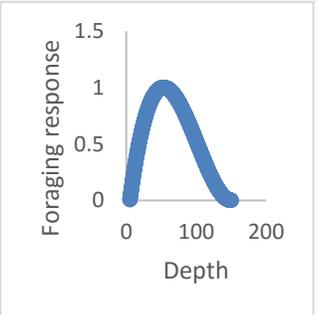
In Ecospace, predictor selection was based on the ecological/biophysical processes being investigated, and the purpose of the model, which was to investigate the impacts of transferring fishing effort from deeper offshore water into shallower areas in the NCW ecosystem (Guisan et al. 2000; Austin 2007, Elith & Leathwick 2009). After calibrating the model in Ecosim, the model was transferred to Ecospace after determining the model area (Figure 4.1), and importing a bathymetric map of that area as the model basemap. Habitat capacity for each functional group was determined. Ecospace considers habitat quality using a habitat foraging capacity model with a continuous habitat suitability factor

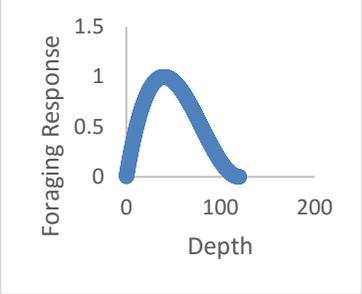
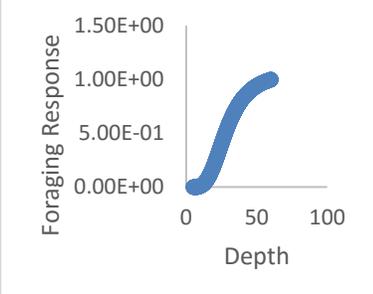
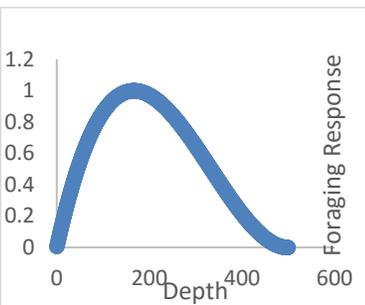
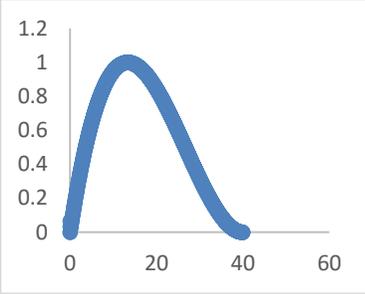
where the area a species can feed in each cell is determined by functional response to environmental factors. Here, foraging can be driven from multiple physical, oceanographic and environmental factors, such as depth, oxygen, temperature and the like. Therefore, the spatial distribution of species is based on the environmental preference for each functional group and the degree to which it is possible to mimic the true distribution for each group (Christensen et al. 2014). For the NCW EwE Ecospace model, instead of having the model compute habitat capacity from environmental parameters in combination with tolerance range for environmental parameters for each modeled group, I assumed fish distribution maps reflect habitat capacity maps, and loaded fish distribution maps as habitat capacity maps, but used bathymetric information as a layer to ensure fish distribution stayed reasonable over time.

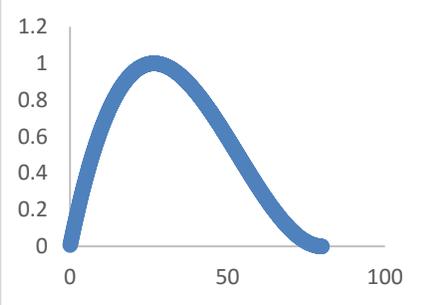
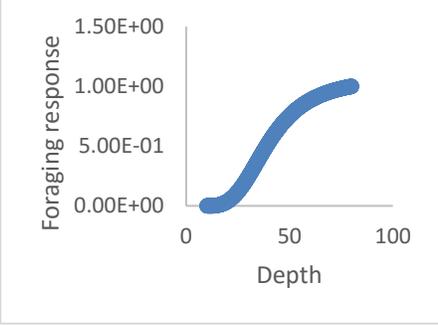
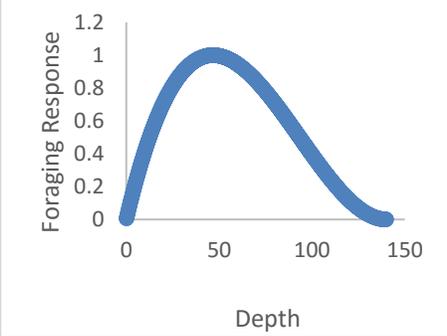
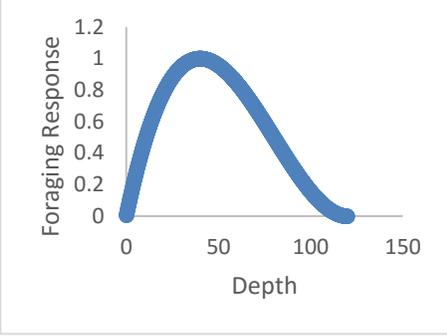
As previously stated, habitat capacity for each modeled group was determined in Ecospace by importing ASCII files of distribution maps for functional groups into Ecospace and using this information along with bathymetric preferences for each modeled group to predict spatial distribution of biomass in Ecospace. Distribution maps were drawn in ESRI ArcMaps 10.3, by using map data obtained from AquaMaps as templates on which EwE input maps were traced. In the habitat based foraging interfaces, foraging response curves of groups based on their depth tolerance ranges were then defined with a variety of functional response curves (Romagnoni et al. 2015; De Mutsert et al. 2016) using ecological information of depth tolerance range for each functional group based on data obtained from (Amire 2003), Fishbase, and Sealifebase (Table 4.1).

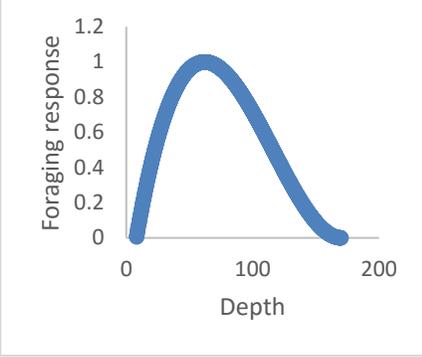
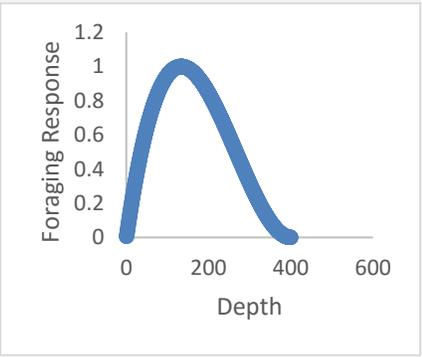
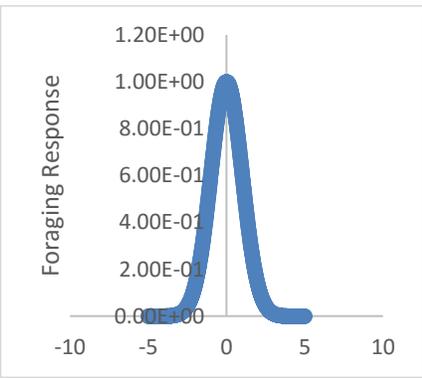
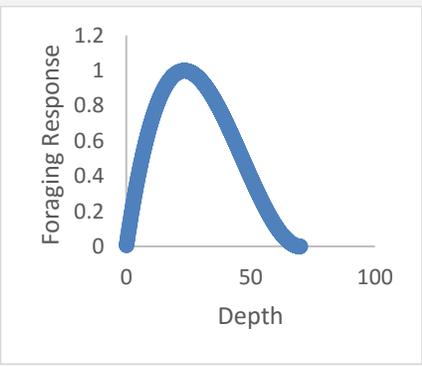
Most of the response curves to depth were sigmoidal, but other shapes such as normal curves were utilized when these shapes better fit the curve of bathymetric preference for the groups concerned.

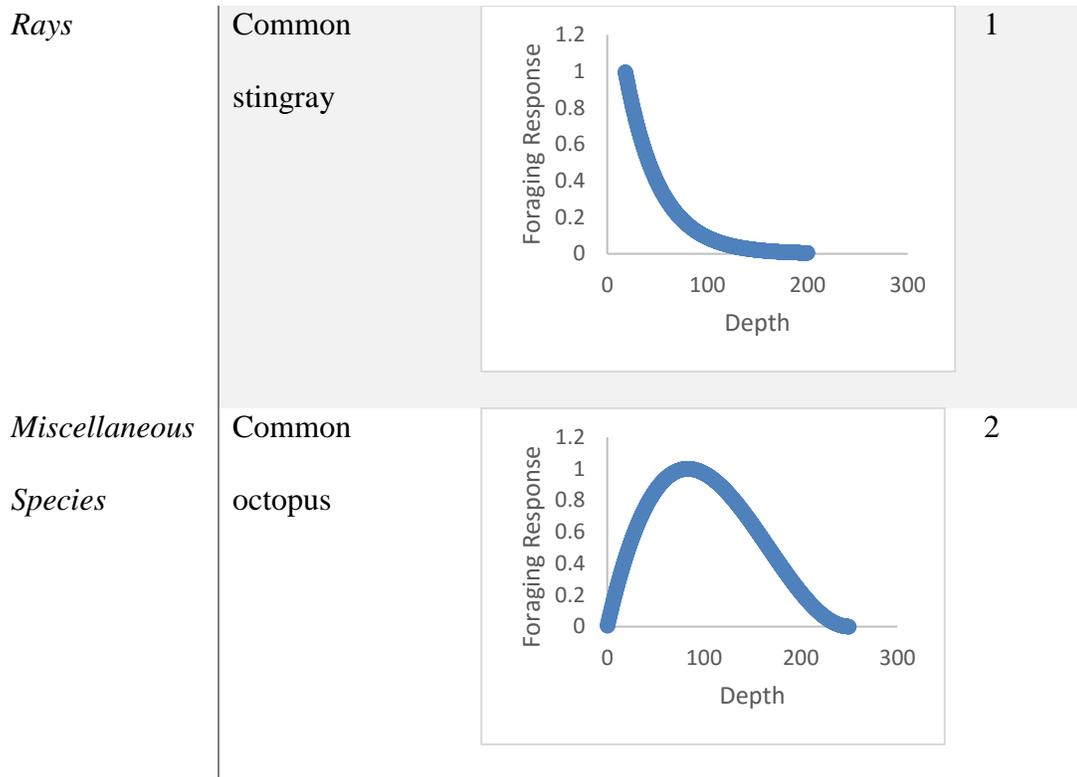
Table 4.1 Depth response curves used for predicting distribution of biomass for functional groups in NCW EwE model. Fishbase¹, Sealifebase² and Amire (2003)³.

<i>Functional Group</i>	<i>Representative Species</i>	<i>Depth Response Curve</i>	<i>Source</i>
<i>Large Benthopelagic</i>	Sand tiger shark		1
<i>Medium Demersal</i>	Benguela hake		1

<i>Reef Fishes</i>	African brown snapper		1
<i>Croakers</i>	Cassava croaker		1
<i>Cetaceans</i>	Northern minke whales		2
<i>Other Shrimps</i>	Guinea shrimp		3

<i>Pink Shrimp</i>	Southern pink shrimp		3
<i>Flatfishes</i>	Senegalese tongue sole		1
<i>Small Pelagic</i>	Maderian sardinella		1
<i>Small Demersal</i>	Royal threadfin		1

<i>Large Pelagic</i>	Blue marlin		1
<i>Medium Pelagic</i>	Cape horse mackerel		1
<i>Large Demersal</i>	Common sawfish		1
<i>Shad</i>	Bonga shad		1



Pink shrimp and other shallow habitat shrimp are most important to this study since the spatial redistribution of the benthic trawler fleet effort occurred in response to depletion of pink shrimp in deeper waters resulting in some benthic trawlers encroaching into the 5 NM no-trawl zone in search for brown shrimp and other shrimps that inhabit these shallower areas of the continental shelf (Figure 4.2).

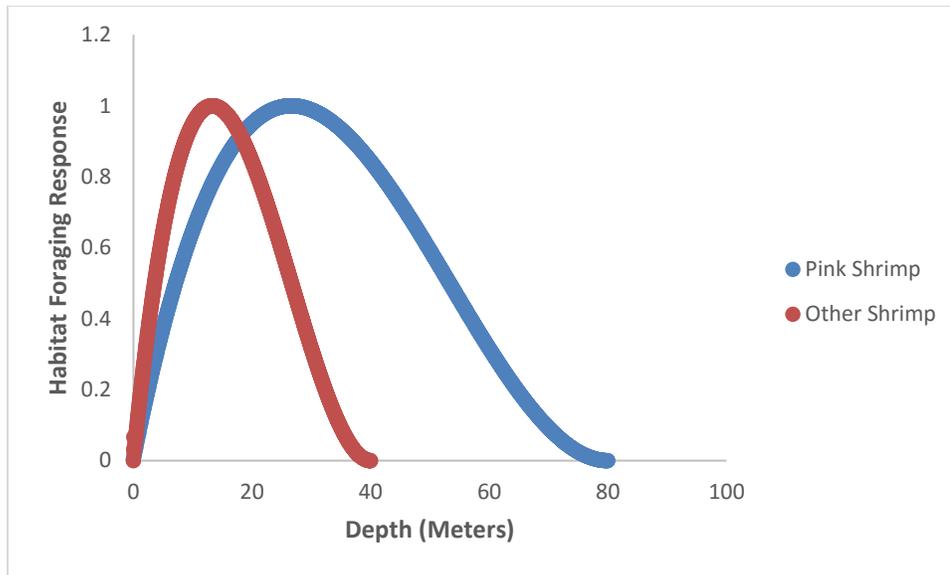


Figure 4.2 Response curves for habitat foraging for shallow habitat and deeper habitat shrimp species in Nigerian coastal waters

My spatial analysis for the NCW Ecospace model focuses on approximately the first 50-m depth, which was the operation area for most fishing fleets operating in the inshore fishing areas in the late 1980s to early 2000s (Most artisanal fishermen only fish down to the 40-m depth, while trawlers trawled up to 50-m depth for *P. notialis*). As such, this depth is sufficient for impact analyses since it covers the inshore area in which fishing interactions were taking place among the inshore based fleets of NCW.

Fisheries

Three fishing fleets were included in the Ecopath model described in Chapter III, including two industrial fleets separately targeting benthic and pelagic resources, and one large artisanal fleet that combined benthic and pelagic fishing. Fleet fishing was regulated

in Ecospace by making adjustments to the parameters—effective power and total efficiency multiplier. These parameters serve as weighting factors in Ecospace. Effective power sets relative catchability in Ecospace, while total efficiency multiplier is a scaling factor for effort by fleets (Romagnoni et al. 2015). Effort was distributed by designating habitats for species assigned to the three fleets, and with a gravity model distributed into cells open to fishing that have suitable bathymetric conditions to support functional groups.

Model Simulations

Spatial simulations were undertaken in Ecospace where biomass for groups, catch rates, and fishing effort in fishing subsectors were spatially distributed across a map of NCW containing a grid of 16,600 square cells. Impacts of fishing was evaluated by simulating two scenarios in Ecospace with the first scenario maintaining a 5 NM non-trawl area beginning from the shorelines and the second scenario allowing benthic trawlers to fish everywhere. The scenarios were manipulated in the fleet/habitat + MPA usage in Ecospace.

MPA settings in Ecospace need to be adjustable or dynamic by allowing access to a fleet with the ability to close access to the same fleet when fishing policy changes. To achieve this in Ecospace, biomass landed for benthic trawlers was split in half in the parameterize EwE model, and effort was adjusted in Ecosim by scaling effort upwards for both split biomass pools. For the scenario where effects of the MPA were tested (Figure 4.3), the first benthic trawler fleets could fish outside the 5 NM non-trawl zone for the first 15 years while the second fleet was dormant (by setting fishing effort to zero) until the 15th

year (2000). The second fleet could fish everywhere including within the MPA in Ecospace beginning from year 2000 to year 2004. This represents the practice of ignoring the regulation that restricts trawling within the MPA which started in 2000. A gravity model spread fishing effort in Ecospace and limited fleets to habitats or to fish in MPA when such fleets were assigned to fish there. For every time step, an Ecosim simulation was run for every cell in Ecospace and fishing effort by fleets, catch rates, and biomass for functional groups were estimated.

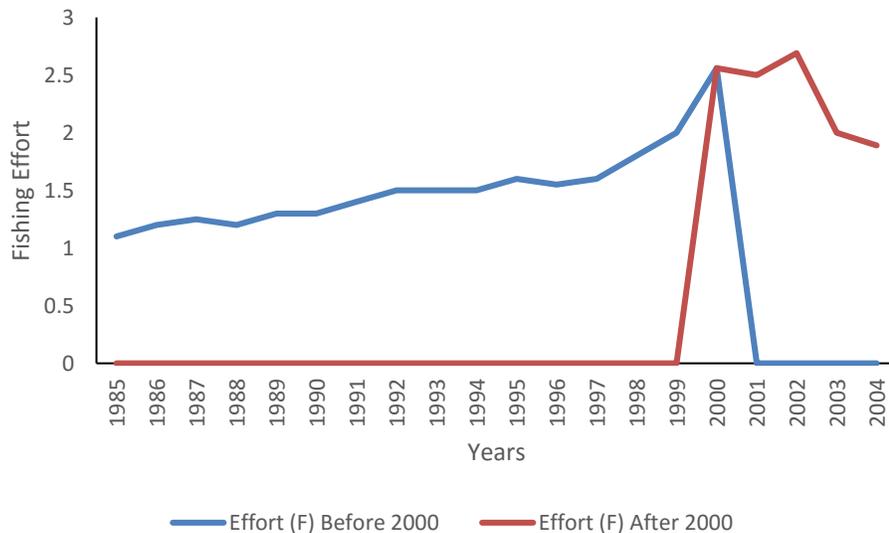


Figure 4.3 Effort partitioning in Ecosim for shrimp trawlers to allow for scenarios with opening and closing of MPA in Ecospace

Results

Model Calibration in Ecosim

Model calibration produced better fits when temperature forcing was included in the anomaly search (SS = 238; AIC = 58.07) than when only fisheries data were used to fit the Ecosim model to data in the vulnerability search (SS= 347.7; AIC = 136). This highlights the importance of using environmental predictors in addition to fishing information for the NCW food web model (Table 4.2).

Table 4.2 Model parameters from fit to time series data in Ecosim

<i>Drivers</i>	<i># of</i>	<i>AIC</i>	<i>Sum of</i>	<i>AIC</i>
	<i>Parameters</i>	<i>Data points</i>	<i>Squares</i>	
<i>Fishing</i>	21.00	238.00	347.70	13.60
<i>Fishing</i> <i>+ Temperature</i>	21.00	238.00	247.50	58.07

Reef fishes were overestimated at the beginning of the time series, medium pelagic species were underestimated, and the model did not adequately capture the increased landings for species with widely fluctuating dynamics such as small pelagic sardinella (**Figure 4.3**). In addition, small demersal fishes were overestimated while predictions for all other groups appeared to follow trends in fisheries data approximately.

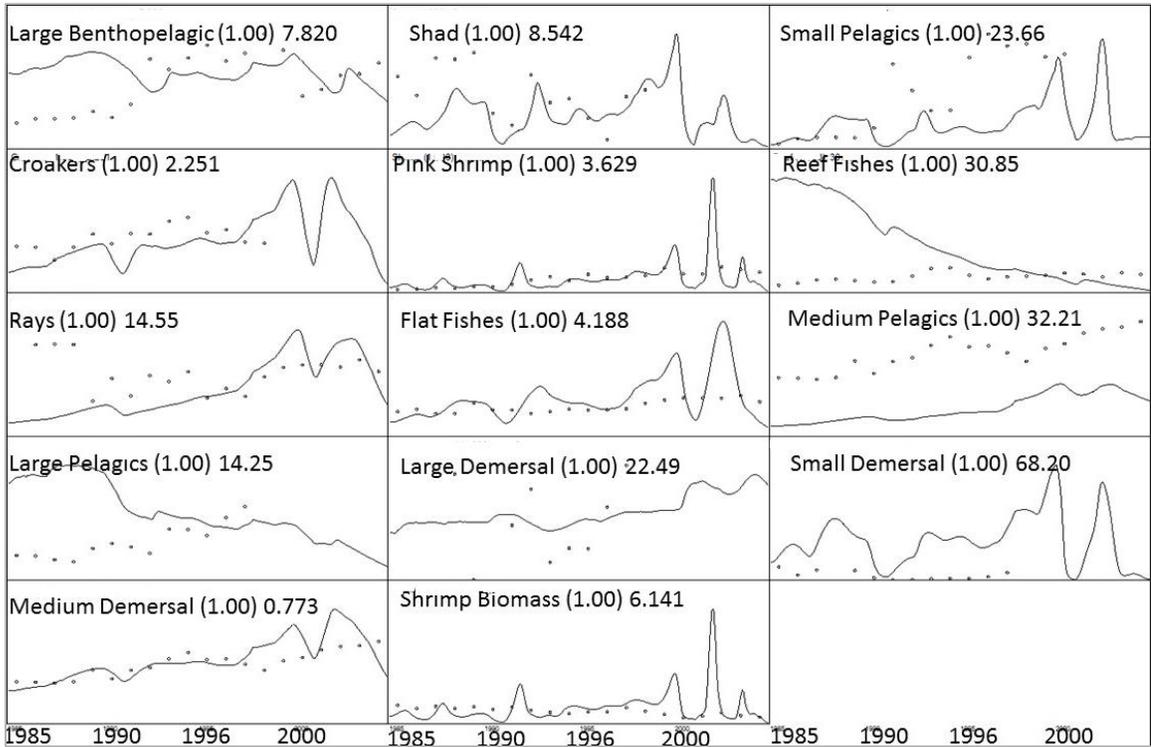


Figure 4.3 Ecosim fits for all fished groups in Nigerian coastal waters with sum of square values for groups, and weight given to estimation in parentheses.

Distribution of Fishing Effort

Fishing effort by artisanal fishermen is spread across the modeled area of the map (the blue-green portion of the map) but concentrates outside the 5 NM designated as fishing grounds for artisanal fisheries along the entire coast in 2004 (Figure 4.4). The fishing effort was however moderately spread, and the intensity of fishing in deeper waters by the artisanal fleets was minimal.

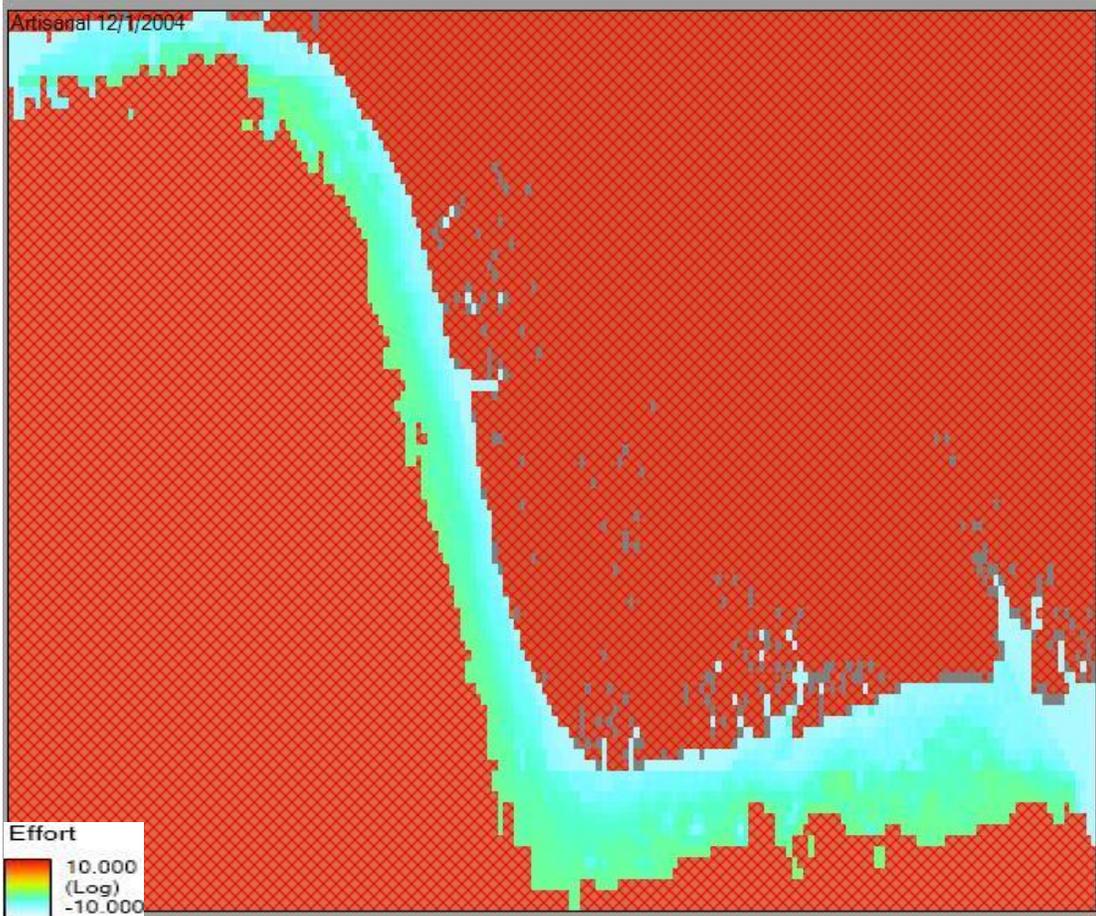


Figure 4.4 Model simulated fishing effort for artisanal fisheries in NCW for 2004. Red hatched areas of the map are excluded cells.

Benthic trawlers exacted a similar pattern of fishing effort as observed in the fishing effort of artisanal fisheries (Figure 4.5). The greater the depth from shore, the more effort appeared to be exacted by benthic trawlers in the inshore fishing area of NCW.

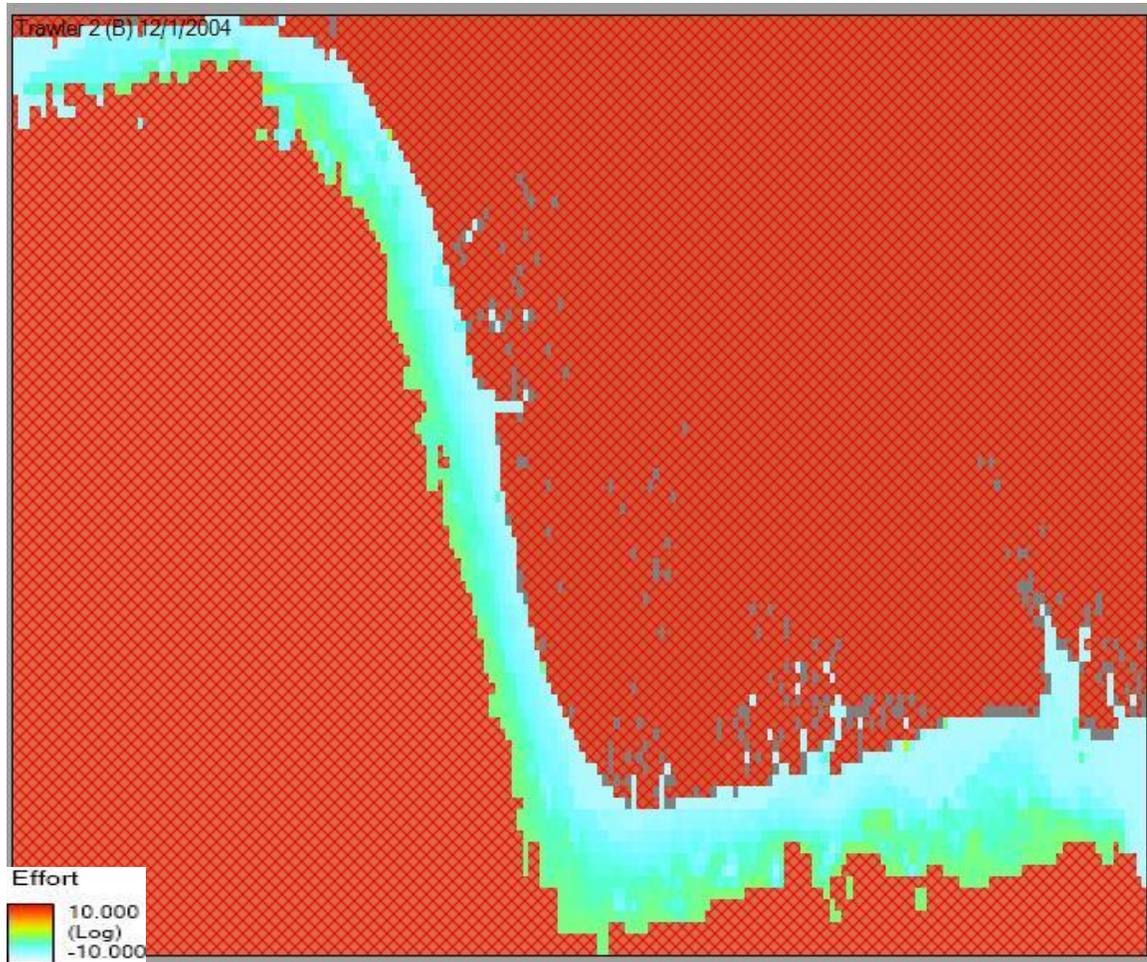


Figure 4.5 Model simulated fishing effort for benthic trawler fisheries in NCW for 2004. Red hatched area of the map is excluded cells.

This model predicted more intense commercial fishing for pelagic species in 2004 than the intensity of fishing effort exacted by artisanal and benthic trawl fisheries in the same year. Although pelagic trawlers utilize the entire inshore area (Outside the first 5NM), effort was concentrated in deeper waters close to the border between Benin and Nigeria, and across the western section of the coast (Figure 4.6). Although considerable amounts of fishing effort were predicted for waters in the southeast region, the model predicted

comparatively less fishing effort for pelagic trawlers in this portion of the Nigerian coast when compared to the western section.

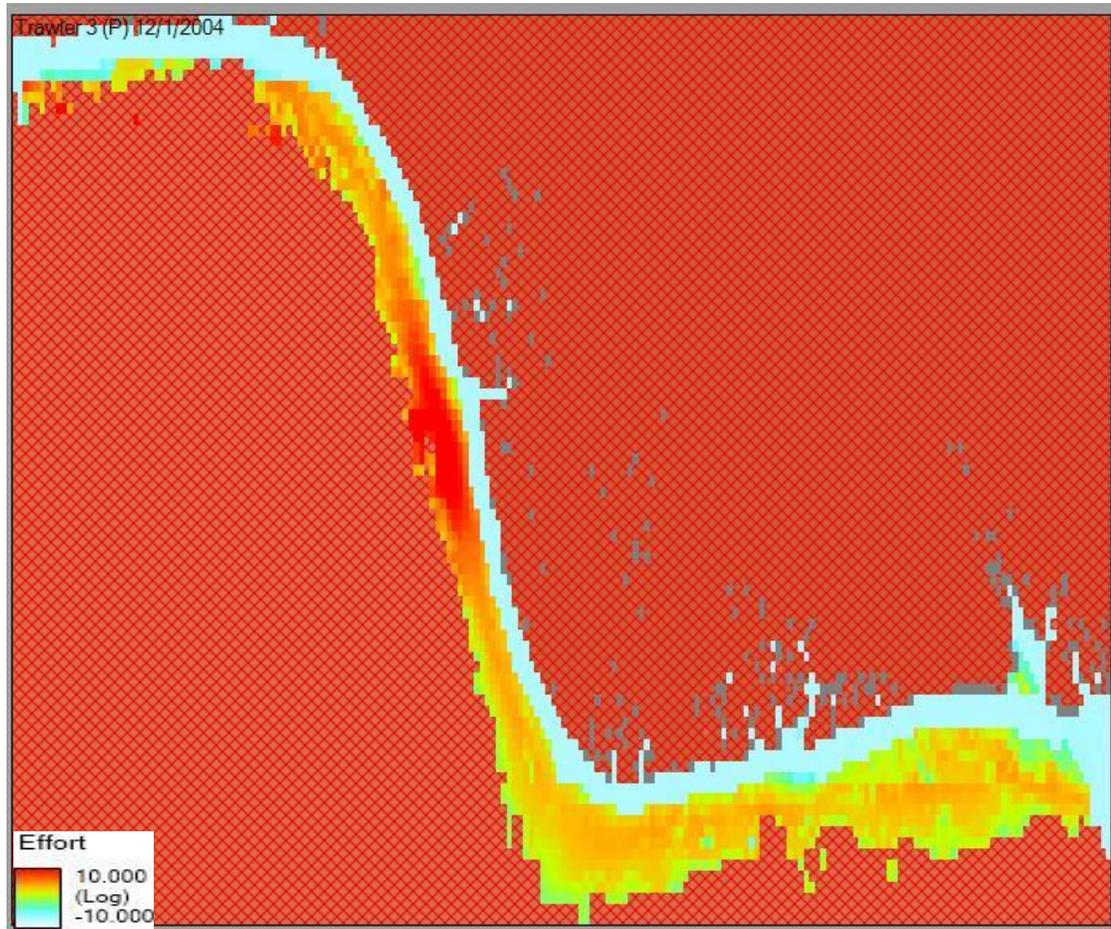


Figure 4.6 Model simulated fishing effort for pelagic trawler fisheries in NCW for 2004. Red hatched areas of the map are excluded cells.

Catch Rates

In the 20 years between 1985 and 2004, fisheries catch rates in NCW generally declined except for pelagic trawlers that were catching slightly more in 2004 than they did

in 1985 (Figure 4.7). Having a 5 NM spatial closure from the shoreline seawards made little impact on catch rates for all fleets, but catch rates in 2000 were approximately halved for benthic trawlers and artisanal fishermen when compared to the 1985 catch rates.

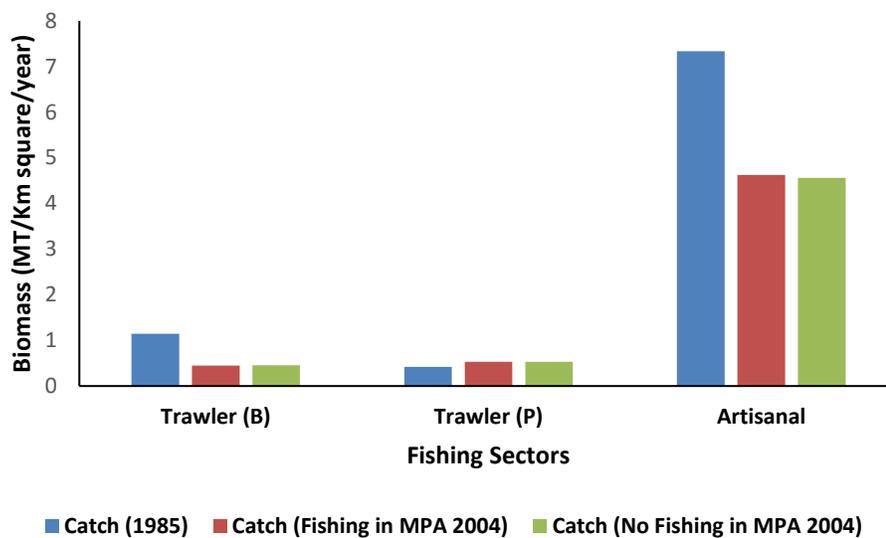


Figure 4.7 Catch rates for fisheries sectors depicting rates in 1985, and for two spatial management scenarios in 2004 that include fishing and no fishing within a MPA placed in the first 5 NM of the Nigerian coast.

Biomass

Biomass for most functional groups decreased in NCW regardless of what spatial management policy was put in place, though certain species had biomass estimate increase with increased fishing effort (Table 4.3). Biomass for flatfishes, rays, and other shrimp species increased along with biomass for miscellaneous species. All other groups had diminishing biomasses with some very significant reductions in biomass for reef fishes,

juvenile pink shrimp, large demersal, large pelagic, croakers, small demersal, and small pelagic.

Table 4.3 Comparison of biomass for functional groups between 1985 and 2004 under different spatial management scenarios simulated in Ecospace – one in which bottom trawling is banned in the first 5 NM of Nigerian coastal, and the other where bottom trawling is allowed.

<i>Group Name</i>	<i>Biomass Trajectory</i>		
	<i>Biomass (w/o MPA)</i>	<i>Biomass (with MPA)</i>	<i>Compared to 1985</i>
<i>Flatfishes</i>	65.96%	65.99%	Increased
<i>Rays</i>	2.05%	4.06 %	Increased
<i>Other shrimp</i>	5.85%	5.85%	Increased
<i>Miscellaneous species</i>	12.86%	12.43%	Increased
<i>Reef fishes</i>	-79.74%	-80.16%	Declined
<i>Juvenile Pink Shrimp</i>	-29.68%	-27.75%	Declined
<i>Large demersal</i>	-81.42%	-16.19%	Declined
<i>Large pelagic</i>	-91.47%	-91.58%	Declined
<i>Croakers</i>	-76.70%	-77.92%	Declined
<i>Small demersal</i>	-61.46%	-62.54%	Declined
<i>Small pelagic</i>	-8.43%	-8.01%	Declined

The contribution to biomass dynamics of having an MPA in place was negligible for all fisheries in NCW except for large demersal fish that had a 65.23% higher biomass when the MPA restriction was in place versus when this was not enforced (Figure 4.9). All other functional groups had $< \pm 5\%$ difference in biomass due to MPA influence.

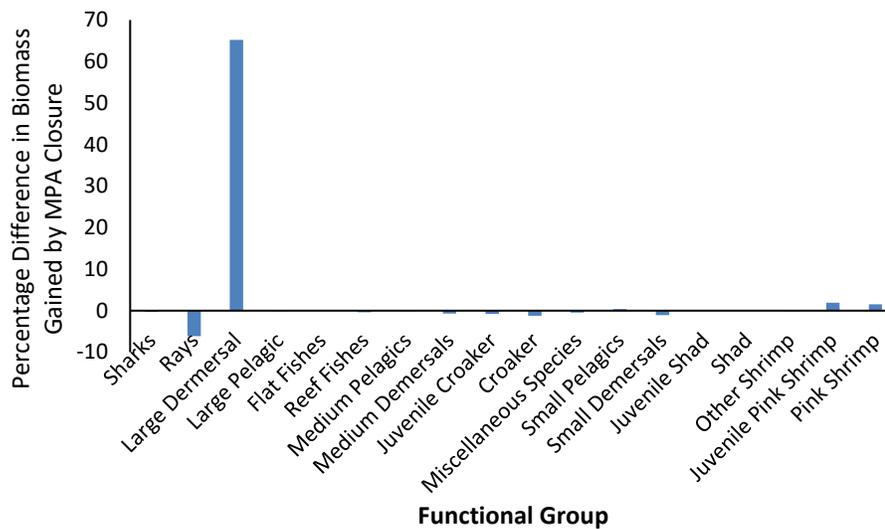


Figure 4.9 Percentage gain or loss in biomass for function groups estimated by subtracting biomass when no MPA is enforced from when one is established for biomass prediction for fish and invertebrates in NCW in 2004.

Discussion

By developing the NCW Ecospace model, it is now possible to verify impacts of industrial shrimping in the first 5 NM that is closed to industrial fishing in NCW (up to 18-meter depth) and to address concerns about impacts for fisheries in NCW (see Ogbona

2001). Potential habitat destruction that accompany encroachment of shrimping boats into the first 5 NM of the Nigerian coast is not modeled in this research, nor conflicts that may arise due to spatial overlap in fishing area within the modeled area. Model results showed that during the first 20 years (1985–2004) of intensive industrial shrimping in NCW, fisheries expanded, catch rates increased slightly for pelagic trawlers while it decreased for artisanal fisheries and benthic trawlers, and biomass for several functional groups was depleted.

Research expectations that redistribution of fishing effort by benthic trawlers from less than 18-meter depth to 50-meter depth will alter spatial characteristics of fisheries in NCW was not supported by modeling results. Research results showed that biomass, catch rates, and spatial patterns of fishing were similar for most modeled parameters in 2004 regardless of spatial policy for managing the inshore fisheries, but overall biomass in the continental shelf declined compared to 1985, perhaps due to greater amount of fishing on coastal fisheries resources.

One unexpected result is the recovery of *P. notialis* biomass predicted by model regardless of the spatial management policy adopted. This might have resulted from ecological resilience due to the biology of shrimps as lower trophic level species with quick turnover. Another important factor is that, as pink shrimp biomass declined in the fishery, other shrimp species such as the brown shrimp *P. monodon* were added as target species. Because of this, shrimpers were fishing in shallower waters which might have led to release

of fishing pressure on pink shrimp biomass that were mainly targeted in deeper waters (50-m depth). This could have resulted in pink shrimp biomass recovery and the continued contribution of pink shrimp biomass to landings in the shrimp fishery for the years following the depletion in biomass that occurred from the late 1990s to early 2000s.

The decrease in catch rates for artisanal fisheries may have resulted from uncontrolled growth in fishing effort. This might have occurred because of the lax fishing regulation and policies for the artisanal fisheries sub-sector in NCW (Asiedu & Nunoo 2015; Lewerenz & Vorrath 2015; Kaitikiro 2012). During the last four decades, artisanal fisheries have become increasingly mechanized; sustained by government subsidies from the 1970s into the 1990s, which probably contributed to overcapitalization and overfishing the fisheries resources in NCW (Moses 2000; Nwafili & Gao 2007).

Although fishing effort is heterogeneously spread across the seascape, model predictions show fishing was mainly concentrated in deeper waters for all three fishing subsectors. Fisheries are moving deeper and seawards, including artisanal fisheries, which is a very important sub-sector that produced > 50% of landings for all fishing subsectors.

Artisanal fisheries have traditionally fished in shallower waters (< 18-m) than industrial fishing fleets (> 18-m), and though the Ecospace model in its current configuration didn't restrict operation area for artisanal fleet, artisanal fisheries that have been previously reported as operating in shallower waters (Ogbona 2001; Amire 2003),

were predicted by the model to concentrate fishing effort in deeper waters than was expected. Because of the small size of most artisanal fishing canoes, artisanal fisheries were expected to limit exploitation to the shallower areas of the coast and to be fishing nearer to the home ports—particularly in inclement weather (Caddy and Carossi 1999)—but by fishing in deeper waters that were further off from shore, the model showed that artisanal fisheries fishing effort was concentrated in deeper waters, perhaps because this is where fish targeted by fishermen are spatially located in NCW.

For artisanal fishermen to operate in waters deeper than 18 meters, fishermen must have vessels that can access these deeper water-depths. During the last 40 years, the rate of motorization of canoe boats operating in NCW has grown due to government intervention programs, such as the Artisanal Inshore Fisheries Development Project and the National Accelerated Fish Production Project (NAFPP), whose objective were to provide fishing inputs, boats and canoe mechanization (Nwafili & Gao 2007). Such projects have increased the number of sea-worthy boats and the reach of artisanal fishermen from within the 5 NM (from shore) they traditionally fished, into deeper parts of the continental shelf where they could compete with industrial fleets for deeper water fish resources.

The higher intensity of effort as observed in distribution maps for industrial pelagic trawls may be the result of the boom in small pelagic fishes, such as sardinella with biomass landings greater than 100,000 MT in year 2000. Since sardinella fisheries in Gulf of Guinea

fluctuate very widely in response to environmental conditions (Amire 2003; FAO FTP 443 2003; Nwafili & Gao 2007), the favorable environmental conditions in the early 2000 resulted not only in recovery of small pelagic fisheries, but intensification of fisheries that target these pelagic resources.

Intense fishing accompanies population growth (Stewart et al. 2010). Between 1985 and 2004 the population of Nigeria grew 62% from 84 million to 136 million, and landings for fisheries products increased during the same period by 68%, and between 1991 and 2000, the number of fishermen increased by 152% (Nwafili & Gao 2007). For large and growing coastal artisanal fisheries, spatial expansion of operation areas is inevitable since fisheries tend to progressively exploit wider envelopes of space through time due to depletion with proximity effects (Caddy & Carossi 1999). The elimination of shallower species from landings data may have occurred because resources located in deeper areas of the continental shelf are less likely to be exploited until nearshore resources located in shallower waters have already been overfished (Caddy & Carocci 1999; Aburto et al. 2009).

Ecospace results corroborate the analysis of fisheries data in chapter II that suggested fisheries are expanding in NCW because of the increasing FIB index. Bathal and Pauly (2008) noted that when the FIB Index increases over time with exploitation, fisheries are likely expanding geographically. Such expansion in fishing area may have implications for the spatial management of coastal resources in Nigeria, which requires that trawlers

only operate their fishing nets outside the 5 NM non-trawl area. The Ecospace model however, predicted that all three fishing subsectors concentrated fishing effort outside this restricted area and the benefit of maintaining this 5 NM non-trawl zone is in question; although, the model predicted that large demersal fishes, such as African croakers, benefited from closure of the first 5 NM to trawling.

Only large demersal fishes benefited from closure of the first 5NM to benthic trawl fishing. There was approximately 65% difference in biomass due to the protection offered by limiting trawling only outside the non-trawl zone. The biomass of large demersal species, when compared to 1985 only showed 20% decline in the MPA scenario versus an 80% decline in the trawl everywhere scenario (Fig. 4.9).

Concentration of fishing effort in deeper waters may partly explain why closure of the first 5NM and the shallower areas of the continental shelf to fishing had little effect on most functional groups when compared to opening it up to fishing in 2000. Fishermen will only fish in deeper waters if fishing grounds located in deeper areas of the continental shelf contain more pristine habitats, better catch rates, and better returns that compensate for effort expended to reach these deeper areas. The Ecospace results showing changes in spatial distribution of effort suggests this happened in NCW; however, these model results are currently only policy screening options and model outputs need verification with field data (Walters et al. 2008).

By evaluating the impacts of trawling in shallower waters of the Nigerian coast, it is possible to visualize dynamics in community structure because of alternative spatial management policies.

First, increase in the biomass of large demersal species because of closure of the MPA may result in a reduction in the biomass for their prey species, such as small (threadfins) and medium-sized demersal fishes (drums/croakers) that are important commercial species. Ecospace predictions show only small declines in biomass for these prey species (croakers, rays, medium demersal and small demersal) when large demersal biomass decreased in the fishing in MPA scenario (Fig. 4.9).

The minimal declines in biomass of large demersal prey species regardless of spatial policy examined may have resulted mainly because of the small contributions in biomass that prey species made to the diet of large demersal species. Although croakers contributed more than 50% to the diet of large demersal species, the biomass of croakers changed by a small percentage regardless of the size of the biomass of large demersal groups. This result occurred perhaps because large demersal biomass is small relative to the size of biomass of all their prey and they also feed on many different benthic groups. This spread predation pressure on several prey items, so that the release in predation pressure when their biomass decline by ~80% or ~20% was not significant enough to cause major changes in biomass response for their prey.

Second, rebuilding the biomass of large benthic species can potentially increase the biomass of species that forage on them, such as elasmobranchs, although no real differences were observed for both sharks and rays in NCW when an MPAs restricted benthic trawlers to areas outside the MPA. The lack of commensurate change in elasmobranch biomass for NCW when large demersal biomass changed drastically may be related to factors other than trophic interactions—especially fishing. It is also important to note that apex predators, such as sharks, are long-lived and often late-maturing species whose response time to biomass difference of their prey may be much longer than the four-years lag between impacts in 2000 and model output for biomass in 2004. Perhaps if longer time-scales of decades were considered, the model may predict positive feedback between large demersal biomass dynamics and the biomass of predators of large demersal species.

Fishing effort in NCW more than doubled in the last 30 years, but fish landings only increased about 70%—a result that is disproportionate to the amount of fishing effort exacted in NCW. This may be a sign of overexploitation, evidenced by average production per capita, which declined for artisanal fisheries from 0.64 MT in the 1980s to 0.36 MT in year 2000 (Nwafili & Gao 2007). In view of this, a reduction in the amount of fishing effort may be more beneficial to fisheries in NCW than a blanket closure of the first 5 NM to industrial fisheries. Such an approach to fisheries managing the fisheries in NCW should reduce impacts in the long run and maintain sustainable fisheries. This approach should also consider the possibility that nearshore waters remain important nursery grounds for

commercial fish stocks, so that adequate research to map out these sensitive habitats must be done and measures taken to protect these valuable habitats.

Given the ecological importance of nearshore waters, it is still a good idea to maintain a 5 NM non-trawl area to protect sensitive nursery habitats from damage by trawlers. Although this aspect of possible habitat destruction was not explicitly modeled in this study, it is a good idea to consider such a regulatory tactic for sustainable fisheries in a country with very high fishing effort like Nigeria. Moreover, this proposed protection can be a temporary approach to management until better surveys are carried out that provide comprehensive information about nursery locations and rearing areas for ecologically and economically important species and functional groups in NCW.

Spatial management of fisheries resources is now possible with predictive models that use information from various sources within frameworks that integrate data from multiple sources for analysis. The increasing availability of data, significant progress in model algorithms, and Geographic Information Systems (GIS), makes it possible for scientists and resource managers to use new approaches for spatial management of ecological systems with open source software such as EwE (Austin 2007).

The NCW EwE model was developed using best estimates available from databases and literature for model configuration, calibration and simulations to explore spatial impacts of fishing the NCW between 1985 and 2004. Boating distance wasn't explicitly

factored into the model. In addition, a valid process that may require further refinement was used in model formulation to open and close the 5 NM coastal MPA by splitting fishing effort into active and inactive states for two benthic trawler fleets that fished in sequence. This simple approach provided a starting point for enquiry that can be made more precise as the NCW EwE model is further developed. In addition, habitat-based foraging response curves used for biomass distribution in Ecospace are estimations based on currently available ecology and depth range data with slight adjustments. These may need to be validated with field data for the NCW Ecospace model to be used as a predictive and management tool.

Some scientists advocate the use of MPAs as a tool for coastal management of marine species because of their potential benefits to both fisheries and for conservation (Roberts et al. 2001, Pitchford et al. 2007), but others resist such an idea, arguing for more critical analysis of an individual MPA's usefulness before selective implementation (Sale et al. 2005, Kaiser 2005). The Nigerian situation suggests the later argument is a reasonable and safer way to go. In NCW, the conservation benefits of a 5 NM MPA may be obvious (protection of habitats and nursery areas), but the conflict reduction and fisheries benefits are harder to prove based on current information available for modeling in EwE. Fisheries benefits need to be evaluated case by case before resources and time are put into placement of reserves in coastal environments if fisheries are a major concern. Marine protected areas are a promising tool for coastal management, but knowledge gaps exist and must be filled

through scientific enquiry before they are implemented as management tools (Sale et al. 2005).

The NCW EwE model was used to predict catch rates, fish distribution, and fishing effort distribution. The models in its current state provides a baseline upon which future refinement and further development will be made. In NCW, fishing is occurring in deeper waters, perhaps because these areas contain more pristine fishing grounds with higher levels of biomass. It could also signal depletion of fisheries resources in nearer shore waters. Furthermore, an increasing number of fishermen have access to deeper areas of the continental shelf beyond the 18-meter isobath in the coastal waters of Nigeria, which implies these deeper areas will be subjected to high levels of fishing effort.

Some trawlers were reported to encroach into nearshore waters shallower than 18-meter depth in search of shrimp species that inhabit these shallower areas of the coast. Despite these encroachment, most fishing effort is predicted to occur in deeper areas of the coast. More research needs to be done and field data collected to verify fished areas along the Nigerian coast. It is important to develop programs that focus on data collection and analysis to understand impacts of fishing the coastal waters of Nigeria, and strengthen monitoring and surveillance to protect valuable oceanic living resources and ensure sustainable fisheries in Nigeria.

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5. SUMMARY AND CONCLUSIONS

Nigerian coastal fisheries have been declining because of overfishing of living marine resources, overcapitalization/rapid expansion of coastal fisheries, and a lack of adequate regulation, enforcement, and management (Kaitikiro & Macusi 2012; Asiedu & Nunoo 2015; Lewerenz & Vorrath 2015).

Between 1985 and 2000, impacts of fisheries increased in the inshore areas of NCW mainly due to increasing fishing effort from both industrial trawl shrimping and artisanal fisheries (Moses 2000; Ogbona 2001; Amire 2003; Nwafili & Gao 2007). These impacts were investigated in chapter II using measures that reflect fishing impacts such as the MTLI, FIB index, and MML based on data from the Sea Around Us Project (www.seaaroundusproject.org). Chapter III focused on impacts of fishing using an Ecopath food web model, developed for NCW by investigating measures such as ecosystem productivity, ecosystem structure, energetic flows, and mixed trophic impacts. In Chapter IV the impact of spatial redistribution of fishing effort was analyzed in Ecospace, with spatial maps of fishing effort constructed for two fishing scenarios that evaluate impacts of alternative spatial management policies in the benthic trawl fisheries of NCW.

Measures that reflect impacts of fishing in NCW such as MTLI and MML declined, particularly during the 1980s, and geographical expansion of fisheries accompanied these declines based on evidence from FIB index (and spatial simulations in Ecospace). These

impacts all appear to be associated with the increase in fishing effort in the inshore areas of the coast, particularly from the 1980s onwards when both the number of artisanal fishermen and number of trawlers operating in the industrial fisheries increased rapidly and more than doubled from ~ 300,000 to ~700,000 (artisanal) / 40 to 200 (trawlers) by the early 2000s due to higher demand for fisheries products locally and internationally (Nwafili and Gao 2007; Ogbona 2001; Amire 2003).

The decline in MML may be associated with declines in MTLI because lower trophic level species tend to be smaller in size (Pauly et al. 1998), thus as MTL decreased due to depletion of higher-TL species, lower-TL smaller fish replaced these in landings. Although the overall trend in fishing data was a decline in MTL and MML, at the end of the time series, a slight increase for both MTL and MML occurred perhaps because of declining shrimp stocks or due to expansion in the fisheries that opened up newer fishing grounds with higher TL species.

Fishing individual fish stocks might have contributed to attenuation of MML because fishermen extract larger and fast-growing fish first, which may result in plastic and perhaps evolutionary responses that yield genetically small-sized-fishes (Swain et al. 2007) as was observed in fishing landings data over the 60-year period for which data on MML are available for NCW (www.searoundusproject.org). Similarly, the increase in FIB index is most likely associated with the geographical expansion of fishing into deeper

waters (chapter III). Because fishermen are increasingly fishing in deeper water, the impact of fishing is extending from nearshore into deeper areas of the continental shelf.

Network analysis in Ecopath revealed increased ecological impacts evidenced by increased homogenization, less energy flows, reduced production and shorter cycle/higher recycling of organic matter for NCW from 1985 to 2000, which are signs of ecological degradation in the Nigerian coastal fisheries ecosystem (Libralato et al. 2002; Coll et al. 2008). Two Ecopath models developed for 1985 and 2000 showed that the coastal food web degraded over the time investigated, with ecological indicators revealing higher impacts of fishing the coastal food web in 2000 than in 1985.

Spatial analysis in Ecospace verified impacts of redistribution of fishing effort from deeper into shallower waters using a MPA to restrict fishing outside of the first 5 NM of the coast for one of two spatial scenarios. The analysis showed that fishing effort was mostly concentrated outside of the MPA at the end of the simulation (2004), and thus the spatial strategy in NCW aimed at management of coastal fisheries by preventing trawling in the first 5 NM (Ogbona 2001) was ineffective for most species and functional groups modeled. The only group that benefited in a meaningful way from restricting fishing outside the first 5 NM throughout the fishing period was the large demersal group that includes species such as African croakers, which are of high economic and commercial importance to fisheries across the West African region (www.fishabse.org).

This result illustrates the importance of ensuring protection for large piscivorous benthic species in NCW. Modeling outputs suggested biomass of these large benthic species have depleted by more than 80% of their previous biomass in the 1980s. Model outputs also suggest that rebuilding the biomass of large benthic predators to 1985 levels will have little impact on the biomass of associated species. This is perhaps because of model diet contribution for large demersal species compared to that of their main predators (elasmobranchs) is small, and the contribution of other functional groups (medium demersal, small demersal and the like) to the diet of large demersal species is small, except for medium-sized croakers such as cassava croaker.

Catch rates were reduced in artisanal fisheries but increased slightly for industrial pelagic fisheries due to environmentally mediated increase in biomass of small pelagic species (Nwafili & Gao 2007; Amire 2003) in 2000 compared to 1985. In 1985, fish landings statistics showed zero contribution of sardinella to the fisheries. The decrease in catch rates might have occurred because for most functional groups, biomass declined between 1985 and 2000. This decrease in catch rates was observed by Nwafili & Gao (2007) who noted a decline in per-capita landings for artisanal fishermen from 0.64 MT in the 1980s to 0.36 MT in 2000.

The allocation of fishing effort in increasingly deeper waters suggests that shallow-water resources have been largely depleted, possibly in recent decades (the history of coastal fishing in west Africa is more than 200 years, Aburto et al. (2009)), and thus

fishermen concentrate fishing effort in increasingly deeper waters. Access to these deeper waters by artisanal fishermen was made possible by government subsidies that increased the number of canoe operators becoming mechanized (Nwafili & Gao 2007). Mechanization and increased access imply an increasingly broader spectrum of impacts by artisanal fisheries in NCW in the decades that ensue (Caddy & Carocci 1999).

There is already evidence of multiple impacts of fisheries in NCW (chapters II, III, and IV), and these impacts will likely increase in severity. Factors that predispose the NCW ecosystem to the impacts assessed in this study need to be addressed by engaging stakeholders, and provide alternatives to the use of coastal fish resources (EJF 2001).

With a fast and rapidly growing population of people that rely on coastal resources for income and sustenance, fisheries in NCW will continue to exact high amounts of pressure on living marine resources. It is imperative to continue to research methods for managing and conserve these valuable resources.

Moreover, fishing impact is only one of several impacts in NCW, and because impacts of fisheries occur in addition to other impacts, joint impacts must be considered in future research. Of importance are interactions among fishing impacts and other impacts, such as hydrocarbon pollution from oil industries in the Niger Delta, and eutrophication from municipal wastes originating from coastal cities. These other anthropogenic impacts may interact with fisheries to exacerbate the effects of fishing, making it more difficult for

the NCW ecosystem to recover from the impacts of intense fishing that occurred in the last three decades (Roberts 1995).

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APPENDIX

R codes for surplus production were adapted from Saya de malha and Nazareth Banks and modified to estimate biomass of modeled groups in R 3.2.2:

```
# Y= Yield(catch) in tons I= abundance index (cpue)kg

#SAYA Catch and Effort data 1989-2004 DYNAMIC BIOMASS MODEL

yrs <- 1989:2004

Y <- c( 2177, 1410, 1782, 2825, 3173, 3142, 2957, 2283, 1798, 2054, 2107, 2099,
1283, 2090, 2354, 1689)

I <- c( 74.3, 73.0, 88.0, 67.7, 69.1, 66.6, 67.0, 57.8, 71.8, 75.9, 70.1, 77.8, 124.1,
83.3, 80.1, 71.2)

#NAZARETH catch and effort data DYNAMIC BIOMASS MODEL 1989-2004

yrs <- 1989:2004

Y
<- c(
837,914,793,952,1358,1494,1533,1253,1720,1086,1121,1080,1366,918,468,855)

I
<- c(
75.7,78.5,81.3,78.2,66.1,66.5,64.3,52.5,66.1,81.4,76.2,90.5,99.2,93.3,72.8,84.2)

# FORMULA==  $B_{y+1} = B_y + r B_y(1 - B_y/K) - Y_y$ 

#  $Y_y$ =yield/catch

# Initial parameters of starting biomass  $B_0$ , Carrying capacity  $K$  and the rate of pop.
growth  $r$ 

#  $q$ = coefficient catchability

# There are four parameters to be estimated  $K$ ,  $B_0$ ,  $r$  and  $q$ 
```

#It is not advisable to estimate all- first estimate K, B0 and r with fixed q, then estimate r and q, then all

```
B0<-2*mean(Y) # biomass greater than catch
```

```
K<-B0*1.3 # K>B0- carrying capacity
```

```
r<-1 # rate of population growth
```

```
q<-mean(I)/B0 # as I=qB
```

```
input<-c(K,B0,r)
```

```
B<-B0
```

```
par(mfrow=c(3,3))
```

```
###
```

```
ssefn<-function(input){
```

```
  K<-input[1]
```

```
  B0<-input[2]
```

```
  r<-input[3]
```

```
  B<-B0
```

```
  Yvec<-NULL
```

```
  Bvec<-NULL
```

```
  lhat<-NULL
```

```
  yrs<-1:length(Y)
```

```
  for (y in yrs){
```

```
    SY<-r*B*(1-B/K)
```

```
    Bvec<-c(Bvec,B)
```

```

Ihat<-c(Ihat,q*B)

B<-B+SY-Y[y]

B<-ifelse(B<0,0,B)

}

SSE<-sum((I-Ihat)^2)

return(SSE)

}

#### to optimise

estA<-nlm(ssefn,input,typsize=input,iterlim=1000) # nlm- nonlinear minimization

estA<-nlm(ssefn,estA$est,typsize=input,iterlim=1000) # using the result of the first
estimate we estimate again

estA

#### estimate r and q

K <- estA$est[1]

B0 <- estA$est[2]

r <- estA$est[3]

q <- mean(I)/B0

input2 <- c(r,q) # now we estimate the two parameters

B <- B0

ssefn2<-function(input){

r<-input[1]

q<-input[2]

```

```
B<-B0
```

```
Yvec<-NULL
```

BIOGRAPHY

Tunde Adebola is a scientist with a background in fisheries ecology. In the spring of 2013 Tunde enrolled in the department of Environmental Science and Public Policy at George Mason University with the aim of developing a coastwide food web model for his native Nigeria. This aim resulted in the development of the first ecosystem model for Nigerian coastal waters, the presentation of his research at science workshops, and completion of a doctoral degree in Environmental Science and Public Policy at George Mason University in August 2017. Tunde aims to teach fisheries and coastal ecology at the university level, and to also make science /educational documentaries to improve ecological understanding and the value of protecting living marine resources for sustainable utilization. He lives in Beltsville MD with his wife Adefolake, and three children Elizabeth, Gabriel and Michael.