# An integrated model for marine fishery management in the Pearl River Estuary: Linking socio-economic systems and ecosystems

## Abstract

The paper devises an integrated ecological–economics–social model to assess the implementation of ecosystem-based fisheries management in the Pearl River Estuary (PRE) in the South China Sea (SCS). In particular, this paper presents the development of an integrated model, which links a regional economics social accounting matrix (SAM) model to an ecological model constructed using Ecopath with Ecosim (EwE) software. The impacts on the ecological–economics–social system are examined by varying fishing efforts for four scenarios, including status quo management, fishing effort reduction policy, fishing gear switch policy, and summer closure extension policy. Key results from the predictions (2010-2020) and policy simulations illustrate that the collapse effect is apparent in the status quo scenario. Further, reducing or switching of fishing effort (e.g. elimination of overfishing and reduced habitat disturbance) positively affects the ecosystem and can lead to economic and social welfare gains in the PRE's economy. The gear switch scenario presents a compromise among the economics, social, and conservation metrics, and also outperforms other scenarios in terms of biomass at the end of the simulation period. The fishing effort reduction policy performs better than the summer closure extension policy in terms of the conservation metrics but does relatively poorly in economic terms.

**Keywords:** Integrated model; Ecopath with Ecosim; Social accounting matrix (SAM); Pearl River Estuary; overfishing

## 1. Introduction

Marine and coastal areas are complex systems formed by the interaction between the population, economy, environment, and resources. Understanding the increasingly rapid and complex changes occurring in a coastal marine ecological–economics–social system, and the dynamic nature of the interactions within and between these systems, requires the knowledge of both nature science and social science [1, 2]. Effective fishery management tools are urgently needed to control the problem of over-fishing in coastal ecosystems. The traditional fisheries management tool, which is based on the Gordon–Schaefer model [3-5], is more suitable for homogeneous fleets targeting one species and cannot easily analyse a large number of species [6]. As marine ecosystems comprise complex ecological interactions among species, many researchers argue that the traditional management of commercial fish stocks as single species is ineffective [7]. In this context, ecosystem-based fishing management (EBFM) has emerged as a promising approach to tackle the limitations of traditional fisheries management tools [8].

In order to analyse systems with a large number of interacting elements, such as species interactions in an ecosystem, or those between industries and consumers in a socio-economic system, ecologists and economists have explored the use of ecosystem models and regional fisheries economics models. Multispecies and ecosystem modelling approaches, such as multispecies production (MSP) models, multispecies virtual population analysis (MSVPA), multispecies bioenergetics (MSBE), and Ecopath with Ecosim (EwE), have shown considerable potential for fisheries management [7, 9]. However, some ecosystem models are still limited and do not recognise that the objective should be not only to protect marine fishery resources but also to improve societal benefits such as livelihood, equity, and harmony in the fishery community. Conversely, fishery economists try to evaluate the economics and distributional effects on fishing communities and related industries by linking regional economic models with marine fisheries. Regional economic impacts of fisheries have often been analysed using linear models [10], such as Input–Output (IO) models [11-16], the Social Accounting Matrix (SAM) [17-22], and non-linear models, such as the Computable General Equilibrium (CGE) model [23-26]. However, fishery regional economics models work in an isolated manner and do not allow the dynamic flow of feedback from the ecological system to the socio-economics system.

To date, few ecosystem approach-based regional fisheries economics models have been implemented, because doing so requires multidisciplinary research [27], which may increase the complexity of the regional economic analysis [28, 29]. Jin et al. [30] and Kaplan et al. [31] developed economic–ecological models by coupling a regional IO model of a coastal economy with a linear ecological model of a marine food web. The SAM has been used widely for policy analysis in recent years, but the potential for its application in ecosystem-based management has not yet been fully explored. Although researchers have begun to investigate the theoretical aspects of these ecosystem-scale models, more study is needed to investigate the practical application of such models as policy decision support tools. The challenge is to develop an economics model that incorporates several key economic sectors related to the ecosystem model, such as fish harvesting and seafood processing, and to estimate the changes in gains and losses within the integrated system when policies are implemented.

This paper presents an integrated ecological–economics–social model for important commercial fishes in the Pearl River Estuary (PRE), China. The integrated model is developed by merging a SAM model of the PRE’s coastal economy with an ecological model constructed using Ecopath with Ecosim (EwE) software. Using this integrated model, the study estimates the impacts of fishery policy simulations on the PRE’s economic, ecological, and social systems.

## 2. Methods and Materials

### 2.1 Study area

After the Yangtze, the Pearl River is China’s second largest river (2200 km) in terms of water discharge. The Pearl River consists of three major tributaries, the West River, the North River, and the East River, which converge at the PRE, forming a complex river network that discharges into the South China Sea (SCS) [32]. These factors have given rise to a very complex tropical marine ecosystem in this region. The interactions among fish species in the Pearl River are quite complex, primarily because of the large variety of species involved and their diverse habits and mechanisms of biological predation [33]. The PRE ecosystem in this study is less than 60 m deep and ranges from 112°30’E to 115°00’ E, 21°30’N to 23°30’N (Fig. 1). According to these boundaries, the scope of this research covers an area of approximately 72490 km$^2$ [34, 35].

***Fig. 1 here***

The PRE is an important fishing ground in the SCS, and it provides abundant fishery resources for Guangdong province. The current trends of overfishing and biodiversity losses in the PRE are responsible for the collapse of many commercial marine fisheries established in the last century [36-39]. Furthermore, large increases in the number of fishing boats, improvements in fishing technology, and intensified fishing pressure on commercial fish species have resulted in a decline in the biomass of many large-size and high-quality species and ‘prey release’ of some low-valued species of small fish [37, 39]. The overcapacities of the PRE’s fishing fleets and overexploitation of its fisheries resources means that greater numbers of marine fishing vessels are no longer economically viable [40, 41]. It is therefore necessary to understand the trade-offs between ecological, social, and economic objectives in the given context. Using the PRE coastal fishery as a case study, this paper explores the relationships between the ecological and socio-economic objectives of fisheries management in an estuary ecosystem. A framework diagram (Fig. 2) illustrates the process and mechanism of integrating social, economic, and ecological systems.

***Fig. 2 here***

## 2.2 PRE ecosystem model

### 2.2.1 Ecopath with Ecosim model

As a typical coastal ecosystem, the PRE ecosystem can be described by the interactions of species in a complex food web. Therefore, understanding the biomass stock and ecological relationships among these species is important to design renewable resource policies. In this paper, the trophic mass balance models for the PRE coastal ecosystem are constructed based on Ecopath with Ecosim (EwE) software (version 6.4), which has been widely used for constructing food web models of marine and other ecosystems [42] (freely available at http://www.ecopath.org/). The EwE model provides an ecosystem-based approach and can be expressed as different equations defining trophic interactions as dynamic relationships that vary with biomass and catch changes [43]. The method and theory of Ecopath with Ecosim modelling are detailed in the EwE user guide [44]. The Ecopath model is based on the mass balance of ecosystem inputs and outputs. The basic components of the mass balance equation for each group can be expressed as

$$B_i \times (P/B)_i \times EE_i = Y_i + \sum_{j=1}^{n} B_j \times (Q/B)_j \times DC_{ij} + E_i \qquad \text{(Eq. (1))}$$

where $B_i$ is the biomass of group $i$, $(P/B)_i$ is the annual production/biomass ratio of $i$, which equals the total mortality coefficient ($Z$), $EE_i$ is the ecotrophic efficiency representing the proportion of the production that is utilized in the system, $Y_i$ is the fishing mortality rate, $(Q/B)_j$ is the annual consumption/biomass ratio of predator $j$, $DC_{ij}$ is the proportion of group $i$ in the diet of its predator $j$, $E_i$ is the net migration rate, and $BA_i$ is the biomass accumulation rate.

However, Ecopath only provides a static picture of the ecosystem’s trophic structure. Ecosim is a dynamic model, which simulates changes in ecosystems described under Ecopath. The basic biomass dynamic differential equation in Ecosim is given by

$$dB_i / dt = g_i \sum_{j=1}^{n} Q_{ji} - \sum_{j=1}^{n} Q_{ij} + I_i - (M_i + F_i + e_i) B_i \qquad \text{(Eq. (2))}$$

where $dB_i/dt$ represents the growth rate of group $i$ during the time interval $dt$ in terms of its biomass $B_i$, $g_i$ is the net growth efficiency, $Q_{ij}$ is the consumption rate of type $i$ biomass by type $j$ organisms, $I_i$ and $e_i$ is the immigration rate and emigration rate respectively, $M_i$ is the non-predation (other) natural mortality rate, and $F_i$ is the fishing mortality rate. The species in the food web are represented by predator–prey relationships, and several of these functional groups are commercial fishes that provide inputs to economic systems.

The Ecopath–PRE ecological modelling and the specific application discussed here are detailed in a previously constructed Ecopath model for the PRE ecosystem [38], which is used as the base for the Ecosim predictions of biomass and catch dynamic. The ecological component of the PRE Ecopath model contains 34 functional groups, ranging from primary production to marine mammals. The parameters of the Ecopath model, price, and catches of 15 commercial fish species are presented in Table 1.

***Table 1 here***

The vulnerability parameter is one of the most important parameters that determine the form of predator–prey relationships in the Ecosim module. Here, observed time-series fishing effort data of five fishing methods from 1981-2010 are used to estimate the vulnerability factors, thus providing some empirical support to the model [37, 38]. Catch data for fish species and fishing effort data for fishing gears used in the PRE fisheries are derived from Fisheries Yearbooks, and biomass data are either estimated by the model or obtained from stock assessment reports, field survey data, or other models. The detailed data resources used for the Ecopath model can be found in a previously published paper [37]. The dynamic changes in the biomass and catch data of each functional group resulting from the Ecosim simulation are then imported into the economics model to calculate the changes in socio-economic impact.

### 2.2.2 Ecosystem indicators

A range of ecological indicators is useful for forecasting changes in the marine ecosystem, and many such indicators have been developed or adapted for use with EwE models [45]. Some of these indicators are related to the maturity status and complexity of an ecosystem [46, 47]. They include trophic flow indices [48], the Finn cycling index (FCI) [7], the fishing-in-balance (FiB) index [49], Kempton's index of biodiversity (Q) [2, 50], the system omnivory index (SOI), the system connectivity index (CI), etc. [47]. This study employs ecosystem maturity, biomass diversity, and sustainability of fisheries to evaluate ecosystem integrity after 40 years of fishing in the PRE ecosystem, which has been subject to a variety of fishing policies.

(1) Ecosystem maturity measured by Finn's cycling index

Cycling is considered an important indicator of the ecosystem's ability to maintain its structure through positive feedback [48]. Cycling is assumed to increase as systems mature [46] and can be quantified using FCI [7]. FCI is calculated as the proportion of the total system throughput (the sum of all flows in the system) that is recycled in the system. It is also used as an index of stress [48] and as an indicator of the maturity of the ecosystem [47, 51, 52].

(2) Biomass diversity measured by Kempton's Q index

Kempton's index of biodiversity (Q) [2] expresses the biomass species diversity of functional groups in an ecosystem. The Q statistic calculated from the interquartile slope of the cumulative functional group abundance curve [50] and can be expressed as

$$Q = S / [2 \log(R_2 / R_1)] \qquad \text{(Eq. (3))}$$

where S is the total number of functional groups in the model; $R_1$ and $R_2$ are the biomass values of the 25th and 75th percentiles in the cumulative abundance distribution. Kempton's Q biodiversity index usually increases with growing biomass of high trophic level species and decreases with increased fishing impacts [39].

(3) Sustainability of fisheries measured by the fishing-in-balance (FiB) index

The related FiB index represents the ratio between the energy required to sustain fishery landings and a baseline value. It was originally devised to assess whether a certain level of exploitation can be sustained by a given marine ecosystem and to detect bottom-up effects [30, 49]. The FiB index can be used to draw inferences about the sustainability of fisheries, particularly high trophic-level (TL) species, in an ecosystem context [49]. The FiB index is calculated as

$$FIB = \log\left(Y_i \cdot (1/TE)^{MTL_i}\right) - \log\left(Y_0 \cdot (1/TE)^{MTL_0}\right) \qquad \text{(Eq. (4))}$$

where 0 refers to any year used as a baseline, i refers to any year i, Y is the catch, MTL is the mean trophic level of the landing and TE is the transfer efficiency. FiB index = 0 indicates higher production at lower trophic levels. FiB index > 0 indicates that the fishery has expanded or that bottom-up effects are occurring; thus, the catch is higher than expected. FiB index < 0 indicates that the fishing impact is so high that the ecosystem function is impaired or that the catch may be discarded (although this is not considered in our analysis) [53].

### 2.3 Economics model

In this study, a SAM provides a consistent database that allows a detailed analysis of the economic structure of a region. It is also a useful tool for simulating the impact of economic policies on the economy as a whole. A SAM can be represented as a square matrix $T$ whose $t_{ij}$ element shows the transaction value, where the income obtained by account $i$ originates from the expenditure by account $j$. The matrix of the direct coefficient in the SAM model, denoted as $T$, is derived as follows.

$$T = \begin{bmatrix} A & 0 & E \\ V & 0 & 0 \\ 0 & Y & H \end{bmatrix} \quad \text{(Eq. (5))}$$

where *T* is the matrix of the SAM's direct coefficients, *A* is the matrix of intra-industry technical coefficients including sales and purchases, *V* is the matrix of value added coefficients and includes payments from production accounts to factors, *Y* is the matrix of value added distribution coefficients and includes factor payments to institutional accounts, *E* is the matrix of expenditure coefficients and includes household purchases of industry output, and *H* is the matrix of institutional and household distribution coefficients and includes inter-household/institutional transfer payments.

The supply and demand balance equations can then be written as follows

$$\begin{bmatrix} x \\ v \\ y \end{bmatrix} = T \begin{bmatrix} x \\ v \\ y \end{bmatrix} + \begin{bmatrix} ex \\ \\ ey \end{bmatrix} \quad \text{(Eq. (6))}$$

where *x* is the vector of total production output, *v* is the vector of total value added, *y* is the vector of total institutional income, *ex* is the vector of exogenous goods and services demand (from exogenous stimulus measures, government expenditure/investment, export demand, or other exogenous resources of demand), and *ey* is the vector of exogenous household transfer payments (primarily government transfer payments).

To estimate the economic linkages of a sector, the multipliers obtained from the SAM's inverse coefficients can be given by the following relationship.

$$\begin{bmatrix} x \\ v \\ y \end{bmatrix} = (I - T)^{-1} \begin{bmatrix} ex \\ \\ ey \end{bmatrix} \quad \text{(Eq. (7))}$$

The SAM provides a consistent database that allows for a detailed analysis of the economic structure of the PRE, and it is a useful tool for assessing the impact of fishing activities on the economy as a whole. The socio-economic impacts, including the changes in fish landings in the harvesting sector, processors, and wholesalers, and the induced impacts on total economic output, income, and employment, are estimated by the SAM–PRE.

Table 2 presents the layout of the SAM table. The SAM–PRE is initially calibrated using the 2010 fishery economic data for the PRE and 2010 extended IO table of Guangdong province (State Statistical Bureau 2010, unpublished). The SAM–PRE model only refers to the commercial fishing sector and seafood processing, with the former being classified into five sub-sectors: Stern and pair trawling, gill net fishery, purse seine, hook and line, and other miscellaneous methods (Table 3).

***Table 2 here***

***Table 3 here***

Data for the additional SAM accounts, namely factors of production and institutional accounts, were retrieved from the Guangdong Financial Yearbook 2011, China Fishery Statistics Yearbook 2011, Guangdong Statistical Yearbook 2011, etc. All values in CNY (¥) are converted into USD ($) assuming a fixed exchange rate of $1 = ¥6.8 using the average 2010 exchange rate. This study assumes that the annual economic discount rate remains at 4% for all simulations and embodied technical change enhances productivity by approximately 1% per year.

According to Table 1 and 2, the total output value of marine capture reached $1404.4 million in 2010, representing 12.5% of the output of Guangdong’s fishing sector ($11234.1 million) at current prices. As detailed in Column 1, the activities in the fishing industry involve intermediate commodity inputs from other sectors ($7425.7 million), labour ($3748.4 million), and capital ($60.0 million). Row 4 shows that of the $11383.5 million of fishing industry commodities, $658.8 million and $7453.0 million worth are intermediate commodity inputs to the fish processing sector and other industries respectively, while commodities worth $2893.1 million are consumed within the PRE region, and catch worth $378.6 million is exported to nearby households/regions (e.g. Hong Kong and Macao).

Like most SAM models, the major assumptions of the SAM–PRE model include the following. (1) Prices of commodities such as raw fish and processed fish, and factors of production, such as diesel fuel, are fixed in 2010 dollars. (2) There is no substitution in production and consumption. This means that the fishery sector will always require the same set of inputs for one unit fish, while households will always purchase the same set of commodities.

### 2.4 Linkages between the SAM–PRE and EwE–PRE models

The economic value of an estuary ecosystem is defined on the basis of its relevant ecological features, and its economic value is equivalent to the net present value of goods and services that flow from uses and 'non-uses' of the resource, which refer to the sum of consumer and producer surpluses associated with identifiable uses of the ocean, such as recreation, commercial fishing, marine transportation, etc.

This paper focuses only on the commercial fishing industry's fish harvests from the ecosystem. The coastal ecosystem model is integrated with the economics–SAM model using the classical harvest function from classical fisheries bio-economics analysis.

$$h = q\,E \qquad \text{(Eq. (8))}$$

where $h$ is the quantity of fish harvested, $q$ is the catchable coefficient, $E$ is the fishing effort, and $x$ is the stock size. According to Eq.8, for a fixed catchable coefficient and a given level of fishing effort, the harvest is proportional to stock size. That is, the marine capture fishery output in an economics model is proportional to the biomass in the ecological model. When there are changes in the fishing strategy, the food web biomass dynamic can be simulated using the Ecopath with Ecosim model. Using the average price data from the 2010 field survey (see Table 1) for all simulation scenarios, the unit cost of fishing and prices of landings are assumed to be constant.

Additionally, the SAM model is used to track changes in the rest of the PRE coastal economy that are caused by changes in the fishery sector output. Table 2 presents the SAM fishery table of Guangdong province in the PRE coastal ecosystem. The SAM–PRE model can calculate the economic impacts resulting from variations in the revenues from the five fishing methods in the EwE–PRE model: stern and pair trawling (M1), gill net fishery (M2), purse seine fishery (M3), hook and line fishery (M4), and other miscellaneous methods (M5) (Table 3). The ecosystem is divided into 34 functional groups in the Ecopath–PRE model (Table 1), and 15 commercially exploited species are selected for the SAM–PRE economics model. They are *Decapterus maruadsi*, *Trachurus japonicas*, *Engraulis japonicas*, *stromateids*, *Pneumatophorus japonicas*, *Argyrosomus argentatus*, *Collichthys lucidus*, *Saurida tumbil,* Nemipterus *virgatus*, *Sparidae*, *Trichiurids,* Shrimp, Crab, and Cephalopods.

While numerous studies have focused on the economic benefits of fishing activities, literature on social welfare is rare. Personal income distribution is commonly regarded as one of the main forces determining the social welfare of fishing activity [54]. It is closely related to wellbeing, poverty, and other income-based social issues [29]. This study assumes that the linkages between the social and economic systems come about through income distribution and that personal income distribution is one of the main forces determining social welfare.

As noted above, one of the advantages of the SAM model is its ability to estimate changes in income. Impacts on income resulting from a change in revenue include direct, indirect, and induced effects. In this study, changes in landings affect the fishery sector directly, which in turn causes indirect effects on other industries that supply inputs to the fishery sector. The induced effects refer to the direct and indirect effects leading to changes in household income and spending. The average wage of a fishery worker is \$4441.84 and the dependency ratio (household members/labour) is 2.04 (China Fishery Statistics Yearbook, 2011).

As expected, based on the linear multipliers used in the SAM–PRE model, the impacts from each sub-sector on the PRE coast economy were proportional to the revenues from that sub-sector; since the impact multipliers per sub-sector are typically close to 1 [20], it is assumed that one dollar of fisheries revenue translates into approximately one dollar of income for the PRE coastal economy.

### 2.5 PRE fishery management scenarios

In this study, a SAM model and an Ecopath model are initially calibrated using economic and ecological data for the study region. The resulting model calculates the status quo quantities for a given baseline set of prices $P_0$. To simulate the effects of any policy change, such as a change in fishing effort by different fishing methods, the model is re-run after changing the levels of the variables. The actual historical time series of catch data spans from 1981 to 2010. Based on the economic input–output data in 2010, the socio-economic and ecological effects associated with different ecosystem states are forecast from 2010 to 2020 using four scenarios.

(1) S1 or status quo: This scenario predicts the performance of the existing levels of harvest including the fishing license system, closed seasons and closed areas, minimum mesh sizes, and prohibition of some types of fishing gear and fishing methods.

(2) S2 or fishing effort reduction: Previous studies suggest that the Northern SCS (north of 12°N) ecosystem could be restored by reducing fishing effort by an annual rate of 5% for 30 years [55]. S2 applies this suggestion; fishing efforts of all fishing gear types are reduced by an annual rate of 5% for 30 years from 1981 to 2010.

(3) S3 or gear switch policy: Trawlers are the most important fishing gear type in the PRE, accounting for 50% of total landings. However, trawlers are considered as one of the least selective gear types, causing significant mortality for all fish ages (which is particularly higher for the younger fish) and leading to high by-catch and discard rates [56]. S3 entails a switch of 25% of fishing effort from trawlers to hook and line fishery in order to reduce the by-catch.

(4) S4 or summer closure extension: The status quo management refers to the fishing moratorium, which was implemented from 15 May to 1 August every year in the Northern SCS. In the fishing moratorium season, all fishing operations, excluding gill net, fishing cage, and hook and line fisheries, are banned to conserve fisheries resources. S4 bans all fishing gear in the moratorium season and extends its duration from 1 May to 1 September.

All four simulation scenarios assume that the implementation of the regulations is much stricter in the PRE coastal fishery. However, unlike the previous analyses, the main purpose of this study is not to evaluate optimal policy options but rather to illustrate how linking two models allows simulation of the effects of different fisheries policies from ecological and socio-economic perspectives.

## 3. Results

### 3.1 The ecological dimension

Under the status quo scenario (S1), all stocks of 15 functional groups are considered to be commercially exploited fish, Squid, shrimp, and crab stocks are predicted to decline over the course of the 40-year (1981-2020) simulation period (Fig. 3). The total biomass of the 15 functional groups decreased by nearly 21% of their respective base biomass levels in 1981, assuming the current rates of exploitation intensity at the end of each simulation year.

Compared with the baseline scenario, total annual production of the 15 functional groups (and thus biomass) for S2, S3, and S4 is higher by 27.8%, 44.3%, and 13.9% respectively. The results show the total biomass increased over all policy simulation scenarios, with the highest increase recorded when 25% of the fishing effort is switched from trawlers to the hook and line mode (S3). The biomass levels of several functional groups, such as anchovy, *Argyrosomus argentatus, Decapterus maruadsi*, etc., show declines that can be attributed to increasing predator biomass. Under the fishing effort reduction policy (S2), the biomass of all commercially exploited species, except shrimps, showed increasing trends, comparable with status quo scenario (S1), thus indicating recovery. This suggests that increased predator biomass will decrease the abundance of small pelagic species, such as *Decapterus maruadsi*, in the lower trophic levels. Such similar rebuilding trends were evident in the summer closure extension scenario (S4), as a result of the high catch rate relative to the productivity of these stocks.

***Fig. 3 here***

This study examined three ecosystem indictors that can be used to evaluate changes in the marine coastal ecosystem: (1) Finn's cycling index (FCI); (2) Kempton's Q-diversity; (3) Fishing-in-balance (FiB). The ecosystem indicators identified significant changes in the PRE ecosystem between 1981 and 2020 (Fig. 4 A-C, Table 4).

***Figs. 4 A-C here***

The implication is that systems with higher values of FCI are more mature. Fig. 4-A shows that the results obtained for the FCI index show a decreasing trend, which could probably be related to the fishing pressure in the ecosystem. The highest declining trends of the FCI under S1 indicate that significant amounts of biomass are being withdrawn from the PRE, a probable indication of the high fishing pressure in the ecosystem. All three scenarios show relatively lower FCI compared with the base year (1981). Despite attempts to reduce fishing pressure in S3 and S4, their FCIs continue to be low, indicating sustained pressure on the PRE ecosystem.

The observed decrease of Kempton's (Q) index (Fig. 4-B) in the status quo scenario (S1) for the PRE coastal ecosystem can be traced back to marked decreases in catches of commercially exploited species. The largest increase in Kempton's Q-diversity index occurred for the fishing effort reduction policy (S2). Moreover, the gear switch policy (S3) and summer closure extension policy (S4) led to slight increases in species diversity, possibly reflecting increases in fished functional groups having high biomass levels.

The FiB index (Fig. 4-C) will increase only if the catches increase faster than predicted by TL declines and decrease if increasing catches fail to compensate for a decrease in TL [30, 49]. The value of the FiB index remains below zero under the status quo scenario (S1), confirming that severe depletion of fish stocks is occurring in the PRE ecosystem. It indicates that fishing operations in the PRE withdraw so much biomass from the ecosystem that it is overexploited; in particular, the large and high TL species increasingly replaced by smaller and low TL fishes. On the other hand, an increase in the FiB index case typically occurs when there is an increase in primary production or in the event of geographic and technological expansions in the fishery sector. The significant increase of the FiB index under the summer closure extension policy (S4) indicates that the expansion of fishing results in higher than expected catch. Constant values of the FiB index and values close to 0 over time identify periods during which the fishing pressure on the ecosystem and its carrying capacity remain stable [49]. The gear switch policy (S3) and fishing effort reduction policy (S2) lead to relatively balanced exploitation, as evidenced by the planned modifications to the fishing effort according to the changes in the ecosystem's carrying capacity.

In general, the results of the above-mentioned ecological indexes to the four coast-wide management scenarios considered in this study primarily stem from alterations to fishing mortality. The fishing effort reduction policy (S2), gear switch policy (S3), and the summer closure extension policy (S4) show positive effects on most ecological metrics, but none of them show the best performance across all the evaluated ecological metrics.

### 3.2 The economic dimension

Changes in the PRE's fishery revenues for 10 years (2011~2020) are simulated using 30 years of historical time-series data of fishing efforts (1981~2010) (Fig. 5). The economic impact multipliers contain direct, indirect, and induced direct impacts. The 40-year simulation is conducted using two assumptions: (1) There is excess capacity in the economy over this entire time period and (2) labour employed on account of secondary impacts is drawn from the ranks of unemployed and not from the ranks of the already employed.

***Fig. 5 here***

Based on the biomass dynamic projected by the PRE model and prices for 2010, the stern and pair trawling, gill net fishery, purse seine, and hook and line sub-sectors show revenues of $591.1 million, $440.1 million, $194.9 million, and $60.2 million respectively (Table 3). Compared with the base year (2010), adopting S3 (gear switch policy) would result in a revenue increase of 13.0% for total marine capture (the dockside value of the landings increases from $1404.4 million to $1587.2 million). However, the total landing revenues decrease by 22.7%, 16.5%, and 15.9% for S1, S2, and S4 respectively. The largest total revenue decrease (22.7%) occurs for the status quo scenario (S1). The gear switch policy (S3) results in the greatest immediate increase (37.5%) for gill net fishery revenue. However, switching 25% of fishing effort from trawlers to hook and line fishery leads to an increase of 12.3% in trawler fishery output and a decrease of 7.5% in the hook and line output. The results show that the gear switch policy can lead to economics gains as fish production increases. It is estimated that the remaining three fishing policies (S2, S3, and S4) will result in higher economic gains than S1. In general, all fishing methods other than gill net fishing show reduced revenue (7.5%~56.0%) in S2 and S4 compared with actual revenue from marine capture in 2010.

### 3.3 The social dimension

Income contribution presents the main link between the social and economic dimensions in the proposed model. Employment effects mirror the trends in economic impacts. As observed in Fig.6, the social welfare trends for the five fishing methods are similar to those for economic revenue, which possibly results from fishery household income being closely related to economic revenue.

***Fig. 6 here***

Impact on fishermen’s income is quite high, ranging from \$12709.3 million to \$8904.6 million (2861.3 thousand to 2004.7 thousand jobs respectively). The decline in labour income and number of jobs is highest for the status quo scenario (from \$10802.5 million and 2432 thousand jobs, using 2010 as the base year, to \$8904.6 million and 2004.7 thousand jobs). The largest increases in income and number of jobs (17.6%) occur for the gear switch scenario, which switched some part of the fishing effort from stern and pair trawlers to hook and line fishery. Impacts from the fishing effort reduction and summer closure extension policies range from \$9556.2 million to \$9627.0 million and 2151.4 thousand to 2167.3 thousand jobs respectively. All three fishing policies (S2, S3, and S4) can therefore improve fishery household benefits compared with status quo (S1), with the gear switch policy (S3) performing better than the summer closure extension (S4) and fishing effort reduction (S2) policies in terms of social benefits.

## 4. Discussion

### 4.1 Valuation using all three dimensions

Integrating the SAM–PRE and EwE–PRE models allows multispecies projections of stock trends through time, which translate into 10-year forecasts of fleet economic revenues, social impact, and impact on number of jobs. The value of four scenarios and associated economic, social, and conservation metrics are summarized in Table 4.

***Table 4 here***

The collapse effect is apparent in the status quo scenario (S1); total revenue from marine capture decreases by \$18.9 million, income of fishermen decreases by \$1897.8 million, and employment in terms of the total economy decreases by 427.3 thousand jobs. The simulation results suggest that the status quo can be improved to optimal levels by reducing or switching fishing efforts. Similar to the results from the ecological dimension, the economic performance metrics indicate clear trade-offs between scenarios. The gear switch policy shows the highest summed revenue over all fishery sectors, followed by the summer closure extension policy. This is also true for three fishing sectors, namely stern and pair trawling, gill net fishery, and purse seine, but the economic revenue from the hook and line method decreases even when 25% of the fishing effort is diverted from trawlers to hook and line fishery. However, the gear switch policy and summer closure extension policy show high performance in terms of two ecological dimensions – ecosystem maturity and sustainability of fisheries – and relatively lower performance in terms of biomass diversity. In general, the gear switch scenario is a compromise between economics, social, and conservation metrics, and it also outperforms the other scenarios in terms of total biomass at the end of simulation period. The fishing effort reduction policy outperforms the summer closure extension policy in terms of the conservation metrics, but it does relatively poorly from the economic viewpoint.

Overall, three fishing management policies can effectively reduce overfishing and moderate negative impacts on fishing communities in the PRE. In terms of the ecological system, decreasing or switching fishing effort would help restore the Ecopath–PRE ecosystem and prevent the depletion of several vulnerable species that have already been heavily fished. Economically, many commercially valuable species are heavily overexploited, leading to diminishing potential economic benefits. However, restoration can increase stock abundance and improve the profitability of fishing activities. It is important, therefore, to implement policies that reduce the fishing efforts of methods having large negative impacts on the ecosystem while contributing relatively minor economic benefits. For example, trawlers have the highest economic and social profits, but they also cause the largest negative impacts on the estuary ecosystem. Purse seiners also generate low economic revenues while exerting negative influences on juvenile fish populations. The gill net and hook and line methods, in contrast, present the most advantageous trade-offs between ecological and socio-economic objectives. Although the economic performance of the gill net and hook and line methods does not match that of the trawlers, they are environmentally friendly. Hence, the gear switch policy is likely to be more effective than the fishing effort reduction policy.

The SAM–EwE model develops an integrated framework in which the economic, ecological, and social systems interact with each other. The societal costs and benefits of fishing activities are assessed from social, economic, and ecological aspects. The results reveal that the societal benefits from fisheries in the PRE are declining and will continue to do so if the status quo is maintained. Therefore, there is a critical need for an effective conservation policy to counter the current strong tendency toward overfishing.

### 4.2 Model assumptions and uncertainties

Biomass and landings are the two factors considered in this ecological assessment. Other environmental impacts are ignored. In terms of economic revenues, under the present situation, stern and pair trawling is the most profitable fishing method, which confirms the fact that trawlers play a significant role in the PRE’s marine fishing activities. However, as stated previously, trawlers are one of the least selective gear types, resulting in significant mortality for all fish ages (particularly high for the younger ones) and high by-catch and discard rates [56]. The impacts of bottom trawlers on the seabed are a serious environmental concern, because trawling can modify seabed habitats, disrupt food webs, and reduce benthic biomass and production [57]. As benthic organisms are the major food source for many commercially exploited species, trawling directly affects this vital resource for commercial fish stocks and harms the ecosystem functions that the benthic species provide. Increasing the fishing efforts of bottom trawlers, therefore, results in the depletion of the commercially valuable predators. However, populations of small prey species may be released from predator pressure and increase, becoming more available for capture. The increase in invertebrate landings might be related to the increase in the economic profits of shrimp trawlers, which target benthic invertebrates. Purse seine fisheries always operate using light. Light purse seine fishing used to be one of the main techniques used in marine capture fisheries in the SCS. However, this gear may therefore accidentally capture a high proportion of juveniles from large pelagic species [58], which may endanger the sustainable production of these valuable fish. Therefore, the use of purse seine gear is discouraged in the PRE, and nowadays, only a few seiners operate in Shenzhen, Zhongshan, and Jiangmen, catching a relatively small amount of fish. Hook and line fishery is also a kind of family-based small-scale fleet in the

PRE coastal region and is generally considered as an environmentally friendly but labour-intensive and inefficient fishing method. Gill nets can select mesh size, twine strength, net length, and depth, all of which are closely regulated to reduce the by-catch of non-target species. Gill nets are the traditional fishing gear in Guangdong province. Because of its low cost, low energy consumption, and stable output, gillneting has become an important fishing method. Most gill net fisheries have an extremely low incidence of catching non-target species. Therefore, these fisheries have little negative impact on the environment, as do hook and line fisheries. On the other hand, gill nets target commercially exploited species at high market prices, generating more economic revenue than purse seine and other fixed gears. These environmental and ecological impact factors of the different fishing methods are not considered in this paper because quantitative analyses of multiple environmental impacts are complex, and the actual ecological costs cannot be accurately reflected.

Multiple linkages exist between the coastal economy and marine ecosystem. By linking an ecosystem model with model of a coastal economy, this study analyses the potential ecological and economic effects of various fishing effort management methods at different levels. For example, the ecosystem model, Ecopath–PRE, incorporates the full trophic spectrum of species, making it appropriate for estimating ecological carrying capacity, while the economics model captures linkages among all the industries in the region. This study uses the results from the ecosystem model as an input for the economics model to develop and test four different scenarios for fisheries and thus provide a more comprehensive understanding of the ecological and economic conditions in the PRE. However, both the Ecopath–Ecosim and SAM models present considerable uncertainties. When applied to fishery resources, integrating these models to capture the endogenous interaction of ecological, economic, and social systems is not only very difficult but also adds to the complexity and uncertainty of the resulting model. The ecological–social–economic system is complex, and it is never possible to include all the impacts in an analysis. The material and energy changes (e.g. circulation of nutrient material) may have considerable effects on the PRE ecosystem. In addition, anthropogenic disturbance, such as marine pollution, that generally accompanies rapid economic and social development, may significantly affect the ecosystem [59]. These factors are likely to drive down the potential benefits accrued from fishery optimization policies. Moreover, the effects of other possible social, economic, and environmental fluctuations are not included in the model, their analyses being limited by lack of series historical data.

### 4.3 Fishing policy optimization

In this paper, the impacts of fishing policy on fishing activities are simulated by an integrated model, which considers economic, social, and ecological aspects. Temporal scales are clearly important for both ecological and socio-economic dynamics. The long-term (10-year) forecast using the SAM–EwE model hopes to reach a steady-state balance, allowing the derivation of dynamic changes in benefits and costs. The simulations predict that the fisheries of the PRE are geared toward short-term economic profits at the expense of ecological gains under the current exploitation level, and the status quo can be improved by reducing fishing efforts. In fact, the actual observations from fisheries data in Northern SCS [60, 61] match the estimation results rather well.

Conventional economic theory predicts that for an overfished ecosystem, profits from the system will increase if fishing capacity is reduced to a level that produces the maximum economic rent [4]. However, this optimal fishing effort translating into maximum societal benefits cannot be obtained using the SAM–EwE model. A numerical optimization ecological model (Ecopath with Ecosim) has been used to explore the trade-offs between conservation and socio-economic objectives in the management of a tropical marine ecosystem [62]. More recently, a trophic ecosystem model constructed by Ecopath with Ecosim was linked to a value chain approach in which the flows (amounts, revenue, and cost) of fish products were explicitly tracked from the ecosystem level through the consumer level [63].

Although linear economics models (e.g. IO and SAM) can handle a large number of industry sectors, they cannot capture some key nonlinear interactions, such as supply and demand for goods and services, in the economy, and thus, they cannot be used to examine economic efficiency and welfare changes. To address these issues, a CGE model incorporating several marine resource development sectors was devised [29]. Extending the integrated model presented here, by incorporating a CGE model, would allow the estimation of normative welfare aspects in an ecological–economic-social system under different scenarios.

## 5. Conclusion

The PRE is regarded as one of the most important ecosystems in China’s coastal sea, as it is highly productive biologically and sustains important commercial fisheries for Guangdong province. However, the status of fishery resources and ecosystem structure in the PRE has changed substantially due to overexploitation. As the contradictions between the economy, society, resources, and environment become gradually apparent, it is necessary to develop an integrated method to evaluate the total societal costs and benefits of policy decisions. When fishery managers attempt to reduce fishing effort substantially, economic forces often lead the other participants in the fishery sector to resist these efforts. For instance, decreased fishing levels would reduce fishermen's earnings and welfare.

This paper devises an integrated ecological–economics–social model for important commercial fishes in the PRE. The model is compatible with the ecosystem models currently used to guide fisheries management and policy. An integrated SAM–EwE model is developed by merging an SAM model of the PRE's coastal economy with an ecological model of the PRE's coastal ecosystem. The resulting model thus bridges the gap between the currently used economic and ecological models. Based on the 2010 fisheries SAM model, the study estimates the impacts of possible fisheries policy simulations on the PRE's economic, ecological, and social systems. An accounting method is developed to evaluate the contribution of environmental assets to the overall economy. The costs and benefits are compared among different fishing methods, leading to the conclusion that management and conservation can be improved by adjusting fishing efforts.

The results of the proposed model demonstrate that reduction of fishing effort (e.g. elimination of overfishing and reduced habitat disturbance) can positively affect the ecosystem and allow economic and social welfare gains in the PRE's economy. When overfishing is eliminated, as in the gear switch policy (S3), the outputs increase as fish production increases. However, the socio-economic impact differs across simulations as fish stocks vary. For instance, under the fishing effort reduction policy (S2) and summer closure extension policy (S4), relieving overfishing results in less benefit to the PRE's economy. A possible consequence of restricting fishing is that part of the labour and capital currently engaged in pair and stern trawling would migrate to coastal hook and line fisheries. Furthermore, the substantial increase in the recreational catch would likely create new employment opportunities in providing services for recreational fisheries. Through shifts in the labour force, part of the increased social net benefits generated by the optimal policy could be directed to those currently practicing trawling.

Multi-objective management remains a great challenge for the fisheries sector, as conflicts between socio-economic and ecological goals are inherent. Therefore, the integrated model provides a useful approach to quantify the trade-offs between ecological and socio-economic systems. In addition, the findings of this study can be applied to other marine ecosystems.

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## Figure captions

Fig.1 Map of the Pearl River Estuary

Fig.2 Framework diagram illustrating the process and mechanism of integrating social, economic, and ecological systems

Fig.3 Biomass ratios of the functional groups over the entire 40-year simulation period. The dotted black line is the base line, for which the relative biomass equals 1. The explanation for the functional group numbers appears in Table 1.

Fig.4 The FCI, Kempton's Q (Q-90) index, and FiB index for the four scenarios between 1981 and 2020

Fig.5 Economic impacts by fishery sub-sector in each scenario

Fig.6 Changes in income and labour numbers for the PRE fishery sector in response to the four fishery management simulation scenarios

## Tables

Table 1 Basic parameters of the PRE coastal ecosystem model (1998)

Table 2 Social accounting matrix (SAM) of Guangdong province for the PRE's coastal economy in 2010

Table 3 Fish production of Guangdong province in the PRE (2010)

Table 4 Values of ecological, economic, and social dimensions for four scenarios at the end of simulation year 2020