SIMULATING THE EFFECT OF SEASONAL FISHING MORATORIUM ON THE PEARL RIVER ESTUARY COASTAL ECOSYSTEM FOR FISHERIES STRATEGIES EXPLORATION

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ABSTRACT

The coastal ecosystem of the Pearl River Estuary (PRE) has been overfished and received a high level of combined pollution in the past decades. The fisheries stock assessments have shown a declining population and have led to a number of management measures, including fishing moratorium. This study evaluated the effect of the fishing moratorium on the sustainability of PRE fisheries through an ecosystem approach. Then, a series of 100 years dynamics simulations were examined in light of five scenarios on the basis of the 1998 Ecopath model to explore better strategies on the fishing moratorium. S0: the present fishing moratorium continuation, S1: No fishing moratorium executed, S2: extending the duration of the moratorium (i.e., 1 June to 1 September), S3: banning all fishing operations in the moratorium season, S4: No fishing moratorium executed but reducing the fishing effort of all fishing gears by 50%. The results show that the fishing moratorium did benefit the ecosystem protection. Comparative analysis among different scenarios indicates that the largest increase (28.0%) in the fish stocks could be obtained in S4. Moreover, it incurred an increase (43%) in total landings. There seemed to be no differences between S0 and S3.

Keywords: Ecopath with Ecosim; fishing efforts; scenarios; seasonal fishing moratorium; the PRE coastal ecosystem

INTRODUCTION

It has been generally believed that estuaries of large rivers and their adjoining coastal waters are typical marine ecosystems. The Pearl River is the second largest river in China, in terms of the flowrate. And, it is the largest river discharging into the north of South China Sea (SCS). Currently, the coastal region of the PRE is a significantly and quickly developing economic zone. As a result of rapid economic development, the PRE region has experienced overfishing and pollution during the recent three decades. A great deal of waste, excessive reclamation, overfishing and frequent oil spills, etc., greatly influenced the water-related environmental quality in the PRE. Increasingly deteriorated environmental conditions exert great influence on the estuarine ecosystem [1-4]. Moreover, the PRE coastal ecosystem has sustained high stress from fisheries since the 1980s and been proposed as the first major human disturbance to coastal areas [5].

Fishing fleets started to be privatized and investment in fisheries increased since the economic reform at the end of 1978, which resulted in a large increase in the number of fishing boats and improvement in fishing technology [6]. Consequently, the landings of different fishing gears in the PRE experienced substantial increase since 1978 and reached the peak values in 1998 (Figure 1). The Total landings in 1998 have been almost five times as high as in 1981. It can be seen from Figure 1 that the trawling contributed to most catches among the fishing gears from 1978 through 2005, while the catch rates of trawlers in the PRE coastal sea dropped by more than 70% from 1986 to 1998[7]. The trawling has severely damaged groundfish stocks. The loss of groundfish stocks has been compensated by a large increase in shellfish. Purse seining has likewise become a problematic issue in the PRE. Purse seiners catch most juvenile species and fully exploited ones, strongly contributing to the overfishing of mostly fully exploited species together with trawlers. With increasingly anthropogenic activities exerting great influence on the estuarine ecosystem, it appeared that the ecosystem has experienced large changes since 1981, switching from large-size and high-value demersal fishes dominated ecosystem to an ecosystem dominated by small-size and low-value pelagic species [6].

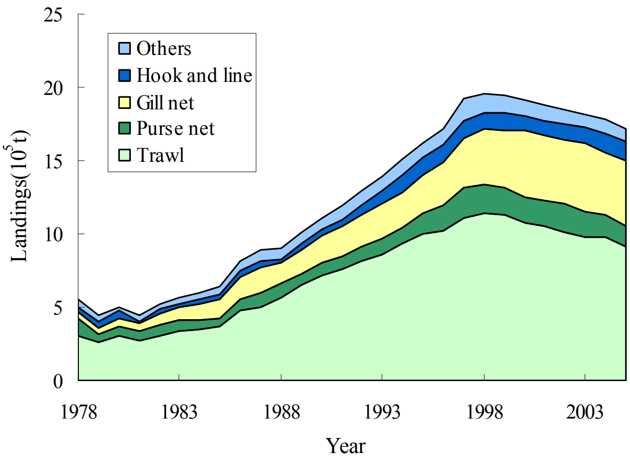

Figure 1. The total landings off the coast of the PRE for gears from 1981 through 2005

With Concern about overfishing, China put forward a zero growth policy on fresh and seawater natural catches in 1999 and imposed a seasonal fishing moratorium. Starting from 1999, the fishing moratorium was implemented from 1 June to 1 August every year in the northern South China Sea (SCS). In the fishing moratorium season, all fishing operations, excluding gillnet, fishing cage and hook and line, are banned to conserve fisheries resources and promote sustainable development of the fishing industry. The approach is considered to be a concrete and effective measure to manage fishing effort and is expected to be of benefit to restore the fisheries resources. According to some researches [8-10], there was a considerable increase in fish catches in the two months immediately following the fishing moratorium as compared with the same period in 1998. And, the fishing moratorium is considered to be effective in protecting fisheries resources and improving production. Up to now, the policy of fishing moratorium has been carried out for more than a decade. The impact of fishing moratorium is still a matter of academic discussion. So far, there have been many studies on the effect of the seasonal moratorium reported recently [11-13]. They were mostly extended qualitatively through comparing of community construction and the constitution of the catch before and after the seasonal moratorium. And, the pros and cons cancel out. Studies [14, 15] using ecosystem simulation models suggested that the effects of the moratorium would be small given the sustained high fishing effort in the region. The published empirical studies that evaluate the effect of the moratorium on the exploited populations or ecosystem dynamics in the PRE are lacking. No detailed quantitative analysis has been conducted so far based on ecosystem simulation. This paper aims to synthesize related information and time series data for dynamic simulation in Ecosim to quantify the changes of the coastal ecosystem under the moratorium as well as the possible impact of the fishing on overall performance of the whole ecosystem. Moreover, some scenarios simulations on fishing moratorium were performed in Ecosim for better fishing strategies exploration in the future.

METHODS AND MATERIALS

The study area

The Pearl River Estuary, located in the south province of Guangdong, represents the typical coastal ecosystem of China. The coastal ecosystem of the PRE in our study, extended from 112°30′E to 115°30′E, 21°00′N to 23°00′N, is a typical ecosystem of China's coastal sea with an area of 72 600 km^2 (Fig. 2). It covers the shelf from the coast to approximately 100m depth. And, it has the characteristics of delta coastal waters driven by salinity gradients arising from the combined influence of watershed and the open sea (Figure 2) with a NE-SW orientation [16].

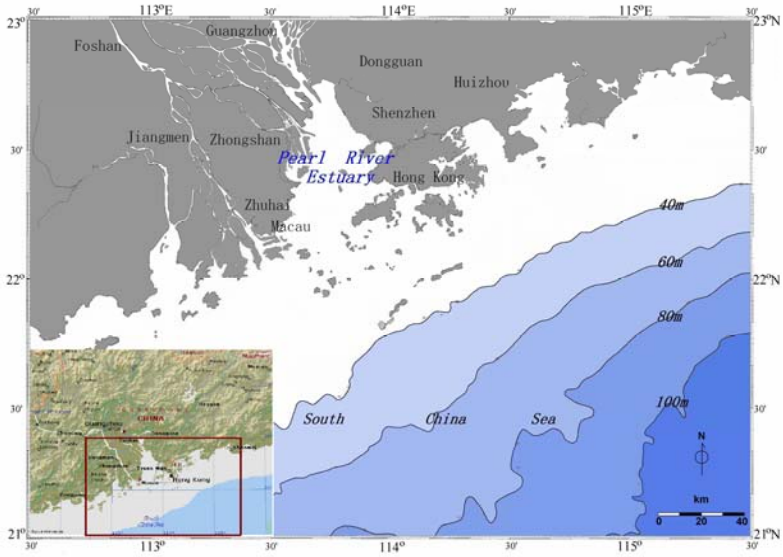

Figure2. Map of the Pearl River Estuary (PRE) coastal ecosystem

The Pearl River Estuary is subjected to the influence of three water sources: the Pearl River discharge, the oceanic waters from the SCS and the coastal waters from the south China coastal current [17]. The resultant nutrient-enriched waters provide large biological productivity and sustain the most important commercial fisheries [18-20]. The PRD coastal ecosystem also plays a role of natural refuge and nursery area for hundreds of species, including some local and endangered species such as *D. maruadsi* (Japanese scad), *S. aurita* (round sardinella), *Larimichthys crocea* (Croceine croaker) and so on. The whole system has diverse productivity, strong fishing activity, and complicated food web relationships [21]. The dramatic expansion of fishing fleets, accompanied with mechanization and other technological advancements, resulted in over-exploitation of near-shore, and later, offshore fisheries resources [22, 23]. These existing fishing fleets are highly capable of bringing already fully exploited fish stocks to an even greater overfished state. Although the fish stocks seem to be able to recover after fishing pressure [24], the recovery rate depends on the productivity of the stocks and the level of depletion [25]. Many marine fishes have collapsed due to overexploitation and it has been reported that many stocks have shown little or even no sigh of recovery after up to 15 years, which suggested that fishes would be depleted to a level in which their recovery may be impaired [26,27]. Therefore, overexploitation in the PRE arouses serious fishery management and biodiversity conservation concern.

The dynamic modelling approach

Ecopath with Ecosim (EwE) is an ecosystem-based analysis software designed for straightforward construction, parameterization and analysis of mass-balance trophic models of aquatic and terrestrial ecosystems [28]. Based on an approach proposed by Polovina [29, 30], and further developed by Christensen and Pauly [31], the Ecopath approach relies on straightforward mass-balance constraints to define trophic fluxes between functional groups. To date, the software has been optimized for direct use in fisheries management as well as for addressing environmental questions through the inclusion of the temporal dynamic model (Ecosim) and the spatial dynamic model (Ecospace) [32]. The prominent advantage of this approach lies in its suitability to the application of a broad field of theories that are useful for ecosystem studies, which includes thermodynamic concepts, information theory, trophic level description and network analysis [33]. It has been used to analyze different aspects of the resulting food web network [34-36]. Moreover, mass-balanced models enable comparisons between different ecosystems and between different periods of the same ecosystem [37-40]. Furthermore, it is often used to explore fisheries management policy options under Ecosim [41-43]. In this paper, the dynamic simulations in Ecosim were performed to investigate the impact of the fishing moratorium on the PRE coastal ecosystem as well as exploring possible fishing strategies.

Ecosim provides a dynamic simulation capability at the ecosystem level, with key initial parameters inherited from the base Ecopath model. It estimates changes of biomass among functional groups in the ecosystem as functions of abundance among other functional groups, and time varying harvest rates, taking into account predator-prey interactions and foraging behaviors [44]. The basics of Ecosim consist of biomass dynamics expressed through a series of coupled differential equations. The equations are derived from the Ecopath master equation and take the form [28]:

$$\mathrm{d}B/\mathrm{d}t = g_i \sum_j Q_{ji} - \sum_j Q_{ij} + I_i - (M_i + F_i + e_i) \cdot B_i \qquad \text{(Eq.1)}$$

and

$$Q_{ij} = \frac{a_{ij} \cdot v_{ij} \cdot B_i \cdot P_j}{2v_{ij} + a_{ij} \cdot P_j} \qquad \text{(Eq.2)}$$

where d*B*/d*t* represents the biomass growth rate of group *i*, g_i is growth efficiency, M_i and F_i are natural and fishing mortalities, I_i and e_i are immigration and emigration rates, Q_{ji} is the consumption of group *j* by group i, v_{ij} and a_{ij} represent rates of behavioral exchange between invulnerable and vulnerable states and a_{ij} represents rate of effective search by predator j for prey type i. a_{ij} is the effective search rate for predator *i* feeding on a prey *j*, v_{ij} is base vulnerability expressing the rate with which prey move between being vulnerable and not vulnerable, B_i is prey biomass, P_j is predator abundance. The behaviour of functional groups in dynamic simulations is heavily affected by the vulnerability factor (*v*), which determines the foraging behaviour of the functional groups in predator-prey interactions. The user-defined *v* setting can range from 1 to the infinity.

The effect of fishing moratorium and fisheries policy exploration

The dynamic simulations were executed based on the improved Ecopath models, developed using EwE 6.0 in previous work[45-47], in which the fisheries were divided into five gears(i.e. trawl, purse net, hook and line, gill net and others) for fishing moratorium simulation. The ecosystem were divided into 24 functional groups in both Ecopath model (1. *Sousa chinensis* 2.Sharks 3.*Trachurus japonicus* 4.*Decapterus maruadsi* 5.*Trichiurus haumela* 6.*Saurida.* 7.*Psenopsis anomala* 8.Upeneus *bensasi* 9.*Nemipterus virgatus* 10.*Priacanthus macracanthus* 11.*Priacanthus tayenus* 12.Other pelagics 13.Other demersals 14.Other zoobenthos 15.Benthic crustaceans 16.Polychaetes 17.Mollusks 18.Echinoderms 19.Cephalopods 20.Jellyfish 21.Zooplankton 22.Phytoplankton 23.Benthic producers 24.Detritus). The model as implemented in Ecosim argues that “top-down vs. bottom-up” control is in fact a continuum, where low *v* implies bottom-up and high *v* means top-down control. And, the result of simulation is very sensitive to the values of *v*. In this study, the *v*'s were attained though time series data fitting. Generally, the more time series data used and the better fitting obtained, the more reliable and reasonable *v*'s we can get. Then the predictions based on the simulation will be more credible. Due to the difficulty in data accessibility, the time series data of the catch and the CPUE data of 7 functional groups from 1981 to 1998 were applied to dynamic simulation in Ecosim under the condition of actually increasing fishing effort until the best fit were obtained (see Figure 3). The catch, CPUE and fishing effort data needed for simulation were all obtained from the local fisheries statistics yearbooks (unpublished).

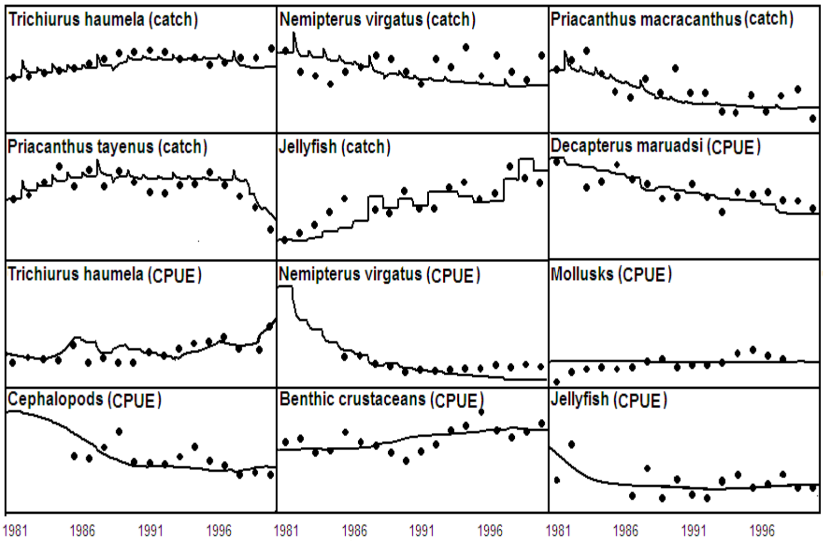

Figure 3. The best fits obtained for 12 sets of times series data on catch and CPUE for 7 groups in dynamic simulations using Ecosim

Then a dynamic simulation from 1981 to 1998 using Ecosim was developed based on the 1981 ecopath model on the assumption that the seasonal moratorium had been ever applied to the PRE fisheries since 1981, in which the *v*'s came from the best time series fitting above. And, the predicted parameters for 1998 through dynamic simulation were used to construct another ecopath model, 1998* model. Then, the cumulative impacts of fishing and the attributes of the ecosystem represented by the 1998* model were compared with that of the actual ecosystem without the fishing moratorium executed. Finally, simulations were developed for a period of 100 years in five scenarios on the basis of the 1998 ecopath model. That is to say, S0: the present fishing moratorium continuation, S1: No fishing moratorium executed, S2: extending the duration of the moratorium (i.e., 1 June to 1 September), S3: listing all fishing gears as banned based on the original fishing moratorium policy, S4: No fishing moratorium executed with reducing the fishing effort of all fishing gears by 50%. All scenario simulations were implemented provided that the fishing effort kept sustained and would not rise in the duration.

RESULTS AND DISCUSSION

Figure 4 shows the cumulative impacts of fishing in both the actual PRE coastal ecosystem and the 1998* model, which indicates the changes of susceptibility of the functional groups to human exploitation. In Figure 4, the positive impacts are shown above the base line and negative impacts are shown below. The impact of the fishing on the specific species varied when the ecosystem was supposed to be under the seasonal moratorium since 1981. For example, the biomass of the Benthic crustaceans, Zooplankton and *Psenopsis anomala* will rise with the fishing effort increased in the 1998* ecosystem. This is contrary to the actual ecosystem. However, the biomass of the benthic producers, echinoderms, other demersals, phytoplankton will decline with the fishing effort increased in the 1998* ecosystem, which is also contrary to the actual ecosystem. This maybe associated with the trophic interactions through the whole food web, which need to be further investigated in the future work. Therefore, the change of one species resulted from fishing will impact on other species through the food chain transfer. Moreover, more functional groups in the 1998* ecosystem showed lower susceptibility to the increase of fishing effort than in the actual ecosystem, which indicates that the ecosystem under seasonal moratorium is more resilient to the anthropic disturbance. That is to say, the seasonal fishing moratorium appears to be effective in protecting the ecosystem from external disturbance.

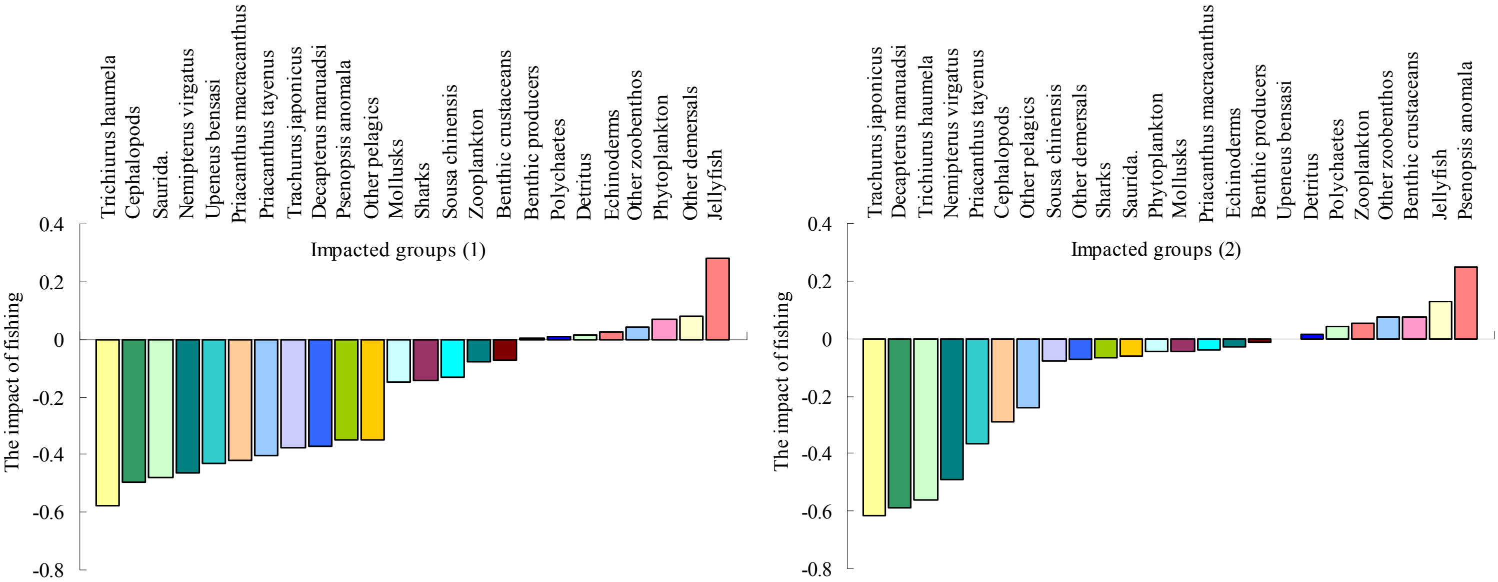

Figure4. The cumulative impacts of fishing gears on functional groups with effort increased by 10%
(1：in actual 1998 ecosystem, 2：in 1998* ecosystem)

There are many attribute indices related to the ecosystem's maturity obtained from the Ecopath model (see Table 1), which follow the theories of Odum and Christensen regarding the developmental stages that ecosystem undergoes [48, 49]. In this study, the predicted parameters originated from the simulation were input the software to construct a new Ecopath model (i.e. 1998* model) for comparative analysis of the system properties. The summary statistics of the 1998* model and the two actual models for 1981 and 1998 were shown in Table 1. It seems that most parameter values of the 1998* model are similar to those of the 1981 model. The connectance index (CI) and the system omnivory index (SOI) are two indices reflecting the complexity of the inner linkage within the ecosystem, which are also used to describe the maturity of an ecosystem and are expected to be higher in a mature system [50]. The 1998* model has almost same CI and SOI values as the 1981 model. The other indices in the 1998* model such as the primary production/biomass ratio (another important descriptor of system maturity), the mean trophic level of the catch, network flow indices in Table 1(excluding Finn's cycling index) and the overhead value (supposed to be used as a possible measure of ecosystem stability) are quite similar to those in the 1981 model. That means the ecosystem would keep sustained provided that the seasonal moratorium had ever been implemented since 1981. Moreover, the ecosystem represented by the 1998* model appears to be a little more mature than in 1981 according to the indices such as the ratio between primary production and total system respiration (PP/R) and the Finn's cycling index (FCI). The PP/R is considered to be an important descriptor of system maturity [50]. It is expected to approach to 1.0 as an ecosystem develops toward "mature" stage and to be higher than 1 in the early developmental stage of a system and lower than 1 when an ecosystem receives large inputs of organic matter from the outside of itself (e.g., one suffering from organic pollution). The PP/R value in 1998* model is 2.59 (Table 1), lower than in 1981 and much lower than in 1998. This suggests that the ecosystem in 1998 would be a little more mature than in 1981 if the fishing moratorium policy had been implemented since 1981. The FCI has been suggested to be correlated with system maturity, resilience and stability [28, 51]. A high FCI is a feature of a mature ecosystem. The FCI of the 1998* ecosystem is 9.62, which is a little higher than in 1981(9.21) and much higher than in 1998 (2.72). The higher FCI value in 1998* model indicates that the ecosystem under fishing moratorium since 1981 would be even more complex and mature than the ecosystem in 1981, not to speak of the actual ecosystem in 1998.

In our previous work [45], the PRE coastal ecosystem has been ever compared through constructing the Ecopath models, which were used in this study as foundation. The comparative analysis indicates that the coastal ecosystem of the PRE in 1981 was in a relatively mature condition compared with that in 1998. However, it was still at an intermediate-low developmental stage even in 1981. In this study, the result of scenario simulation implies that the ecosystem under the fishing moratorium since 1981 will keep the ecosystem sustained after eighteen years over-exploitation. That is to say the fishing moratorium policy is effective on ecosystem protection. However, it just protects the ecosystem from exacerbation but accomplished little in ecosystem recovery under the condition of keeping fishing effort increasing.

Table 1：Summary of the Indices for the PRE Coastal Ecosystem in 1981, 1998 and 1998*

Parameter（unit）	1981[45]	1998*	1998[45]
Ecosystem theory indices			
Total system throughput (t km^{-2} $year^{-1}$)	4799	4565	1764
Mean trophic level of the catch	2.85	2.83	2.30
Gross efficiency (catch/net p.p.)	0.001	0.002	0.005
Calculated total net primary production (t km^{-2} $year^{-1}$)	1681	1559	749
Total primary production/total respiration	2.86	2.59	5.83
Net system production (t km^{-2} $year^{-1}$)	1094	957	621
Total primary production/total biomass	23.51	23.22	22.76
Total biomass/total throughput	0.015	0.015	0.019
Total biomass (excluding detritus) (t km^{-2})	71.53	67.14	32.93
Total catches (t km^{-2} $year^{-1}$)	1.56	3.34	3.49
Connectance Index	0.276	0.263	0.274
System Omnivory Index	0.167	0.173	0.127
Network flow indices			
Finn's cycling index（% of total throughput）	9.21	9.62	2.72
Predatory cycling index (%of throughput withoutdetritus)	1.78	1.94	1.77
Finn's mean path length	2.85	2.90	2.31
Information indices			
Ascendency (% of capacity)	29.50	29.36	34.10
Overhead (% of capacity)	70.50	70.64	65.90

The positive impact of the fishing moratorium on the ecosystem has been confirmed as above. However, the simulation above was just performed in no more than 20 years. The long-term effect of the fishing moratorium is unknown. Moreover, it has been suggested to prolong the duration of fishing closure and the gill net is generally considered to stress the fisheries and therefore should be banned in moratorium season. Then five scenarios, which have been expatiated in method and materials section, were performed in Ecosim on the basis of the Ecopath model in 1998 to explore better fishing strategies as well as the long-time effect of the fishing moratorium policy on the fish stocks. All these simulations were executed given fishing effort sustained in the duration.

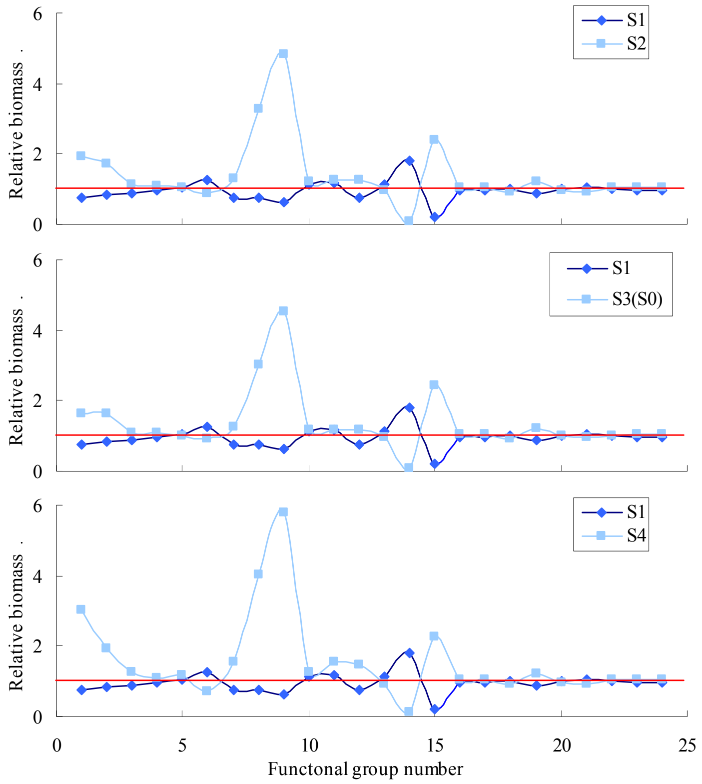

Figure 5. Responses of functional groups to various fishing scenarios
(The red line imply baseline with the relative biomass equaling to 1.
The functional numbers and scenarios introduction refer to “methods and materials” section)

In Figure 5, all scenarios except S1 surprisingly presented quite similar variation trend of the species abundance. Moreover, the trend is just opposite to that in S1 simulations. As can be seen from the Figure 5, the relative biomass values of most functional groups are under the baseline in S1, which indicates that the stocks of most functional groups will shrink without fishing moratorium executed even if there is no fishing effort increased. In the other four scenarios, most functional groups appeared to recovery more or less from over exploitation. This is the case for most fish species (3.*Trachurus japonicus*, 4.*Decapterus maruadsi*, 5.*Trichiurus haumela*, 7.*Psenopsis anomala,* 8.*Upeneus bensasi,* 9.*Nemipterus virgatus,* 10.*Priacanthus macracanthus,* 11.*Priacanthus tayenus,* 12. other pelagics) and the predators at the top of the food web (1.*Sousa chinensis* and 2.Sharks). The largest increase (28.0%) in the fish stocks could be obtained in S4. The functional group 15 (benthic crustaceans) and 19 (cephalopods) also presented obvious increase in abundance. However, banning all fishing operations (S3) during the moratorium season or prolonging the moratorium duration (S2) seemed not to be more beneficial to the stocks recovery than S0, in which the fishing operations were carried out according to the present fishing moratorium policy. Especially in the S3 simulation, the system output was completely same with S0. In the S4 simulation, there was a more prominent increase in abundance for most fish species than in S0, S2 and S3.

All above synthetically indicates that the recovery of fishing stocks will represent a similar tendency either under the condition of intermittent control on the fishing effort such as fishing moratorium(as in S0, S2 and S3) or through reducing the fishing effort straightforwardly (as in S4). Of course, the premise is that there is no increase in fishing effort all along. Furthermore, the control on the fishing effort will not cut down the landings as assumed. It appeared that the predicted landings in 100 years would rise in various degrees in S0, S2, S3 and S4 though the fishing effort got controlled in different way (Table 2).

There are more prominent changes in the landings of all gears in S4 than in other scenarios. It incurred an increase (43%) in total landings in S4. On the contrary, the landings were predicted to decline after 100 years in S1 though there was no any control on the fishing effort. In table 2, the landings of the trawl and the other gears appeared to change obviously. The landings change of the gill net and the hook and line seemed not so abrupt. The differences in the degree of landing changes among different gears lead to the trend of the species stocks in Figure 5 through trophic interaction and fishing cumulative impact, which need further research in the future. On the whole, the fishing moratorium will make the ecosystem recover from overfhsing given fishing effort in the ecosystem controlled. Moreover, the control on the fishing effort will not arouse the landings decline. On the contrary, it can improve the fishery production as well as promote the recovery of the fishery stocks. However, not all species were able to recover from the overexploited in the simulations. Some species kept sustained or even fell to the verge of collapse. That means the ecosystem may not completely recover from overfishing just through fishing effort control. It is essential to explore other fishery resources protection policies.

Table 2: The Landing Changes ($Landing_{end}/Landing_{start}$) of Different Fishing Gears in Simulations

Gear	S1	S2	S3(S0)	S4
Others	0.62	1.58	1.55	1.65
Trawl	0.75	1.43	1.4	1.48
Purse net	0.80	1.22	1.15	1.40
Gill net	0.92	1.17	1.13	1.29
Hook and line	0.92	1.17	1.13	1.28
Total	0.79	1.34	1.31	1.43

CONCLUSION

It is generally conceived that the fishing moratorium accords with its purpose to protect young fish aggregations as the moratorium period coincides with the growth period of most young fishes of various species. Moreover, it is considered that this fishing restriction has injected more energy to the ecology, economy and society. However, the debate on the impact of the fishing moratorium has never stopped since it occurred. In this context, this study is an important effort to investigate the impact of fishing moratorium policy and explore different management and conservation strategies using EwE.

The results indicate that the seasonal fishing moratorium has a beneficial influence on ecosystem protection and should be advocated and encouraged. However, it appeared that the fishing moratorium just protected the ecosystem from degeneration but accomplished little in ecosystem recovery under the condition of keeping fishing effort increasing in the simulation. If there was no increase in fishing effort, the ecosystem would recover from overfishing either through intermittent control on the fishing effort such as fishing moratorium (S0, S2 and S3) or through reducing the fishing effort straightforwardly (S4). The scenario simulations in such two modes (S0, S2, S3, S4) would have similar trends in species abundance change, which were just opposite to S1. Moreover, the control on the fishing effort would not arouse the landings decline and improve the fishery production instead. Extending the fishing season or enlarging the banning range of fishing operations seemed similar to the effect of the present fishing moratorium policy. In addition, not all species were able to recovery from the overexploited in the simulations. Some species kept sustained or even fell to the verge of collapse. That means the ecosystem may not completely recover from overfishing just through fishing effort control. Therefore, it is necessary and urgent to explore other complementary fishery resources protection policies, which is the future direction of research.

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