Estimate populations dynamics of tropical tunas using ecosystem modelling in the Indian Ocean

Xiaodong Li[1,2], Jiangfeng Zhu[1,2*], Yanan Li[1,2]

[1] College of Marine Sciences, Shanghai Ocean University, 999 Hucheng Huan Road, Shanghai 201306, China

[2] Key Laboratory of Oceanic Fisheries Exploration, Ministry of Agriculture, 999 Hucheng Huan Road, Shanghai 201306, China

Abstract: With the development of fisheries research, there has been a gradual shift from a single-species management model to an ecosystem-based fisheries management model (EBFM). The concept of EBFM is increasingly accepted by researchers and regional fisheries management organizations, but there is little relevant research and application in Indian Ocean tuna fisheries. In this study, a multi-species ecological model (LeMaRns) based on body-length structure was constructed based on publicly available data and studies from the Indian Ocean Tuna Commission (IOTC) to analyse the effects of different fishing fleets on stock status and ecosystem structure under different fishing effort. The results of the study showed that an increase in fishing effort resulted in a decrease in population biomass and that predatory and competitive relationships between species also influenced changes in population biomass. Two ecosystem indicators, Large Fish Index (LFI) and Mean Maximum Length (MML), may be more sensitive to the longline (LL) fleet, and both LFI and MML showed a decreasing trend with increasing fishing effort, suggesting that the proportion of small and medium-sized individuals in the community is increasing, which can have important implications for the stability of ecosystem structure. As fishing effort continued to increase, the number of stocks at risk of collapse began to gradually increase, and the number of stocks at risk of collapse may be more sensitive to the longline (LL) fleet. Therefore, inter-species relationships and the impacts of different fishing fleets on stock dynamics and marine ecosystems need to be fully considered in future fisheries management.

Keywords: LeMaRns model; ecosystems; populations dynamics; tuna fisheries; Indian Ocean

1. Introduction

The sustainable use of fishery resources is the main goal of current fishery research. Current fisheries management is mainly concerned with the stock status of target species, and fisheries resources assessment is generally based on single-species assessment models, such as the Surplus Yield Model and Stock Synthesis, etc. These models provide a powerful tool to further our understanding of the pattern of changes in fisheries resources, and they are also the mainstream models used in current fisheries management. However, it also has certain limitations. The single-species assessment model takes the target species as the object of study and focuses on the direct impacts of the fishery, i.e., the role of fishing activities on the composition, reproduction and replenishment of the target species' population. Its management objective is to maximise production while ignoring the indirect impacts of the fishery, such as the destruction of the habitats of target species and the changes in inter-species predation, competitive relationships and fish community structure within the marine ecosystem caused by fishing activities (Anne et al., 2000; Pikitch et al., 2004). For most marine fish species, in addition to human harvesting, food competition and predation mortality are important causes of changes in fish stocks, and the relationships between species are changing as humans continue to exploit fishery resources.

Single-species models are suitable for assessing the current state of a population and making short-term predictions, but for long-term predictions, population mortality, abundance, and biomass are vulnerable to interactions between the populations (Spence et al., 2004). A number of multi-species models and ecosystem models have been developed internationally, including size spectrum model (SSM) (Blanchard et al., 2014), Ecopath with Ecosim (EwE) (Daniel et al., 2014) and Atlantis (Fulton et al., 2005), among others, and these models often incorporate predatory relationships between species. LeMaRns (A Length-based Multi-species analysis by numerical simulation in R) is a length-based multi-species model developed by Hall (Hall et al., 2006), which can be used to analyse the dynamics of fish stocks and the impact of fishing on marine ecosystems. The model can be used to analyse fish population dynamics and the impact of fishing on marine ecosystems. LeMaRns have been applied to assess the impacts of mixed fisheries (Thorpe et al., 2016) and the effects of harvest control rules (Thorpe et al., 2019), among others. Since the LeMaRns model requires less data than other ecological models and has been successfully applied in the North Sea, the LeMaRns model was chosen to analyse the population dynamics of tropical tuna in the Indian Ocean.

In this study, we used the LeMaRns model to simulate the changes in tuna population dynamics and ecosystem structure under different fishing fleets and fishing levels, taking the main target species and bycatch species of tuna fisheries in the Indian Ocean as the objects of study. The results of this study may provide a reference for the sustainable use of tropical tuna resources and mixed fisheries management in the Indian Ocean. The results of this study may provide a reference for sustainable exploitation and mixed fisheries management of tropical tuna in the Indian Ocean.

2.Materials and Methods

2.1 Data sources

A total of 19 species were selected for modelling in this study, which were mainly target and bycatch species in the Indian Ocean tuna fisheries, as well as species at the bottom of the food web that have feeding relationships with tuna. The data on catch (C), biomass (B) and fishing mortality (F) required for modelling were obtained from publicly available data from the IOTC and research reports from relevant working groups. The above data spans a 10-year period from 2010-2019. Data required for species for which IOTC did not conduct a stock assessment were estimated based on relevant research literature.

Table 1 shows the biological parameters required for modelling, with data taken from the research literature on related species in the Indian Ocean and from the fishbase website. The productivity parameter *a* and the density-related parameter *b* related to the Ricker stock-recruitment relationship, which could not be found to be available, were calculated according to the following equations (Stephen et al., 2006):

$$\mathrm{a} = \mathrm{e}^{11-2.3\ln \mathrm{L}_{\infty}}$$

$$\mathrm{b} = \mathrm{e}^{0.1513-0.9484\ln \mathrm{S}_{\mathrm{max}}}$$

Where: L_{∞} is the asymptotic body length of the species; S_{max} is the maximum observed spawning stock size.

Table 1. Biological parameters of the 19 species in the model

Common name	Scientific name	L_{inf}	*W_a*	*W_b*	*k*	L_{mat}	*a*	*b*
Tropical two-wing flyingfish	*Exocoetus volitans*	31.5	0.00427	3.12	1.08	14.7905	21.4351	8020
Pacific chub mackerel	*Scomber japonicus*	41.6	0.00759	3.05	0.3	20.8656	11.3064	2370
Bullet tuna	*Auxis rochei*	44	0.00955	3.06	0.57	22.2022	9.9380	246
Frigate tuna	*Auxis thazard*	49	0.00955	3.07	0.95	25.1994	7.7587	148
Indo-Pacific king mackerel	*Scomberomorus guttatus*	69.6	0.00794	3.01	0.75	35.4373	3.4613	64
Kawakawa	*Euthynnus affinis*	81.7	0.00955	3.05	0.67	41.8066	2.3940	83.9
Skipjack tuna	*Katsuwonus pelamis*	82	0.01122	3.11	0.59	42.8506	2.3739	178
Longtail tuna	*Thunnus tonggol*	111	0.01549	2.97	0.32	60.4327	1.1830	29.4
Albacore	*Thunnus alalunga*	134	0.01862	2.99	0.15	73.5408	0.7672	5.03
Narrow-barred Spanish mackerel	*Scomberomorus commerson*	146	0.00676	3	0.4	80.1265	0.6298	34.2
Yellowfin tuna	*Thunnus albacares*	183	0.01514	3.02	0.4	104.5313	0.3746	11.8
Bigeye tuna	*Thunnus obesus*	203	0.01413	3.02	0.24	114.1149	0.2951	7.18
Long snouted lancetfish	*Alepisaurus ferox*	218.5	0.00389	3.12	0.77	43.3708	0.2492	1.45
Indo-Pacific sailfish	*Istiophorus platypterus*	241	0.00575	3.14	0.15	138.3514	0.1989	0.84
Swordfish	*Xiphias gladius*	252.2	0.0038	3.15	0.13	146.0899	0.1792	0.63
Striped marlin	*Tetrapturus audax*	264	0.0055	3.15	0.53	155.3917	0.1613	0.0444
Black marlin	*Istiompax indica*	306	0.00447	3.13	0.16	177.6091	0.1148	0.5
Blue shark	*Prionace glauca*	340	0.00447	3.1	0.12	200.5263	0.0901	0.22
Blue marlin	*Makaira nigricans*	363	0.00427	3.11	0.39	210.2721	0.0775	0.247

Note: L_{inf}, the von-Bertalanffy asymptotic length of each species (cm); *W_a* and *W_b*, length-weight conversion parameters; *k*, the von-Bertalanffy growth parameter; L_{mat}, the length at which 50% of the individuals are mature (cm); *a* and *b*, Ricker stock-recruitment relationship parameter.

Table 2 shows the food web matrix of the 19 species in the model, and the data were obtained from the results of stomach contents analyses and a review of relevant research literature (Xu et al., 2008; Zhu et al., 2008).

Table 2. The food web matrix for the 19 species in the model

		Species	Predator																		
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
	1	Tropical two-wing flyingfish	0	0	0	0	0	1	1	0	0	0	1	1	0	1	1	1	1	1	1
	2	Pacific chub mackerel	0	0	1	1	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1
	3	Bullet tuna	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	1	0	1	1
	4	Frigate tuna	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	1	0	1	1
	5	Indo-Pacific king mackerel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	6	Kawakawa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1
	7	Skipjack tuna	0	0	0	0	0	0	1	0	0	0	1	0	0	1	1	1	1	1	1
	8	Longtail tuna	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1
	9	Albacore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1
Prey	10	Narrow-barred Spanish mackerel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	11	Yellowfin tuna	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1
	12	Bigeye tuna	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1
	13	Long snouted lancetfish	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	1	0
	14	Indo-Pacific sailfish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	15	Swordfish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	16	Striped marlin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	17	Black marlin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	18	Blue shark	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	19	Blue marlin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Note: 1. Predation relationship; 0. No predation relationship.

1.2 Constructing the model

The LeMaRns model is a length-structured fish community model, with the fish community being represented in terms of both species and length (Hall et al. 2006). In fisheries, body length data are more readily available than body weight data (Lynda et al., 2017), and in addition, fishing selectivity is often correlated with body length and gear structure, making it easier to perform model parameterisation for mixed fishery situations (Spence et al., 2020). The LeMaRns model constructs community structure based on the length structure of the fish, reducing predation behaviour to a function of the relative lengths of the predator and prey, with feeding changing as the individual fish grows (Simon et al., 2002). The LeMaRns model represents many life-history processes, including fishing mortality, natural mortality, and predation mortality, as a function of body length and can be modelled to reproduce community dynamics with a relatively small number of parameters, making the model suitable for fisheries with limited data. The basic equations for the LeMaRns model and ecological indicators are presented in Table 3, and detailed information on the model equations can be found in (Spence et al., 2020).

Table 3. Basic equations for the LeMaRns model and ecological indicators

Growth	
von Bertalanffy	$L_{t,i} = L_{\infty,i}\left[1 - e^{-k_i\left(t - t_{0,1}\right)}\right]$
Mature ratio	$M_{j,i} = \dfrac{1}{1 + exp\left\{-\kappa_i\left(L_j - L_i^{(mat)}\right)\right\}}$
Recruitment	
Ricker function	$R_i = \alpha_i S_i e^{-\beta_i S_i}$
Spawning stock biomass (kt)	$S_i = \dfrac{1}{10^9}\sum_{j=1}^{n_l} M_{j,i} N_{j,i} W_{j,i}$
Mortality	
Predation mortality (M2)	$M_{2(m,n)} = \sum_i \sum_j I_{i,j} N_{i,j} \dfrac{v_{i,j,m,n}}{\sum_k \sum_l v_{i,j,k,l} W_{k,l} N_{k,l} + O}$

Fishing mortality	$F_{j,i} = \sum_{k=1}^{H} e_k q_{i,k}(L_j)$
Catchability	
Logistic curve	$q(L) = \frac{1}{1 + exp(-\eta(L - L_{50}))}$
Indicators	
Large fish indicator (LFI)	$LFI_t = \frac{\sum_{i=1}^{n_s} \sum_{j=1}^{n_l} N_{j,i,t} W_{j,i} I(L_i \geq L_{LFI})}{\sum_{i=1}^{n_s} B_{i,t}}$
Mean maximum length (MML)	$MML_T = \frac{\sum_{i=1}^{n_s} B_{i,t} L_{\infty,i}}{\sum_{i=1}^{n_s} B_{i,t}}$

In this paper, fishing effort is used to represent the level of fishing, and for the same species being fished by the same fleet, fishing effort is related to fishing mortality as follows:

$$F = E \frac{F_{2010-2019}}{E_{2010-2019}}$$

where E represents the assumed fishing effort and $E_{2010-2019}$represents the average fishing effort from 2010-2019, and $F_{2010-2019}$(**Table 4**) represents the average fishing mortality rate of the fleet from 2010-2019. By making the effort coefficient $X = \frac{E}{E_{2010-2019}}$, F can be expressed as $F = XF_{2010-2019}$. Setting the fishing mortality rate can then be adjusted by adjusting the assumed effort coefficient X.

In this paper, it is assumed that there are four different fishing fleets in the Indian Ocean tuna fishery, including longline (LL), gillnet (GN), purse seine (PS) and other (OT). Actual fishing activities are complex and variable, and to simplify the model and make it easier to study, it is assumed that each species can only be fished by one fleet. Based on the proportion of each species' catch by each fleet to the total catch of that species in 2010-2019, the fleet with the largest proportion was selected to be assumed to be the only fishing fleet for that species (**Table 4**).

Table 4. Fishing fleet and average fishing mortality rate ($F_{2010-2019}$) for each species

Species	Gear	$F_{2010-2019}$
Tropical two-wing flyingfish	OT	0.01
Pacific chub mackerel	OT	0.01
Bullet tuna	LL	0.4843
Frigate tuna	LL	0.4843
Indo-Pacific king mackerel	GN	0.4843
Kawakawa	GN	0.4849
Skipjack tuna	PS	0.3985
Longtail tuna	GN	0.5563
Albacore	LL	0.2669
Narrow-barred Spanish mackerel	GN	0.4902
Yellowfin tuna	PS	0.1901
Bigeye tuna	LL	0.2141
Long snouted lancetfish	OT	0.01
Indo-Pacific sailfish	GN	0.2796
Swordfish	LL	0.1134
Striped marlin	LL	0.5367
Black marlin	GN	0.3098
Blue shark	LL	0.2458
Blue marlin	LL	0.2716

2.3 Model fitting and validation

Uncertainty in the model parameters is an important factor causing model error, and in order to reduce the uncertainty in the model parameters, the uncertain parameters b of the LeMaRns model were fitted in this study using a Bayesian framework (Spence et al., 2016). Within this framework, we use a Markov chain Monte Carlo (MCMC) algorithm (Gelman et al., 2013) with parallel tempering (Swendsen et al., 1986) to sample from the posterior distribution.

To obtain reasonable results, the initial model should meet the following two criteria (Thorpe et al., 2016): (1) run the model in the unfished scenario, where all species should persist and ultimately reach equilibrium; and (2) Using the final equilibrium state of validation criterion (1) as a starting point, run the model for 30 years with current fishing effort ($1 \times E_{2010-2019}$). The resulting ratio of predicted biomass B_i to the 2010-2019 average biomass ($B_{2010-2019}$) assessed by the IOTC single-species assessment model ranges from 0.5 to 2.0.

It was verified that after 50 years of running the model without fishing, all 19 species persisted and eventually the biomass of each species reached equilibrium (Fig. 1), and the ecosystem indicators MML and LFI also reached equilibrium after fluctuating in the early period (Fig. 2), which meets the validation criteria (1) of the model. Using the end state at equilibrium as a starting point, after 30 years of model runs at the current level of fishing effort ($1 \times E_{2010-2019}$), the ratio of biomass B_i to $B_{2010-2019}$ for each species ranged from 0.5 to 2.0 (Table 5), which meets the validation criteria (2) of the model. In summary, the LeMaRns established for modelling tropical tuna fisheries ecosystems in the Indian Ocean is reasonable.

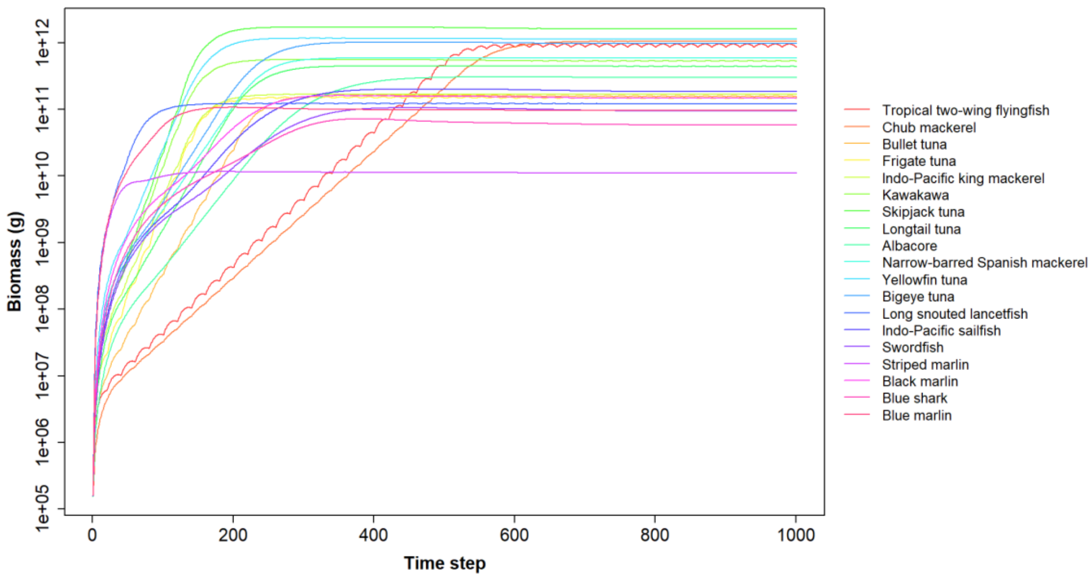


Fig.1. Changes in biomass of each species over 50 years of running the model under a no-fishing scenario

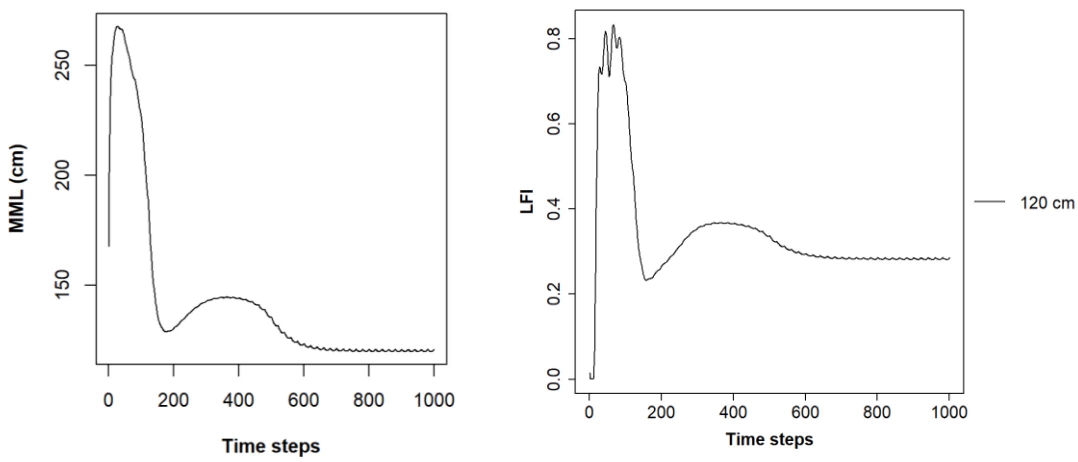


Fig.2. Changes in ecosystem indicators over 50 years of running the model under a no-fishing scenario

Table 5. Ratio of LeMaRns model predicted biomass B_i to IOTC single species model biomass estimates $B_{2010-2019}$

Species	$B_i/B_{2010-2019}$
Tropical two-wing flyingfish	1.04
Pacific chub mackerel	0.92
Bullet tuna	1.01
Frigate tuna	0.99
Indo-Pacific king mackerel	1.03
Kawakawa	0.91
Skipjack tuna	0.98
Longtail tuna	0.78
Albacore	1.05
Narrow-barred Spanish mackerel	1.03
Yellowfin tuna	0.99
Bigeye tuna	1.08
Long snouted lancetfish	0.98
Indo-Pacific sailfish	0.97
Swordfish	1.07
Striped marlin	0.90
Black marlin	1.06
Blue shark	0.90
Blue marlin	0.95

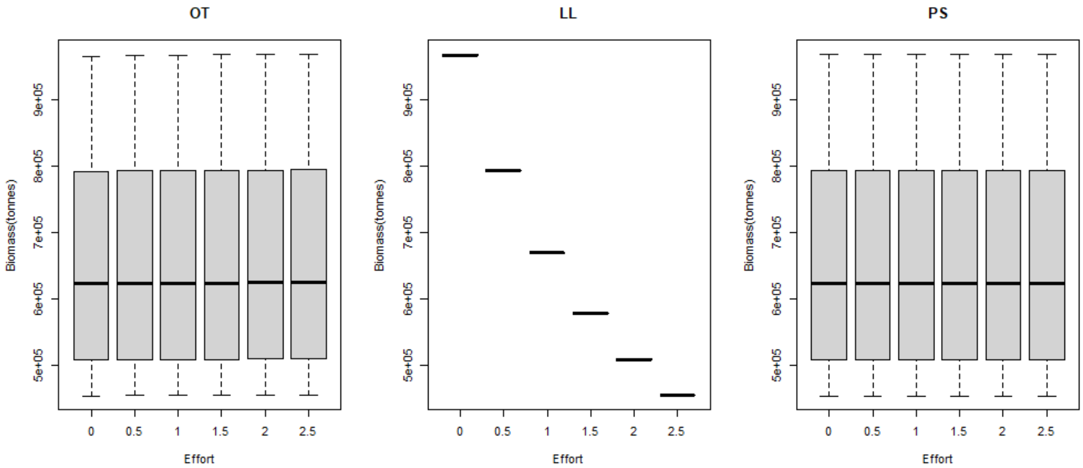
2.4 Model run

As the IOTC has banned fishing with gillnets in the high seas areas of the Indian Ocean from 2022, only three types of fishing fleets other than gillnets are analysed in this study. Using the end state of validation criterion 2 as a starting point, it was assumed that the three fishing fleets fished for 50 years at five levels of fishing effort $[(0、0.5、1、1.5、2、2.5) \times E_{2010-2019}]$. The changes in biomass and population status of each species were observed under different fishing scenarios, while changes in fish community structure and ecosystem stability were monitored through Large Fish Index (LFI), Mean Maximum Length (MML).

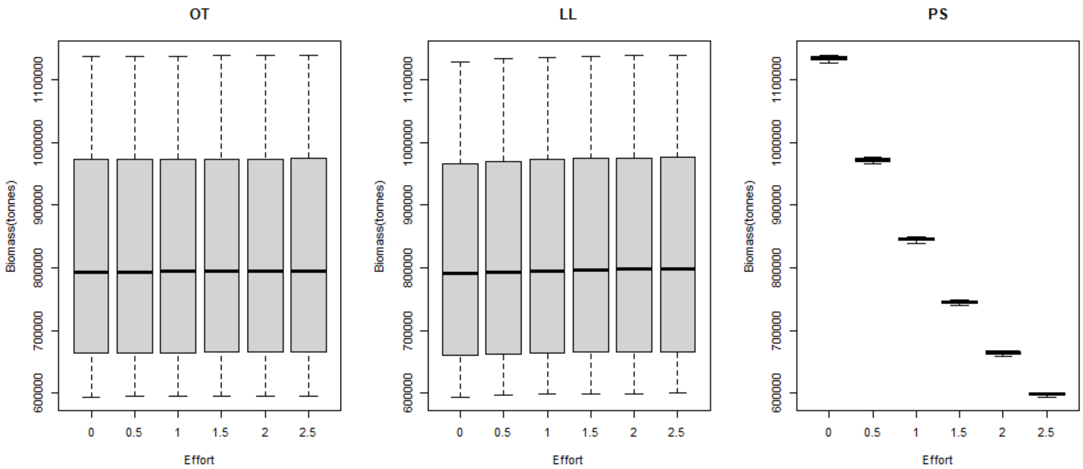
3. Results

3.1 Biomass of each species

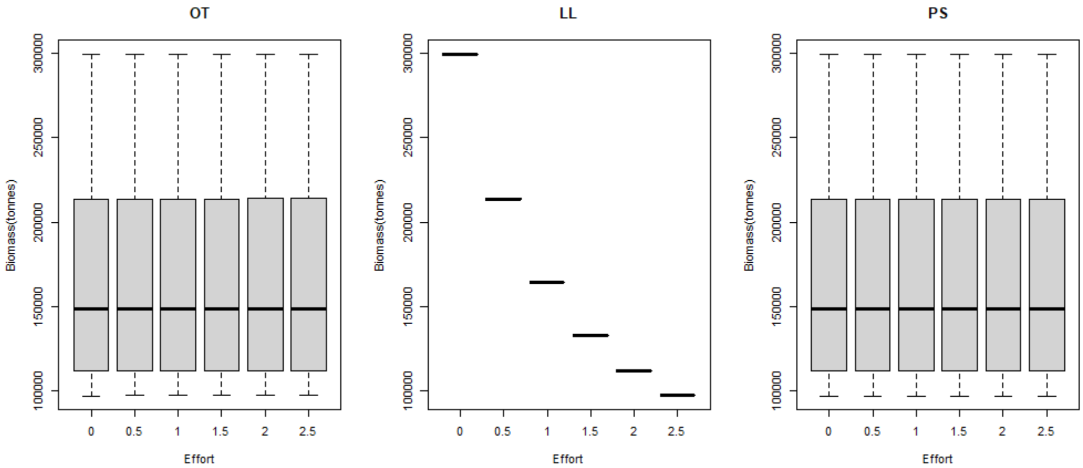
The results of the study showed that as fishing effort increased, the biomass of each species showed a clear downward trend based on the model setup of a single fishing fleet (**Fig.3.**). The biomass of bigeye tuna, yellowfin tuna, albacore tuna and skipjack tuna were less affected by other fishing fleets, but the biomass of swordfish and blue shark were affected by other fishing fleets in addition to a single fishing fleet set up by the model, which is closely related to predation and competition between species.



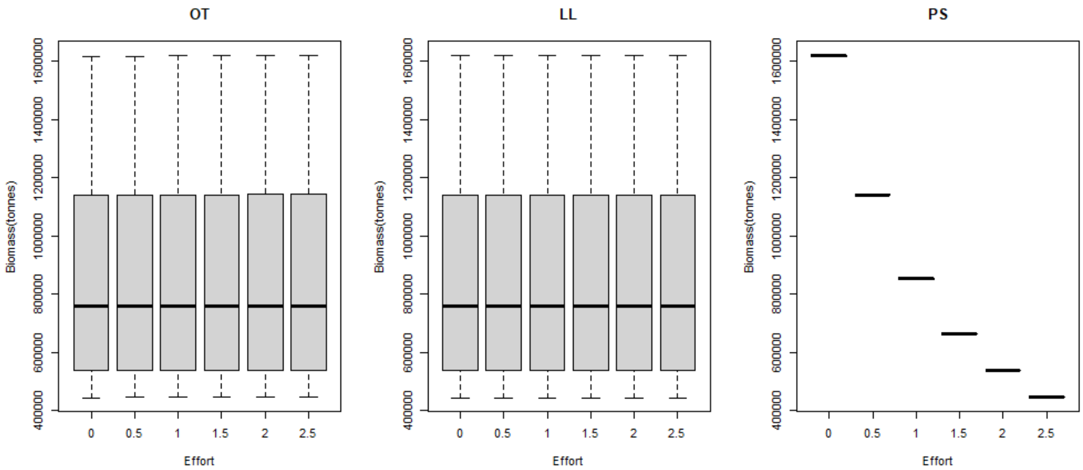
(a) Bigeye tuna



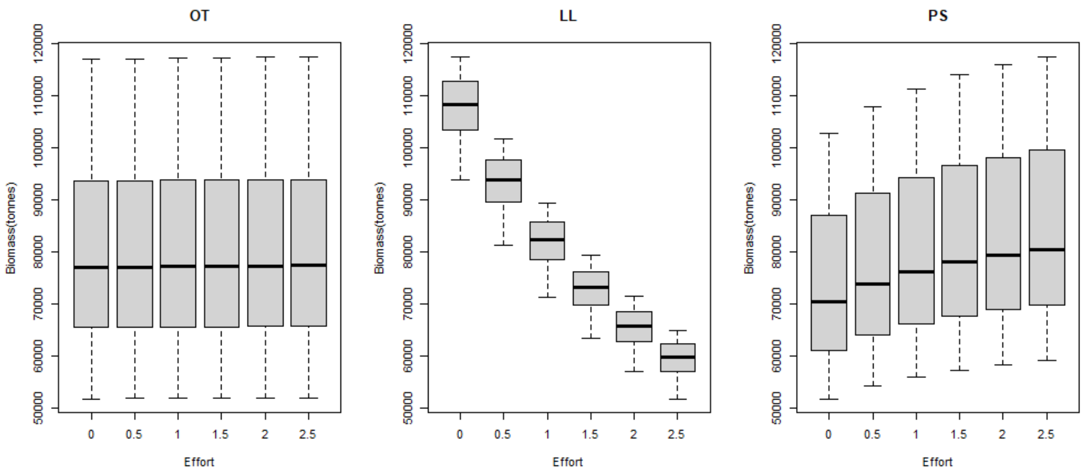
(b) Yellowfin tuna



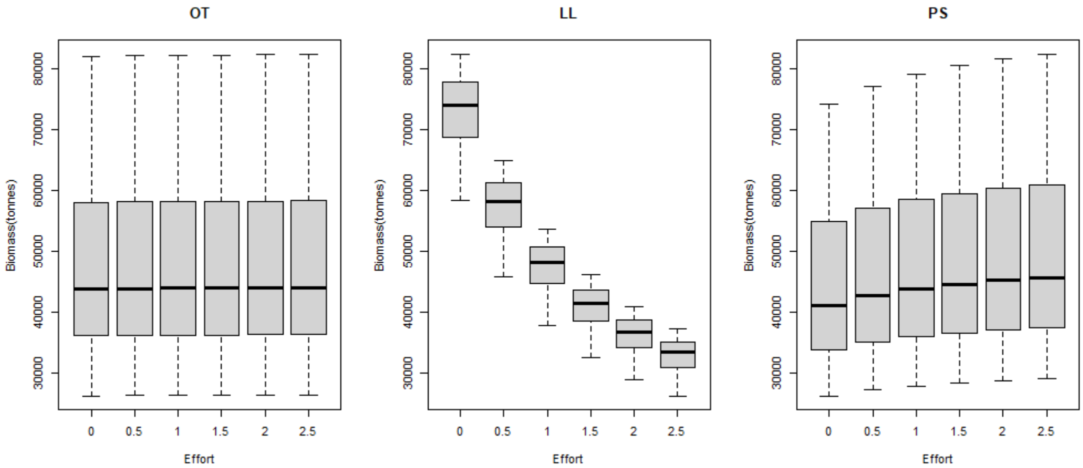
(c) Albacore tuna



(d) Skipjack tuna



(e) Swordfish

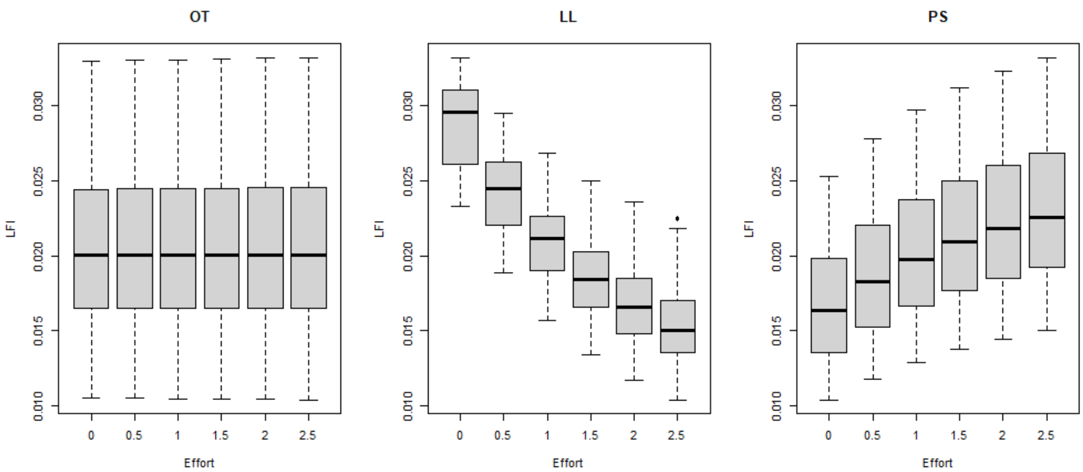


(f) Blue shark

Fig.3. The effect of varying fishing effort on the biomass of each species.

3.2 Ecosystem indicators

The ecological indicators showed different trends with increasing fishing effort under different fishing fleets.(**Fig.4.**) As the fishing effort of the LL fleet increased, both LFI and MML showed a downward trend; as the fishing effort of the PS fleet increased, LFI showed an upward trend, and MML showed an upward trend followed by a gradual downward trend.(**Fig.4.**) Overall, LFI and MML are more sensitive to the LL fleet.



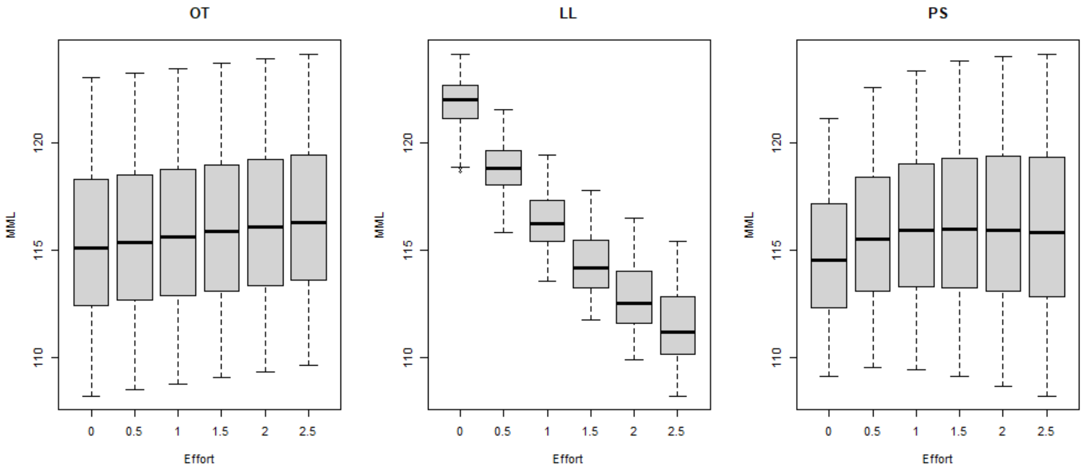


Fig.4. The effect of varying fishing effort on the ecological indicators (LFI and MML).

3.3 Risk of stock collapse

A stock is deemed to have collapsed if its spawning stock biomass (SSB) falls below 10% of its unfished SSB (Worm et al., 2009). **Fig.5.** depicts the number of stocks at risk for each fleet at different levels of fishing effort. As fishing effort increased, the number of stocks at risk of collapse for species fished by the other two fleets except OT began to increase, and the number of stocks at risk of collapse was primarily sensitive to the effort of the LL fleet.

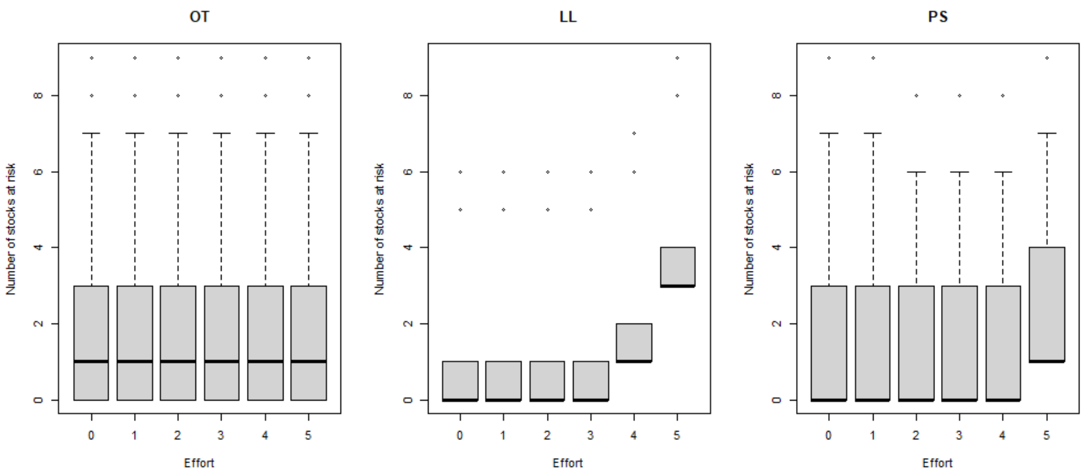


Fig.5. The effect of varying fishing effort on the number of stocks at risk of collapse.

4. Discussion

4.1 Effects of fishing on species biomass

The results of this study showed that with increasing fishing effort, the biomass of each species showed a decreasing trend based on a single fishing fleet in the model setup, which is consistent with the results of related studies (Feng et al., 2019). The biomass of species such as swordfish and blue shark responded to fishing fleets other than the one set up by the model, e.g., as the fishing effort of the PS fleet increased, the biomass of swordfish and blue shark nevertheless showed an increasing trend (**Fig. 3.**). This is related to predatory and competitive relationships between species, e.g. a reduction in food competitors will indirectly lead to a rise in their biomass.

4.2 Impacts of fishing on ecosystems

Ecosystem indicators can be used to monitor the status of fish communities and to analyse the effects of fishing on fish community structure. Both LFI and MML have proven their utility in studying marine ecosystems in past studies (Thorpe et al., 2014). In tuna fisheries, individuals caught in longline fisheries are generally larger, i.e. the main target is individuals in the medium to high length groups. As two length-based ecosystem indicators, both LFI and MML are more sensitive to LL fishing fleets, suggesting that fleets fishing for larger fish have a greater impact on ecosystem structure. Decreases in LFI and MML indicate a decrease in the proportion of large individual fish and an increase in the proportion of small individual fish in the ecosystem, which may have a negative impact on ecosystem stability. A deeper understanding of how the LL fleet operates and careful trade-offs with the rest of the fleet are therefore central to achieving the objectives of mixed fisheries management in fisheries management.

4.3 Risk of stock collapse

In the results of this study, the number of populations at risk of collapse began to gradually increase as fishing effort increased, which is consistent with the actual pattern of population change, i.e., when increasing fishing effort reaches a certain threshold it will result in population collapse. Especially after fishing effort exceeded $3\times E_{2010-2019}$, the number of stocks at risk of collapse began to gradually increase. Fishing effort should therefore be reasonably controlled to avoid the occurrence of stock collapse. The effects of different fishing gears on stock status should be fully considered in future studies to achieve sustainable use of fishery resources.

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