Spatial simulation of redistribution of fishing effort in Nigerian coastal waters using Ecospace

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Citation: Adebola, T., and K. de Mutsert. 2019. Spatial simulation of redistribution of fishing effort in Nigerian coastal waters using Ecospace. Ecosphere 10(3):e02623. 10.1002/ecs2.2623

Abstract. In the late 1990s, depletion of the target species *Penaeus notialis* (Pink Shrimp) in deeper waters (50 m) of the Nigerian coast resulted in a change of target species from *P. notialis* (Pink Shrimp) to shallower water species such as *Penaeus monodon* (Brown Shrimp). This study investigates the hypothesis that ecosystem impacts increased as industrial fleets increased fishing in shallower areas of the Nigerian coast by comparing the state of the ecosystem before and 20 yr after commercial shrimping commenced in Nigerian coastal waters (NCW). Two fishing scenarios were developed in Ecospace, the spatial modeling module of Ecopath with Ecosim software (Ecopath with Ecosim is a mass balanced trophic model that accounts for fishing impacts on food webs), with one having trawlers fishing everywhere beginning at the turn of the century (year 2000) and the other with no trawling in the first 5 nautical miles off the Nigerian coast through the entire period of model simulation (1985–2004). Modeling results showed increases in catch for some fisheries during the study period. In addition, estimated biomass for some functional groups increased especially for Small Pelagic fishes along with Rays, Reef fishes, Large Pelagics, and shallow water shrimps. All other exploited species in our modeling scenarios were estimated to have declining biomasses. Our expectation that redistribution of fishing effort in NCW will increase negative impacts of fishing the nearshore ecosystem was not supported by model results. This counterintuitive result may be because fishing effort on average was mostly distributed in the deeper areas of the inshore waters. Although species such as Reef fishes appear to benefit from closure of the first 5 NM to fishing, the benefits appear to be negligible. We present the first ecosystem model developed for NCW, and our research contributes to fisheries ecology by furthering understanding of tropical coastal food webs and ecological response to fishing, especially in highly perturbed ecosystems like NCW.

Key words: coastal ecosystems; ecosystem fisheries management; marine protected area; redistribution of fishing effort.

Received 20 November 2018; accepted 14 January 2019. Corresponding Editor: Sean P. Powers.

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INTRODUCTION

Impacts of fisheries in coastal ecosystems ought to be investigated from spatial perspectives since traditional assessment models may sometimes limit our ability to investigate and understand important ecological processes (Walters et al. 1999). There is a spatial component to fisheries, and the allocation of fishing effort is influenced by the spatial distribution of fish resources (Aburto et al. 2009). As an example, European fisheries expanded into the global oceans after many coastal inshore fisheries in the EU were depleted (Watson et al. 2011). For proper assessment of fishing impacts, the spatial component of fisheries should be assessed along with other biological and temporal information (Jennings et al. 1999).

In this study, we investigate whether spatial redistribution of industrial fishing effort from
waters up to 50 m deep into waters <18 m deep by shrimp trawlers operating in Nigerian coastal waters (NCW) between 1985 and 2004 increased impacts of fishing on nearshore waters that serve as important habitat and nursery areas in NCW.

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 nautical miles (NM) non-trawling zone which places restrictions on trawling in sea water area covering 7898.78 km$^2$ of the Nigerian continental shelf essentially to protect the nursery ground from indiscriminate fishing. It is also to protect the artisanal fishers who operate within this zone, as well as to reduce conflict between them and trawler operators.”

The inshore fishing area in NCW covers 36,472 km$^2$ and is divided spatially into two distinct sections with the first 5 NM (waters up to 18 m deep) from the shoreline reserved for artisanal fishers, but both artisanal and industrial fisheries can operate from the 18- to 40-m contours (Amire 2003). Most artisanal fishers target a variety of taxa, including sardinella, Bonga Shad, Croakers, Tonguefishes, Catfishes, and a variety of elasmobranchs. Industrial benthic fish trawlers concentrated on exploiting shrimp resources in NCW (1985–2004).

*Peneus notialis* (Pink Shrimps) accounted for more than 90% of decapod landings and the fisheries operated in deeper inshore areas (up to 50 m deep; Ajayi and Adetayo 1982). Shrimping grounds stretch from 5°0’E to 8°30’E, extending up to 80 m depths from the shoreline (Ajayi and Adetayo 1982), but overcapitalization of the shrimp fisheries during the 1990s led to depletion of the main target species, Pink Shrimp (Ogbona 2001).

After overfishing and depleting of the Pink Shrimp stock in the late 1990s, some shrimp trawlers were encroaching into shallower nearshore waters in search of alternative shrimp species (Guinea Shrimp, *Parapanaeus atlantica*; Brown Shrimp, *Peneus monodon*; and Estuarine Shrimp, *Nematopalaemon hastatus*) that occupy shallower nearshore waters in NCW than Pink Shrimps. These shrimpers ignored the spatial regulations designed to separate the two major fishing subsectors and were able to maintain undiminished shrimp catches even after the depletion of the Pink Shrimp fishery, by targeting shallower water shrimp species (Ogbona 2001).

The main species targeted was the exotic Brown Shrimp (*P. monodon*), a species that occupies spatially distinct oceanic habitats than the depleted *P. notialis* stocks previously targeted in deeper waters.

The redistribution of industrial fishing effort that occurred because of this fishing tactic may mean that fishing effort from the two fishing subsectors became concentrated in time and space. This occurred 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, by deploying trawl nets aimed at targeting shallow water shrimps, industrial shrimping trawlers may increase bycatch of artisanal target species and juveniles of other commercial species that use this area as nursery grounds.

This might have resulted in growth overfishing if juveniles were caught in nursery areas before they grow, migrate into deeper waters, and recruit into the coastal industrial fisheries (Ogbona 2001). Such approach to fishing will, in the end, limit overall fisheries production for coastal fisheries in Nigeria. The ecological and economic consequences of this fishing tactic that violated fishing regulations in the late 1990s and early 2000s have yet to be investigated in a spatial context.

From a management standpoint, it is desirable to minimize conflicts among fishers, which was one of the reasons the spatial regulation was put in place. Separating fishing areas should ensure only minimal overlap in operation areas for the main fishing subsectors (artisanal and industrial fisheries) in NCW.

We aim to evaluate potential impacts of spatial redistribution of fishing effort from deeper inshore waters into nearshore waters in NCW that occurred from the late 1990s to the early 2000s. One approach to quantifying impacts is to compare alternative policies for use and management/conservation of oceanic resources (Halpern et al. 2008). Here, we compare two alternative fishing policies to better understand ecosystem impacts of fisheries in a spatial context.

We use an ecosystem model developed in Ecopath with Ecosim (EwE) 6.5. 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. Impacts were estimated using EcoSpace, the spatial module of the EwE modeling tool (www.ecopath.org), which we used to help gain understanding of how biomass, catch rates, and spatial distribution of fishing effort changed under alternative spatial management scenarios.

Integrating spatial dynamics and trophic interactions in an ecosystem food web model should provide valuable insights into coastal ecosystem processes within the inshore fishing area of NCW (Romagnoni et al. 2015). Furthermore, several developing countries have spatial management policies in their inshore fisheries like the observed 5NM non-trawling zone in NCW (Bailey et al. 2018). Fisheries with such similar spatial configurations may benefit from information provided in our research.

We hypothesize that displacement of fishing effort by shrimp trawlers from deeper inshore waters 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 fisheries catch, along with changes in spatial distribution of fishing effort.

**Methods**

**Study area**

Nigeria’s inshore fishing area (Fig. 1) covers ~36,000 km², but only 30% of this area is trawleable. The western portion of the continental shelf extends only 15 km off Lagos, whereas the shallow part of the continental shelf reaches 80 km around Efiat (Cross River) in the east. The narrowness of the continental shelf limits fish abundance and areas where trawlers can operate (Amire 2003).

**Model calibration in Ecopath and Ecosim**

We used the 1985 NCW EwE model from Adebola and de Mutsert (2019) (more details about the model and the data used in parameterizing it can be found in the Appendix S1). Estimates of Pink Shrimp biomass and fisheries catch data (reconstruction data from Sea Around Us) were used to calibrate the model dynamically to evaluate predictive capability of the model in Ecosim where biomass dynamics are expressed as follows:

\[
\frac{d N_i}{dt} = \gamma_i \sum_{j=1}^{n} Q_{ij}(B_j(t), B_i(t)) - \sum_{j=1}^{n} Q_{ji}(B_i(t), B_j(t)) + I_i - (M_0_i(t) + F_i(t) + e_i)B_i(t)
\]

(1)

where \(B_i(t)\) is the biomass of \(i\) at time \(t\), \(\gamma_i\) is the growth efficiency, \(I_i\) is the immigration rate; \(M_0_i\) is the natural mortality, \(F_i(t)\) is the fishing mortality, \(e_i\) is the emigration rate, \(Q_{ij}\) represents the consumption due to predation on \(i\) by predator \(j\), and \(Q_{ji}\) represent the consumption due to predation on group \(j\) by predator \(i\) (Christensen and Walters 2004).

Functional groups were modeled in two states—as either vulnerable or invulnerable to predation based 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 2007):

\[
\frac{d (N_i - V_{ij})}{dt} = -v_{ij}(N_i - V_{ij}) + v'_{ij} - V_{ij}
\]

(2)

where vulnerable prey dynamics were 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 (SS) formula:

\[
SS = \sum_{i}^{nts} \left( \sum_{i}^{nob} w_i \log \left( \frac{o_{ij}}{p_{ij}} \right)^2 \right)
\]

(3)

where SS is the sum of squares, \(nts\) is the number of time series loaded, \(nob\) is the number of observations in time series \(i\), and \(o_{ij}\) is the observed value in time series \(i\) at time step \(t\) (DeMutsert et al. 2016).

In the anomaly search routine, temperature time series from the NOAA COPEPODA database (https://www.st.nmfs.noaa.gov/copepod/) was utilized as a forcing function to fit the
model to data and further reduce the sum of square errors. Reasonable fits were obtained for most groups in the model based on Eq. 3.

**Ecospace setup**

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 and Zimmermann 2000, Austin 2007, Elith and Leathwick 2009). After calibrating the model in Ecosim and determining the model area, the modeling data were promoted into Ecospace along with a bathymetric map that served as a base map of study area.

Habitat capacity for each functional group was then determined in Ecospace by using the new habitat capacity model. Ecospace considers habitat quality using a continuous habitat suitability factor where the area a species can feed in each cell is determined by its functional response to environmental factors. Here, foraging area can be determined by multiple physical, oceanographic, and environmental factors, such as depth, oxygen, and temperature. The spatial distribution of species is then 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 ranges for environmental parameters for each modeled group (Christensen et al. 2014), we assumed fish distribution reflects habitat capacity, and loaded fish distribution maps as habitat capacity maps, but used bathymetric information as a layer to ensure fish distribution stayed reasonable over time. To this end, ASCII files of distribution maps for functional groups were imported into Ecospace and used along with bathymetric preferences for each modeled group to determine spatial distribution of biomass in Ecospace. The distribution maps used 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

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Fig. 1. Coastal map of Nigeria showing the study area with waters up to 50 m deep.
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 (Fig. 2). Most of the response curves to depth were sigmoidal (Fig. 2), but other shapes such as normal curves were utilized when these shapes better fit the curve of bathymetric preference for the groups concerned.

Fig. 2. Depth response curves used for predicting distribution of biomass for functional groups in NCW EwE model.
For this study, it is most important to have the depth preference distinction between the deep water and shallow water shrimps correct since the spatial redistribution of industrial fishing effort occurred in response to depletion of Pink Shrimp in deeper waters when some benthic trawlers encroached into the 5 NM no-trawl zone in search of other shrimps that inhabit these shallower areas of the Nigerian continental shelf.

Our 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 inshore in the late 1980s–early 2000s (most artisanal fishermen only fish down to the 40 m depth, while bottom trawlers trawled up to and beyond the 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.

Inclusion of fisheries

The industrial inshore fishing fleets target similar fish resources as the artisanal fisheries (Ajayi and Talabi 1984). According to Ajayi and Adetayo (1982), four fish groups account for about 45% of landings including Croakers, Catfishes, Sole, and Grunts. We included three fishing fleets in the Ecopath model used in this study. The first two are industrial fleets separately targeting benthic and pelagic resources, and the third one consists of a large artisanal fleet that combined benthic and pelagic fishing. Fleet fishing was regulated in Ecospace by adjusting 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 from 1985 to 2004 with biomass for groups, catch, and fishing effort of fishing subsectors spatially distributed across a map of NCW containing a grid of 16,600 square cells. Impacts of fishing were evaluated by simulating two scenarios in Ecospace including (1) artisanal inshore fishing only, a scenario that maintains a 5 NM non-trawl area beginning from the shorelines, and (2) benthic trawling allowed throughout NCW from year 2000. 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 a fishing policy changes. To achieve this in Ecospace, biomass landed for benthic trawlers was split in half in the parameterized 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, the first benthic trawler fleets could fish outside the 5 NM non-trawl zone for the first 15 yr 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 we modeled as starting 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.

RESULTS

Model calibration in Ecosim

The best fitting model based on Akaike information criterion (AIC) was chosen after fitting with fishing information from Ecopath and using temperature forcing with data from NOAA COPEPODA databases (https://www.nmfs.noaa.gov/copepod/; SS = 284.4; AIC = 93.56; Table 1). Catch data for Bonga Shad, Large Demersals, and Large Benthopelagic Sharks were overestimated by the models, but Flatfishes and Medium Pelagic species catch statistics were underestimated (Fig. 3). Simulations of all other groups appeared to approximately follow trends in fisheries data with reasonable SS fit. Moreover,
shrimp simulations had good fits with relatively low SS for both the catch and biomass data fit.

**Distribution of fishing effort**

Fishing effort by artisanal fishermen was spread across the modeled area of the map (the blue-green portion of the map) at the end of a 20-yr simulation, but this was concentrated outside the 5 NM designated as fishing grounds for artisanal fisheries along the entire coast in 2004 (Fig. 4). The fishing effort was, however, moderate, and the intensity of fishing within the inshore waters by the artisanal fleets appeared low.

The pattern of distribution of fishing effort for benthic trawlers is like the fishing effort observed in the artisanal fisheries (Fig. 5). More fishing effort was deployed by benthic trawlers in the deeper parts of the inshore fishing area of NCW.

Moreover, the intensity of commercial fishing for pelagic species in 2004 was more than artisanal and benthic trawl fishing. Pelagic trawlers concentrated fishing effort at the extreme east and west of the map (Fig. 6). The model also predicted a moderate amount of fishing effort for pelagic fisheries along the delta region of the Nigerian coast.

**Fisheries catch**

In the 20 yr between 1985 and 2004, fisheries catch in NCW generally increased and fish catch almost doubled for all fishing subsectors (Fig. 7). Having a 5 NM spatial closure from the shoreline seawards had little impact on catch for all fleets when 2004 catch were compared under the alternative fishing scenarios, as can be seen in the catch statistics for 2004 (Fig. 7).

**Biomass**

Biomass for several functional groups was estimated to be depleted in NCW by 2004; however, certain species had more biomass at the end of scenario simulations (Fig. 8; Table 2). Biomass for Small Pelagic fishes increases by 962%, and

### Table 1. Model parameters from fit-to-time series data in Ecosim.

| Drivers         | No. of parameters | Sum of squares | Akaike information criterion |
|-----------------|-------------------|----------------|------------------------------|
| Fishing         | 30.00             | 313.80         | 134.80                       |
| Fishing + temp  | 22.00             | 284.40         | 93.56                        |

Fig. 3. Ecosim model fit to data for catch and biomass data for Nigerian coastal waters. (The numbers after colons are sum of squares).
Reef fishes and Rays more than doubled their biomass. Other groups such as medium pelagic fishes, medium demersal fishes, and shallow water shrimps were estimated to have increases in biomass too. All other functional groups were estimated to have diminishing biomasses—especially Pink Shrimps, Croakers, and the group labeled Miscellaneous species.

The contribution to biomass dynamics of having a MPA in place was negligible for most commercial fisheries in NCW except for Large Demersals, Pink Shrimps, Reef fishes, and Rays (Fig. 9). The other functional groups in our model had negligible differences in biomass due to MPA influence.

**DISCUSSION**

By developing the NCW Ecospace model, it was possible to verify impacts of industrial shrimping in the first 5 NM that are closed to industrial fishing and to address concerns about impacts of fisheries in NCW (see Ogbona 2001).

It is important to note that potential habitat destruction that accompanies encroachment of shrimping boats into the first 5 NM of the Nigerian coast is not modeled in this research, nor did we model conflicts that may arise due to spatial overlap among the various fishing subsectors. Model scenarios for the first 20 yr (1985–2004) and the redistribution of industrial benthic fishing effort reported in the literature did not make any major difference in fishing patterns, amount of catch, and the distribution of fish and invertebrate biomass in NCW. Over the course of the study period, all fishing subsectors had increasing catch, and the MPA location made little or no difference in estimated model parameters. Overall, the biomass for several functional groups was depleted, while biomass for some groups (Small Pelagics, Reef fishes, and Rays) increased (Fig. 8).

**Spatial pattern of fishing**

Our research expectations that redistribution of fishing effort by industrial shrimp trawlers...
from 50 m depth to waters <18 m deep would alter the spatial characteristics of fisheries in NCW was not supported by modeling results. Results showed that biomass, catch, and spatial patterns of fishing were similar in 2004 regardless of the fishing policy implemented in our Eco-space simulations.

Although fishing effort is heterogeneously spread across the seascape, model predictions for 2004 showed 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 subsector that produced >50% of landings for all fishing subsectors.

Ecospace results corroborate information obtained from analyses of Sea Around Us Project data for NCW (seaaroundusproject.org), which showed that fisheries are expanding in NCW as indicated by an increasing fish in balance (FIB) index from 1950 to 2010. Bathal and Pauly (2008) noted that when the FIB Index increases over time with exploitation, fisheries are likely expanding geographically.

All three fishing subsectors were predicted to concentrate fishing effort outside the 5NM restricted for artisanal fisheries. Such expansion in fishing area may have implications for the spatial management of coastal resources in Nigeria since this result calls the benefit of maintaining the 5 NM non-trawl zone in question. The model, however, also predicted minute amounts of protection benefits for Reef fishes, Small Pelagic fishes, Large Demersal fishes, Rays, and shallow water shrimps, due to closure of the first 5 NM to trawling.

The Ecospace model in its current configuration did not restrict operation area for the artisanal fishing fleet, and artisanal fisheries were predicted by the model to concentrate fishing effort in deeper waters than was expected. These fisheries have traditionally operated fishing vessels in shallower waters than industrial fishing fleets because of the small size of most artisanal...
fishing canoes (Caddy and Carocci 1999). For artisanal fishermen to operate in waters deeper than 18 m, these fishermen must have vessels capable of accessing deeper water depths. The model prediction of fishing occurring further off-shore may well be possible since, during the last four decades, artisanal fisheries have become increasingly mechanized with vessels that are.
able to fish deeper in the inshore areas of the coast.

Sustained by government intervention/subsidy projects, the rate of canoe motorization in NCW continued to increase in recent decades. Development-focused programs, such as the Artisanal Inshore Fisheries Development Project and the National Accelerated Fish Production Project (NAFPP), were implemented to boost fish production (Nwaforli and Gao 2007). Such projects have increased the number of seaworthy boats and the reach of artisanal fishermen from within the 5 NM (from shore) they traditionally fished, into deeper parts of the continental shelf and potentially more pristine fishing areas.

**Ecosystem biomass**

Overall, the modeled biomass in the continental shelf increased in 2004 compared to 1985, due to increases in Small Pelagic fishes, Rays, and Reef fish biomasses over the course of the period studied in our research. The greatest contribution to

![Fig. 8. Estimation of biomass distribution for fished groups in Nigerian coastal Ecospace model.](image-url)
biomass was made by Small Pelagic fishes such as sardinella. Modeled sardinella biomass increased more than ninefold (962%). Catch statistics from Sea Around Us Projects show that catch rose from 0 MT landed in 1985 to 77,000 MT landed in 2004. Sardinella fisheries in Gulf of Guinea (of which the sardinella stock in NCW is a part) have often been overexploited (Garcia et al. 2003), and their biomass fluctuates according to environmental trends (Amire 2003, Nwafili and Gao 2007).

Pink Shrimp biomass declined, but other shallow water shrimp species such as *P. monodon* were added to replace the loss in Pink Shrimp biomass. Because of this, shrimpers were fishing in shallower waters which might have led to release of fishing pressure on Pink Shrimp biomass that was mainly targeted in deeper waters. This could have resulted in release of fishing pressure on the Pink Shrimp biomass enabling continued contribution of Pink Shrimp to landings in the shrimp fishery for the years following the depletion in biomass that occurred from the late 1990s to early 2000s.

There was ~1.5% difference in biomass for Reef fish species due to the protection offered by limiting trawling only outside the non-trawl zone through the simulation period. Pink Shrimps and Large Benthopelagic species have small amounts of negative impacts due to placement of the MPA.

![Graph](https://example.com/graph.png)

**Fig. 9.** Percentage difference in biomass of fished taxa due to influence of MPA in the first 5 NM of the Nigerian coast.

| Group Name      | Biomass (w/o Mpa) | Biomass (with Mpa) | Reference species   |
|-----------------|-------------------|--------------------|---------------------|
| Flatfishes      | -40.74%           | -40.74%            | Tongue Sole         |
| Rays            | 153.81%           | 154.06%            | Bull Ray            |
| Other Shrimps   | 24.41%            | 24.68%             | Guinea Shrimp       |
| Miscellaneous Species | -31.86%       | -31.91%            | Angel Squids        |
| Reef Fishes     | 203.10%           | 204.66%            | African Pompano     |
| Large Demersal  | -91.98%           | -91.43%            | White Grouper       |
| Large Pelagic   | 30.21%            | 32.4%              | Skipjack Tuna       |
| Juvenile Croaker| -97.62%           | -97.6%             | Cassava Croaker     |
| Juvenile Croaker| -92.58%           | -92.67%            | Cassava Croaker     |
| Small Demersal  | 9.53%             | 9.55%              | Hairy Blenny        |
| Small Pelagics  | 962.45%           | 963.22%            | West African Ilsha  |
| Large Benthopelagics | -8.79%       | -9.24%             | Bull Shark          |
| Medium Pelagics | 171.03%           | 171.09%            | Bony Tongue         |
| Medium Demersals| 69.57%            | 69.57%             | African Threadfin   |
| Juvenile Shad   | -67.68%           | -67.68%            | Bonga Shad          |
| Shad            | -22.79%           | -67.68%            | Bonga Shad          |
| Juvenile Pink Shrimp | -42.31%     | -43.06%            | Southern Pink Shrimp|
| Pink Shrimp     | -54.29%           | -54.65%            | Southern Pink Shrimp|

**Table 2. Comparison of biomass for functional groups in 2004 to baseline estimated in 1985 under different spatial management scenarios in Ecospace, one in which bottom trawling is banned in the first 5 NM of Nigerian coastal waters and the other where bottom trawling is allowed.**
along the coast. It would be expected that biomass of exploited species should build up in the 5NM non-trawl area of NCW if industrial fishing is prohibited in this area (Walters et al. 1999). The fact that this is not the case may mean that results and estimate from Ecospace were due to processes outside the 5NM non-trawl area or simply because biomass of commercial species was already depleted in the modeled 5 NM MPA section of the continental shelf.

By comparing alternative management scenarios in Ecospace, it was possible to investigate the impact of trawling in nearshore waters on the commercial fisheries in NCW, and the model suggests that the protection offered by MPA (based on percentage difference in biomass) from impacts of redistribution of fishing effort into nearshore water was minimal at best. The MPA only offered 1.56% protection benefits for Reef fishes, 0.8% for Small Pelagic fishes, and 0.55% benefits for Large Demersal species (Fig. 9).

**Fisheries catch**

An increase in catch for artisanal fisheries in 2004 occurred for both modeled policy scenarios. In the first scenario, trawling within the first 5 NM was prohibited, and in the other modeled scenario, no trawling was permitted in the first 5 NM of the Nigerian coast. The increase in catch may have resulted from continued growth in fishing effort in this subsector due to the open access nature of artisanal fisheries in NCW where the number of fishermen operating in the fisheries is not regulated, thereby allowing many more fishermen to enter into the fishery particularly when there are few substitute occupation they can pursue in rural coastal fishing villages (Kaitikiko and Macusi 2012, Asiedu and Nunoo 2015, Lewerenz and Vorath 2015). An alternative explanation for increased catch may be related to the increase in fish biomasses estimated for the Small Pelagic, Reef, and elasmobranch fisheries.

The localized higher intensity of industrial pelagic fishing observed in the extreme eastern and western part of the coast (Fig. 7) may be the result of the boom in Small Pelagic fishes (particularly sardinaela), with biomass landings from the continental shelf >100,000 MT in year 2000. Since sardinella fisheries in Gulf of Guinea fluctuate very widely in response to environmental conditions (Amire 2003, Garcia et al. 2003, Nwafili and Gao 2007), the favorable environmental conditions in the early 2000 resulted not only in recovery of Small Pelagic fisheries, but also in intensification of fisheries that target these pelagic resources.

Intense fishing accompanies population growth. 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 and Gao 2007).

For large and growing coastal artisanal fisheries, spatial expansion of operation areas is inevitable since industries tend to progressively exploit wider envelopes of space through time due to depletion with proximity effects (Caddy and Caracci 1999). It is important to note that the expansion of fisheries into deeper inshore waters predicted for NCW should not be confused with the encroachment of industrial fishing fleets into nearer-shore waters when trawlers went in search of shallow water shrimps. We emphasize this distinction to foster understanding of the results presented.

Nwafili and Gao (2007) indicated that fishing effort in NCW more than doubled in the last 30 yr, but fish landings only increased about 70%, which is disproportionate to the amount of fishing effort exacted in NCW. This may be a sign of overexploitation, evidenced by a decline in average production per capita for artisanal fisheries from 0.64 MT in the 1980s to 0.36 MT in year 2000. 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 managing the fisheries in NCW should reduce impacts in the long run and maintain sustainable fisheries. Given the ecological importance of nearshore waters, it is still a good idea to maintain a 5 NM no-trawl area to protect sensitive nursery habitats from damage by trawlers. Such an approach would consider the possibility that nearshore waters remain as important nursery grounds for commercial fish stocks, so that adequate research to map out these sensitive habitats is done in combination with a reduction in fishing efforts, and measures to protect these valuable habitats are taken.

Although we did not explicitly model trawler-induced habitat destruction for nearshore coastal areas in this study, it is prudent to consider a regulatory tactic that controls the amount of fishing...
effort allowed in the coastal fisheries. This is to prevent potential damage to habitats and coastal fish resources, so that sustainable fisheries may be attained in a country like Nigeria where fishing effort is very high. This proposed protection can be a temporary approach to management until better surveys are carried out to provide comprehensive information about nursery locations and rearing areas for ecologically and economically important species and functional groups in NCW.

CONCLUSIONS

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. Logic dictates that fishermen should 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. Since the NCW Ecospace model does not include distance traveled to fishing grounds in the revenue calculation of the gravity model that determines effort distribution, additional socio-economic modeling is needed to verify whether higher fishing effort would be allocated in the deeper area of the continental shelf when cost of fishing is considered. In addition, model outputs should benefit from validation with additional data such as fishery-independent data (Walters et al. 2008).

Spatial management of fisheries resources is now possible with simulation 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) make 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 (more information about the data used can be found in the Appendix S1) available from databases and literature for model configuration, calibration, and simulations to explore spatial impacts of fishing the NCW between 1985 and 2004. While economic factors such as boating distance were not explicitly factored into the model, this simple approach provided a starting point for enquiry that can be refined as the NCW EwE model is further developed. Furthermore, the distribution curves used in Ecospace are estimations based on currently available ecology and depth range data. These need to be validated with field data in future research for the NCW Ecospace model to be used as a predictive management tool. 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 to strengthen monitoring and surveillance to protect valuable oceanic living resources and ensure sustainable fisheries in Nigeria.

At the turn of the last century, some trawlers in NCW were reported to have encroached into nearshore waters shallower than 18 m depth in search of shrimp species that inhabit these shallower areas of the coast. We used an Ecospace model to investigate possible impacts of spatial displacement of fishing effort from deeper areas of the continental shelf into more shallow areas. We found that for the most part, fisheries catch, fishing effort, and ecosystem biomass were similar under two distinct management scenarios, with one involving protection for nearshore waters from trawling and the other one allowing trawlers to operate in these shallow sensitive nearshore areas. Despite encroachment of trawlers into nearshore waters, most fishing effort in NCW was predicted by the Ecospace model to have occurred in deeper areas of the coast.

ACKNOWLEDGMENTS

We do not have any conflict of interest to disclose. We acknowledge with thanks comments from reviewers that helped improve the manuscript. We are also thankful for funding through the Provost office at George Mason University that supported the research and writing phases of this project.

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**Supporting Information**

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2623/full