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PRELIMINARY MODEL EXAMINING THE EFFECTS OF THE TUNA PURSE-SEINE FISHERY ON THE ECOSYSTEM OF THE GULF OF GUINEA

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SUMMARY

The FAD fishery in the eastern tropical Atlantic has increased in recent decades and accounts for over 60% of the tropical tuna catch from purse seine vessels. The use of FADs has raised concerns due to the wide array of species that are associated with these floating objects and are caught as by-catch along with tuna. An Ecopath model of the northern Gulf of Guinea was developed to investigate the effects of the FAD fishery on the ecosystem. The model is composed of 27 functional groups ranging from high trophic level pelagic predators to zooplankton and detritus groups. Bigeye and yellowfin tuna were split into multi-stanza groups to account for differences in diets and size composition of catches. The four major fisheries in the area; FAD and free school purse seine, longline and baitboat, were included in the model along with a discard group. The EU observer database was used to estimate composition and amounts of by-catch from the purse-seine fisheries. Primary production required for the current levels of catch was at 6%, compared to 4% found by an earlier version of the model for the smaller South Sherbro Area.

RÉSUMÉ

La pêcherie sous DCP menée dans l'Est de l'océan Atlantique tropical s'est accrue ces dernières décennies et représente plus de 60% de la prise de thonidés tropicaux réalisée par des senneurs. L'utilisation des DCP a suscité des préoccupations en raison de la vaste gamme d'espèces qui sont associées à ces objets flottants et sont capturées en tant que prise accessoire avec les thonidés. Un modèle Ecopath pour le Nord du golfe de Guinée a été mis au point afin d'étudier les effets de la pêcherie opérant sous DCP sur l'écosystème. Le modèle est composé de 27 groupes fonctionnels allant de prédateurs pélagiques de haut niveau trophique aux groupes de zooplancton et de détritus. Le thon obèse et l'albacore ont été divisés en groupes de plusieurs stances afin de tenir compte des différences de régimes et de composition par taille des captures. Les quatre principales pêcheries actives dans la zone (à la senne sous DCP et bancs libres, à la palangre et à la canne) ont été incluses dans le modèle ainsi qu'un groupe de rejet. La base de données des observateurs de l'UE a été utilisée pour estimer la composition et les volumes de prise accessoire des pêcheries de senneurs. La production primaire requise pour les niveaux actuels de capture s'élevait à 6%, par rapport aux 4% obtenus dans une version antérieure du modèle pour la zone plus petite du Sud du Sherbro.

RESUMEN

La pesquería con DCP en el Atlántico tropical oriental se ha incrementado en las últimas décadas y responde del 60% de las capturas de túnidos tropicales realizadas por los cerqueros. El uso de los DCP ha suscitado preocupación debido al amplio espectro de especies que están asociadas a esos objetos flotantes y que se capturan fortuitamente junto con los túnidos. Se desarrolló un modelo Ecopath en el golfo de Guinea septentrional para investigar los efectos de la pesquería de DCP en el ecosistema. Este consta de 27 grupos funcionales, que van desde los depredadores pelágicos de alto nivel trófico hasta los grupos de zooplancton y detritus. Se dividió al patudo y al rabil en grupos multiestanza para reflejar las diferencias en la dieta y en la composición por talla de las capturas. Se incluyeron en el modelo las cuatro grandes pesquerías activas en la zona (el cerco con DCP y con banco libre, el palangre y el cebo vivo), además de un grupo de descartes. Se utilizó la base de datos de observadores de la UE para estimar la composición y cantidades de captura fortuita de las pesquerías de cerco. La producción primaria requerida para los niveles actuales de captura era del 6%, en lugar del 4% arrojado por una versión anterior del modelo para la Zona sur de Sherbro, de menor tamaño.

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KEYWORDS

Ecosystem model, Ecopath, FAD school, Purse seine

1. Introduction

Fisheries impact both the species that are being targeted as well as the surrounding ecosystems through modifications in community structure, diversity, changes in trophic interactions and bycatch species mortality (Amandè *et al*., 2010; Cox *et al*., 2002; Pauly *et al*., 2002). These changes can be difficult to quantify as historically attention has been focused on single species assessment models for areas of study and management. Ecopath with Ecosim models can provide a framework to assess the status of ecosystems and identify changes in recent decades due to fishing pressure.

Tuna fisheries operate in the open ocean, away from artisanal fishing fleets and land-based influences. Modeling open-ocean ecosystems is challenging due to the underlying assumption of many ecosystem models of a closed system. However, several Ecopath models have been developed for pelagic systems, including a tropical eastern Pacific Ocean model (ETP) developed by the Inter-American Tropical Tuna Commission (IATTC) and models of the western and central Pacific (CNP) (Cox *et al*.. 2002b, Olson and Watters 2003, Griffiths 2013). Ecopath is currently the most extensively employed ecosystem modeling software available (Christensen and Walters, 2004a; Plagányi, 2007; Araujo *et al.*, 2008). It allows for the trophic flows between discrete trophic levels, or functional groups, to be described and quantified (Polovina, 1984; Walters *et al*., 1997; Pauly *et al*., 2000) and combines the theory of classical ecology, food chains and linkages, to the concept of mass balance and energy conservation (Christensen and Walters, 2004).

This Ecopath model was developed using a previously published Ecopath model for a smaller region of the Gulf of Guinea, termed the PICOLO model, and enlarged and updated for this paper's purposes (Schultz and Menard 2003). Using European Union observer data, ICCAT Task I and Task II databases as well as published scientific literature, a model of the northern Gulf of Guinea was developed. The goal of the model is to examine the role of the teleost species in the ecosystem that are caught as bycatch by the large tuna purse seine fishery that operates in the region.

2. Materials and Methods

2.1 Ecopath approach

Ecopath allows for trophic flows between species or groups of species, termed functional groups, to be quantified in a steady state model (Christensen 2004). It is run from a series of linear equations balancing the net production of each functional group to all sources of mortality, migration or change:

$$P_i = \sum_j B_j \cdot M2_{ij} + Y_i + E_i + BA_i + P_i \cdot (1 - EE_i) \quad (1)$$

where the production (*P*) of the ith component, or functional group, of the ecosystem is divided into predation mortality (*M2ij*) caused by the biomass of the other predators (*Bj*); exports from the system both from fishing catches (*Yi*) and emigration (*Ei*); biomass accumulation in the ecosystem (*BAi*); and other mortality or mortality not captured by the model (*1-EEi*). *EEi* is the ecotrophic efficiency of the group within the system, or the proportion of the production Pi that is exported out of the ecosystem (i.e., by fishing activity) or consumed by predators within it. Equation (1) can be re-expressed as:

$$B \cdot \left(P/_B\right)_i = \sum_j B_j \cdot \left(Q/_B\right)_j \cdot DC_{ij} + Y_i + E_i + BA_j + B_j \cdot \left(P/_B\right)_i \cdot (1 - EE_i) \quad (2)$$

where *(P/B)i* indicates the production of functional group i per unit of biomass and is equivalent to total mortality, or Z, under steady-state conditions (Allen, 1971); *(Q/B)i* is the consumption of i per unit of biomass; and *DCij* indicates the proportion of i that is in the diet of predator j in terms of volume or weight units. EwE parameterizes the model by describing a system of linear equations for all the functional groups in the model, where for each equation at least three of the basic parameters: *Bi, (P/B)i, (Q/B)i* or *EEi* have to be known for each group i, in addition to the diet composition. The energy balance within each group is ensured when the sum of consumption by group i equals the sum of production by i, respiration by i and food that is unassimilated by i (Forrestal *et al.,* 2012).

2.2 Model structure and parameterization

The model area is 3,837,000 km^2 and encompasses the region from 12°N to 5°S and from 20°W to 10°E, following the shelf break. The model represents the averages of the ecosystem from 2003-2013 using stock assessments and catch data. The main focus is on the major bycatch families or functional groups that are observed in the offshore tuna fishery; Scombridae, Carangidae, Balistidae, and Coryphaenidae. The parameter resolution is highest for these functional groups and the tropical tuna species.

The Gulf of Guinea region has been poorly studied relative to other large ocean regions and as such some of the functional groups lack information specific to that region. Data available on abundance and occurrence of species in the region were used, as were bycatch amounts from the tuna purse seine fishery. In cases where species were reported in the area but no detailed information was available to develop the necessary parameters to run Ecopath, parameter values from the PICOLO model were used or values from previously published models of pelagic systems were used. Diet composition was gathered from Fishbase.org unless otherwise noted in the text.

2.3 Functional groups

2.3.1 Seabirds

Migratory seabirds and breeding colonies on islands in Gulf of Guinea were included in the seabird functional group. Seabird species present in the Gulf of Guinea were identified through the British Ornithologists Union checklist for the birds of the Gulf of Guinea (Jones and Tye, 2006). Birds classified as offshore species or as migrants to the area were included in the functional group. The 12 species included belong to four families: Procellidae (petrels and shearwaters), Hydrobatidae (storm petrels), Sulidae (boobies), and Sternidae (terns).

Biomass estimates for *Sula leucogaster, Sterna fuscata, Anous stolidus,* and *A. minutus* were taken from a survey conducted by Birdlife International on the breeding colonies found on two islands of São Tomé e Principe (Valle *et al.* n.d.). The survey was conducted in February 2013 and counted breeding pairs of species. For the biomass estimates, it was assumed that these species remained in the ecosystem for the entire year.

Biomass estimates for the remaining seabirds species were obtained through estimates from the Ecopath model of the central Atlantic developed by Vasconellos and Watson (2004). It was assumed for Procellidae species remained in the region for half of the year as the Vasconellos and Watson model encompassed the entire central Atlantic. For the Hydrobatidae species, it was assumed they remained in the system for one season, as these species inhabit the southern or northern hemispheres depending on the specific range. Weighting factors were found from proportional biomass amounts for each species and these were used to calculate Q/B and P/B values for the functional group. P/B was found using adult annual survival rates from values obtained in (Vasconcellos and Watson 2004). Q/B ratios were found using values obtained through diet studies (Nilsson and Nilsson 1976).

2.3.2 Sharks

Shark species present in the model were identified through the entries in the observer database and species that were present in the original PICOLO model. While there are several species within the functional group (**Table 1**), the majority of the discarded species were silky sharks, followed by several species of hammerhead. As a result, this functional group has been parameterized based on silky shark and hammerhead P/B and Q/B values. Shark biomass was calculated through the observer database and original PIC model. P/B was estimated using total instantaneous mortality; von Bertlanffy growth parameters and the natural mortality equation were used to estimate M and F was estimated at F=0.8M (Pauly 1980b, Branstetter 1987, Piercy *et al.* 2010, Griffiths 2013). Q/B was estimated through von Bertalanffy parameters and the empirical equation developed by Palomares and Pauly (1998) (Palomares and Pauly 1989). The diet matrix was estimated through studies in similar ecosystems and previously published models (Cabrera-Chávez-Costa et al. 2010, Griffiths 2013).

2.3.3 Marine Mammals

The 19 species contained in the marine mammal functional group were determined from a list of marine mammal sightings in the Gulf of Guinea (Weir, 2010; Weir, 2011). These include both baleen whales and toothed whales. 28 species have been documented, however, many of the sighting or occurrences are from whaling records or strandings; this information does not allow for information of abundance or range at sea. There is a lack of information on the cetacean species found within the region (Bamy et al., 2010; Weir, 2011). A survey of the documented species shows support for a resident population of cetaceans in the tropical waters of the eastern Atlantic. The exception to this is *Megaptera novaeangliae*, which use the region exclusively as a breeding and calving ground (Bamy *et al*., 2010; Weir, 2011). Species biomass estimates where calculated from a previous Ecopath model of the central Atlantic (Vasconcellos and Watson 2004). The biomass estimates are quite tentative, as the marine mammals in the Gulf of Guinea have been poorly described. It was assumed all marine mammals, with the exception of *M. novaeangliae*, remained in the region of the model for a full year. Values of Q/B and P/B were obtained from a model of the Central Atlantic and weighted to account for the proportional biomass of each species (Vasconcellos and Watson 2004).

2.3.4 Rays

The ray functional group is comprised of Mobulidae species (devil-rays), Manta rays and pelagic stingrays. The bycatch of rays is primarily devil-rays (*Mobula japonica*) with manta and pelagic stingrays making up a smaller proportion. Initial biomass estimates were obtained through the observer database. The P/B and Q/B values were estimated from previously published values (Olson and Watters 2003). Diet composition was estimated from previously published reports (Notarbartolo-di-Sciara 1987).

2.3.5 Sea turtles

This functional group is comprised of species present in the observer bycatch database: Green turtles (*Chelonia mydas*), Hawksvilles (*Eretmochelys imbricate*), Leatherback (*Dermoche1ys coriacea*), Kemp’s ridley (*Lepidochelys kempii*), and Olive ridley (*Lepidochelys olivecea*). The principal species within the database are leatherback (56%) and olive ridley (23%). The P/B and Q/B parameters were weighted to reflect this; these values were obtained through a previously published model (Olson and Watters 2003). The islands within the Gulf of Guinea, Principe and São Tomé, Annobón and Bioko, are important nesting grounds for the leatherback, Olive ridley, green and hawksbill turtles. These nesting populations have been severely depleted on these islands due to overexploitation of the species from the meat and egg trades (Castroviejo *et al.* 1994).

2.3.6 Tunas

Skipjack biomass was estimated from the most recent stock assessment from ICCAT (Anonymous 2014a). P/B was estimated using the total instantaneous mortality, reflecting the recent ICCAT stock assessment estimation of fishing mortality at 0.4 and natural mortality of 0.8 (ICCAT, 2015). Q/B was estimated through von Bertalanffy parameters and empirical equations (Palomares and Pauly 1989). The diet composition was estimated from stomach content analysis conducted in the South Sherbro Area (Menard *et al.* 2000).

The yellowfin tuna were split into a multi-stanza group to reflect differences in diet composition and the different size classes that are caught by various fisheries. Maturity is assumed to be knife-edge at 3 yrs, around 100 cm. Relative frequencies of size classes were calculated using ICCAT catch-at-size data, and this information was used to calculate landings of juvenile and adult yellowfin (**Figure 1**). P/B estimates for both juvenile and adult yellowfin were obtained through the most recent stock assessment for yellowfin and Q/B was estimated through the empirical equation developed by Palomares and Pauly (1998). Biomass estimates for adult yellowfin were estimated from the most recent stock assessment and Ecopath estimated juvenile biomass from the life history parameters (Anonymous 2011a).

Stomach content analysis done onboard a purse seine vessel targeting monospecific schools of large yellowfin occurring at the equator found YFT were feeding exclusively on *Cubiceps spp.* (Bard *et al.* 2002). In contrast, a study by Menard (2000) identified *Vinciguerria nimbaria* (small epipelagic) as the main prey item.

The bigeye tuna biomass amounts were calculated from the most recent ICCAT stock assessment (Anonymous 2011b). Like yellowfin, bigeye tuna were split into a multi-stanza group to reflect differences in diet composition and the different size classes that are caught by various fisheries (**Figure 2**). Length and weight parameters were used to calculate multi-stanza parameters (Zhu *et al.* 2009). P/B estimates for both juvenile and adult bigeye tuna were obtained through the most recent bigeye assessment and Q/B was estimated through the empirical equation developed by Palomares and Pauly (1998). The diet composition was estimated through stomach content analysis done onboard purse seine vessels in the South Sherbro Area (Menard *et al.* 2000).

Biomass of albacore was estimated from stock assessments and from amounts in the observer database (Anonymous 2014b). The P/B and Q/B parameters were obtained from a previously published model (Olson and Watters 2003). The diet of this functional group is mostly imports as albacore are primarily a colder water species (Cox *et al*. 2002a).

2.3.7 Scombridae

The scombridae functional group is comprised of four species, wahoo (*Acanthocybium solandri*), (*Auxis thazard and A. rochei*) and (*Euthynnus alletteratus*). These species are characterized as fast growing, short lived with a high mortality (McBride et al 2008). Biomass estimates were developed from the following equation:

$$B_i = \frac{1}{E_{i,j}} \sum_j \left(\frac{Y_{i,j}^{obs}}{Y_{T,j}^{obs}} Y_{T,j} \right) \quad (3)$$

where $\boldsymbol{Y_{i,j}^{obs}}$ represents the total bycatch for each functional group by fishing mode j during the observed trips and $\boldsymbol{Y_{T,j}^{obs}}$ is the total tuna catch associated with the observed bycatch during fishing mode j (Schultz and Menard 2003). The total observed tuna catch $\boldsymbol{Y_{T,j}}$ was used to estimated the total by-catch using the ratio estimator method (Stratoudakis *et al.* 1999). The average bycatch and catch from 2003-2013 were used and the exploitation rate E was calculated from the natural mortality and fishing mortality for each functional group. P/B and Q/B estimates were estimated from life history parameters and the previously discussed empirically based equations (Pauly 1980a, Palomares and Pauly 1989, Kahraman *et al.* 2011).

2.3.8 Billfish

Billfish biomass was calculated from available stock assessments conducted by ICCAT as well as calculations from the supplemental information on population declines (Collette *et al.* 2011, Anonymous 2014c). P/B and Q/B values were obtained from previously published model (Olson and Watters 2003).

2.3.9 Carangidae, Coryphaena, Balistidae

These species comprise the majority of the discards within the FAD associated purse-seine catch and have been well studied with in other ocean regions. Biomass estimates were obtained though the observer database using the average observed bycatch from 2003-2013 and by applying equation 3. The exploitation rate E was calculated from the natural mortality and fishing mortality for each functional group. As fishing mortality is unknown for bycatch species, estimates were obtained by F=0.8M (Griffiths 2013). P/B and Q/B values as well as the diet composition were obtained through previously published reports (Goodwin and Johnson 1986, Vose and Nelson 1994, Rudershausen *et al.* 2010).

2.3.10 Epipelagic I and II, Small Epipelagics

The epipelagic I functional group contains piscivorous predators found within the observer bycatch database; *Lobotes surinamensis*, *Ruvettus pretiosus* and *Sphyraena barracuda*. The bycatch amounts of *Ruvettus pretiosus* is quite low and as a result the functional group is parameterized for *Lobotes surinamensis* and *Sphyraena barracuda.*

Epipelagic II functional group contains species found in the bycatch database whose primary prey source includes crustaceans, copepods and encrusting algae.

The small epipelagic functional group is made up of 12 species. The most important component of this group, *Vinciguerria nimbaria*, was grouped separately as a functional group in the original PICOLO model as it was identified as a major component of the tuna species' diet, however, up to date information on biomass of this species is not available so it was grouped within the small epipelagic group.

Biomass was estimated from the PICCOLO model and the observer database using equation 3. Epipelagic P/B and Q/B where found from previously published models while small epipelagic P/B and Q/B were obtained through a weighted combination of small epipelagics and *V. nimbaria* from the original PICCOLO model (Griffiths 2013).

2.3.11 Small mesopelagics, Cephalopods, Gelatinous and Zooplankton

The original PICOLO model was developed using data collected from cruises conducted within the South Sherbro Area in the 1990's. There is a lack of new data from this region so it was assumed that biomass, P/B and Q/B values remained the same from the first model.

2.3.12 Fisheries

The landing information for longline and baitboat (pole and line) fisheries were found using values in the ICCAT Task I database while the landings from purse seine free and purse seine FAD sets were estimated from the ICCAT Task II database. Discards were calculated from the purse seine observer database and from published records for the longline and baitboat fisheries.

3. Results and discussion

In order for the model to balance, P/B and the diet composition matrix were adjusted from the originally calculated values (**Table 2**). The model was balanced when all functional groups had an ecotrophic efficiency under 1 and were considered reasonable. Ecotrophic efficiencies represent the fraction of the functional group utilized by the system. Generally, small forage species that have several predators or species that are heavily exploited will have EE values very close to 1. Those functional groups with few predators or that are very small and abundant such as zooplankton groups have a lower EE value. The adult yellowfin and bigeye tuna as well as the billfish functional group had lower than expected EE values. This is most likely the result of the migrations these species undertake. The original assumption was that these species stay within the model area for the whole year. However, this is not the case and subsequent iterations of the Gulf of Guinea model will take that into account.

The model’s thermodynamic stability was determined through regressions of longevity against trophic level as well trophic level against the respiration to assimilation ratio **(Figure 3** and **Figure 4**). Both regressions showed positive relationships, demonstrating that the model had appropriate biological responses for the system. The mixed trophic impact of each functional group was used as a sensitivity analysis to examine negative and positive trophic interactions. The largest interactions were seen between the fisheries and functional groups that make up the bycatch of those fisheries (**Figure 5**).

The system statistics were compared to the results from the PICOLO model from the early 1990s to determine changes to the ecosystem. The omnivory index was estimated at 55%, compared to 34% from the PICOLO model showing an increase in the complexity between trophic levels. However, this is most likely an artifact of the model as the PICOLO model had fewer functional groups than the current model. The total primary production required to maintain the fishery was estimated at 6%, a 2% increase from the PICOLO model, representative of an increase in fishing pressure.

The EU observer database contains information on the fate of the discard species, including if they were discarded dead or alive. Currently, the model assumes all discarded fish are discarded dead. Future versions of this model will include discard fate using the database as well results from post-release survival studies conducted on Balistidae (Forrestal, *in prep*). Discards will be further modified to reflect the recent determination that the Ghanaian baitboat landings should be classified as purse seine catches and these landings will be included in the raising factor for determining total bycatch (Anonymous 2015).

The model will be fitted to several time series from the fisheries within the region to further tune the model. Once appropriate fits have been achieved, the base Gulf of Guinea model will be used to explore several different scenarios for the fishery, including full retention of bycatch.

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Table 1. Species make-up of functional groups with more than one species.

Functional Group	Species
Seabirds	*Sterna fuscata*
	Anous stolidus
	Anous minutus
	Sula dacylatra
	Sula leucogaster
	Calonectris diomedea
	Oceanites oceanicus
	Fregetta tropica
	Hydrobates pelagicus
	Oceanodrama castro
	Oceanodrama leucoroa
	Puffinus gravis
Sharks	*Alopias vulpinus*
	Galeocerdo cuvier
	Carcharhinus limbatus
	Carcharodon carcharias
	Isurus oxyrinchus
	Carcharhinidae spp
	Carcharhinus falciformis
	Carcharhinus longimanus
	Prionace glauca
	Sphyrna lewini
	Sphyrna mokarran
	Sphyrna zygaena
	Rhincodon typus
Sea turtles	*Chelonia mydas*
	Dermochelys coriacea
	Lepidochelys kempii
	Lepidochelys olivacea
Ray	*Dasyatys violacea*
	Manta birostris
	Mobula mobular
Billfish	*Istiophorus albicans*
	Makaira indica
	Makaira nigricans
	Tetrapturus albidus
	Tetrapturus angustirostris
	Tetrapturus pfluegeri
	Xiphias gladius
Marine Mammals	*Balaenoptera borealis*
	Balaenoptera edeni
	Balaenoptera physalus
	Megaptera novaeangliae
	Delphinus delphis
	Globicephala macrorhynchus
	Grampus griseus
	Kogia simus
	Lagenodelphis hosei
	Orcinus orca
	Peponocephala electra
	Physeter macrocephalus
	Pseudorca crassidens
	Stenella attenuata
	Stenella clymene
	Stenella frontalis
	Stenella longirostris
	Steno bredanensis
	Tursiops truncatus

Functional Group	Species
Carangidae	*Caranx crysos*
	Elagatis bipinnulata
	Naucrates ductor
	Seriola rivoliana
	Uraspis secunda
Coryphaena	*Coryphaena equiselis*
	Coryphaena hippurus
Balistidae	*Balistes capriscus*
	Balistes punctatus
	Canthidermis maculata
Scombridae	*Acanthocybium solandri*
	Auxis thazard/rochei
	Euthynnus alletteratus
Epipelagic I	*Lobotes surinamensis*
	Ruvettus pretiosus
	Sphyraena barracuda
Epipelagic II	*Tetraodontidae*
	Aluterus monoceros
	Kyphosus sectatrix
	Remora remora
Small Mesopelagics	Family
	Myctophidae
	Sternoptychidae
	Stomiidae
	Gempylidae
	Gonostomidae
	Photichthyidae
	Argentidae
	Melanostomidae
	Opisthroproctidae
Small Epipelagic	*Cheilopogon cyanopterus*
	Cheilopogon melanurus
	Cheilopogon milleri
	Cheilopogon nigricans
	Cheilopogon pinnatibarbatus
	Fodiator acutus
	Hirundichthys affinis
	Oxyporhamphus micropterus
	Parexocoetus brachypterus
	Prognichthys gibbifrons
	Vinciguerria nimbaria
	Cubiceps pauciradiatus
Macrozooplankton	Crustaceans
	Fish larvae
	Small molluscs
Mesozooplankton	Copepods
Microzooplankton	Copepod larvae
	Foraminifera
	Radiolarians
	Tintinnèdes
	Pteropods

Table 2. Input parameters for Gulf of Guinea model, those in bold estimated by Ecopath.

	Group name	TL	B	P/B	Q/B	EE	P/Q
1	Seabirds	4.85	0.01	0.07	73.03	**0.54**	**0.00**
2	Sharks	5.37	0.01	0.57	3.50	**0.78**	**0.16**
3	Marine mammals	3.55	0.04	0.02	4.78	**0.48**	**0.00**
4	Rays	3.08	0.00	0.25	3.90	**0.81**	**0.06**
5	Sea turtles	3.41	0.00	0.25	3.90	**0.80**	**0.06**
6	Skipjack	4.69	0.05	1.88	16.90	**0.91**	**0.11**
7	YFT adult	5.03	0.02	1.35	15.60	**0.20**	**0.09**
8	YFT juvenile	4.68	0.08	1.00	22.94	**0.41**	**0.04**
9	BET adult	5.01	0.01	0.65	13.00	**0.34**	**0.05**
10	BET juvenile	4.62	0.02	1.00	26.05	**0.85**	**0.04**
11	Albacore	4.04	0.00	0.77	17.00	**0.72**	**0.05**
12	Scombridae	4.32	0.08	0.98	8.00	**0.77**	**0.12**
13	Billfish	5.60	0.00	0.90	4.64	**0.19**	**0.19**
14	Carangidae	4.16	0.02	1.47	8.00	**0.25**	**0.18**
15	Coryphaena	4.80	0.00	3.50	20.40	**0.41**	**0.17**
16	Balistidae	4.27	0.01	0.68	7.75	**0.80**	**0.09**
17	Epipelagic I	4.20	0.01	3.40	14.00	**0.36**	**0.24**
18	Epipelagic II	2.82	0.00	1.08	7.67	**0.26**	**0.14**
19	Small epipelagics	3.51	3.45	8.25	22.00	**0.99**	**0.38**
20	Small mesopelagics	3.11	11.66	1.53	11.00	**0.70**	**0.14**
21	Cephalopods	4.20	2.50	2.50	17.00	**0.94**	**0.15**
22	Gelatinous	2.39	5.50	5.00	25.00	**0.83**	**0.20**
23	Macrozooplankton	2.44	4.20	10.00	31.70	**0.82**	**0.32**
24	Mesozooplankton	2.11	24.00	53.00	170.97	**0.18**	**0.31**
25	Microzooplankton	2.11	2.00	450.00	818.18	**0.65**	**0.55**
26	Phytoplankton	1.00	37.00	200.00	-	**0.41**	
27	Fishery discards	1.00	0.01				
28	Detritus	1.00	488.00			**0.31**	

Table 3. Summary statistics and indices of the Gulf of Guinea

	GoG	PICOLO	Units
Sum of all consumption	6,262.17	7,361.00	$t/km^2/yr$
Sum of all exports	5,273.78	4,507.00	$t/km^2/yr$
Sum of all respiratory flows	2,128.05	2,894.00	$t/km^2/yr$
Sum of all flows into detritus	7,603.95	7,133.00	$t/km^2/yr$
Total system throughput	21,267.95	21,897.00	$t/km^2/yr$
Sum of all production	9,694.42	9,734.00	$t/km^2/yr$
Mean trophic level of the catch	4.72	4.43	
Gross efficiency (catch/net p.p.)	0.00	0.00	
Calculated total net primary production	7,400.00	7,400.00	$t/km^2/yr$
Total primary production/total respiration	3.48		
Net system production	5,271.95	4,505.00	$t/km^2/yr$
Total primary production/total biomass	81.62		
Total biomass/total throughput	0.00		$Year^{-1}$
Total biomass (excluding detritus)	90.67	115.65	t/km^2
Total catch	0.06	0.08	$t/km^2/yr$
Connectance Index	0.18		
System Omnivory Index	0.55	0.34	

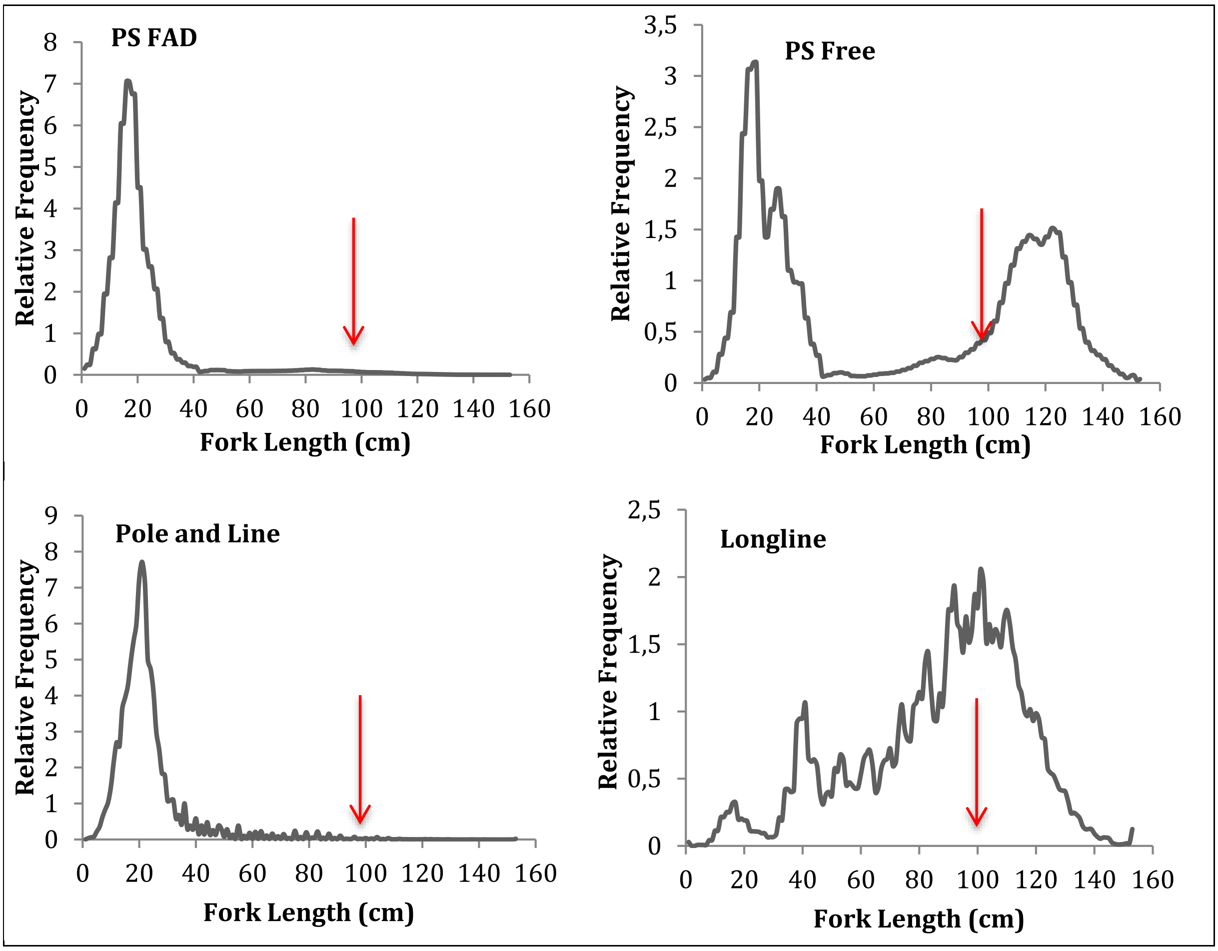

Figure 1. Size composition of catch of yellowfin tuna by gear group. Red arrow represents size at maturity.

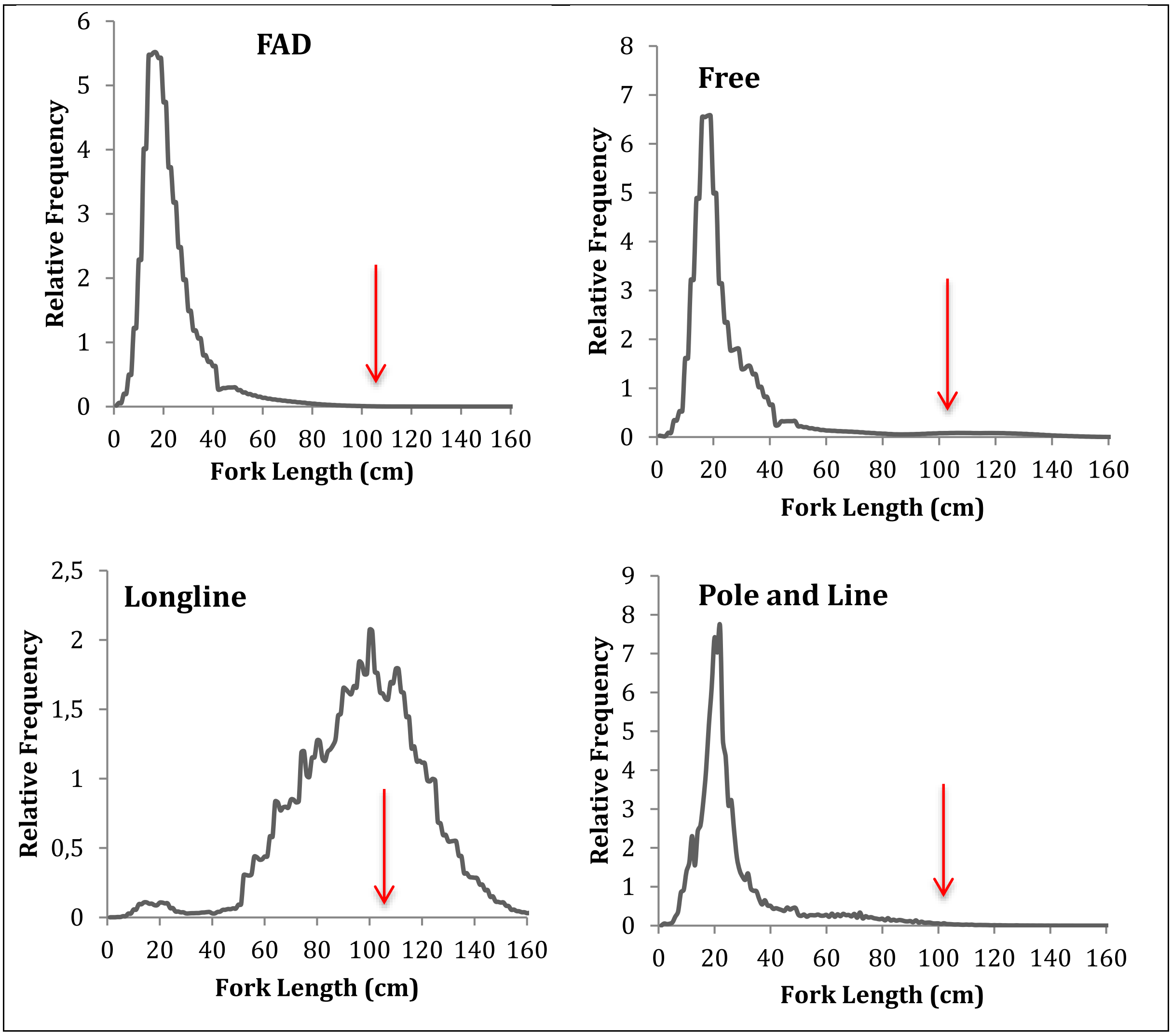

Figure 2. Size composition of catch of bigeye tuna by gear group. Red arrow represents size at maturity.

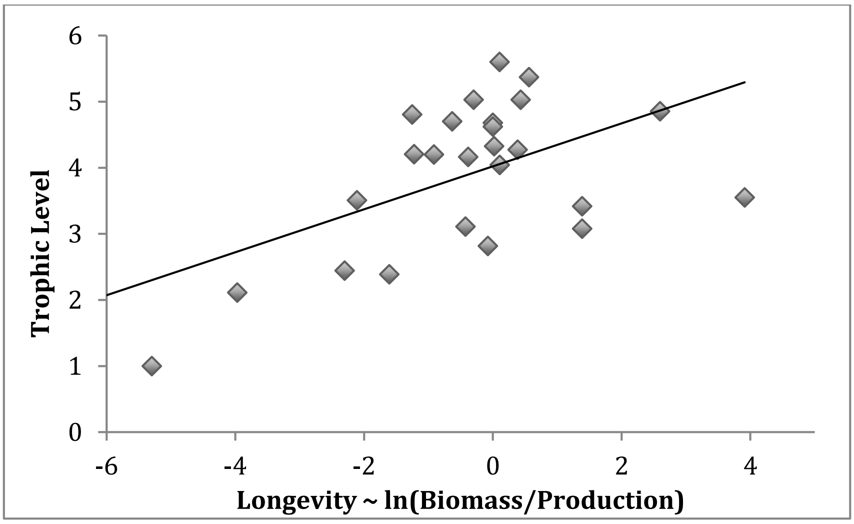

Figure 3. Regression of the longevity of each functional group against their respective trophic levels used to assess thermodynamic stability.

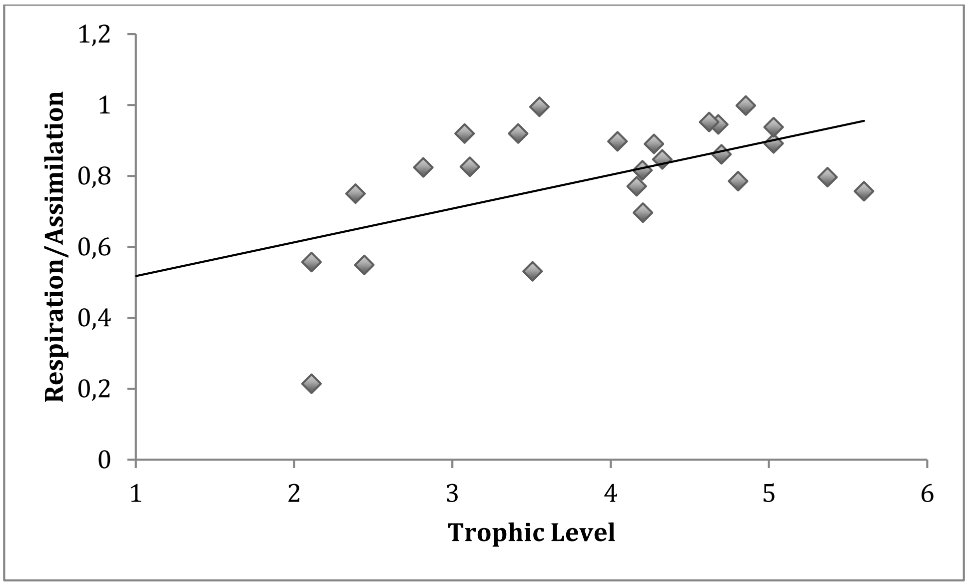

Figure 4. Regression of the trophic levels of each functional group against their respiration to assimilation ratio used to assess thermodynamic stability.

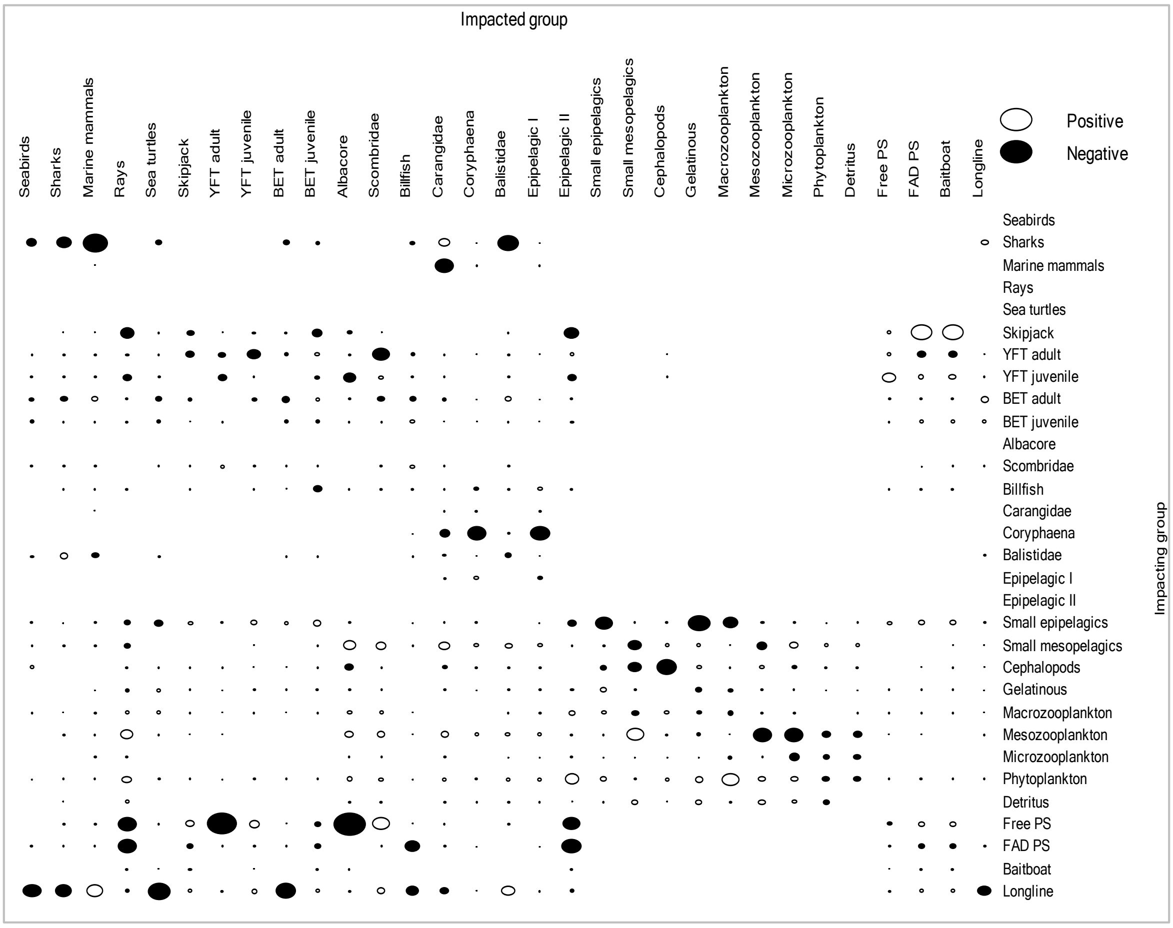

Figure 5. Mixed Trophic Impact analysis for Gulf of Guinean model. Size and color of ovals represent positive and negative interaction amounts.