INTEGRATED SOCIAL-ECONOMIC-ECOLOGICAL MODELLING FOR FISHERIES: THE ECOST MODEL

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Abstract

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Marine and coastal areas are complex systems formed by the interaction among the local population, economy, environment and resources and there is an increasing tendency for recent studies in fisheries research to incorporate interdisciplinary methods in their approach. In this paper, the ECOST model is structured with three modules each of which intends to characterize some relevant aspects of social, economic and ecological systems, respectively. At the heart of the model stands a fisheries economic module describing the fisheries economy; within the model the economic module is extended to the areas of fisheries sociology and biology or ecology where social and ecological aspects of fisheries are modelled following appropriate theory and methodology, respectively.

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Contribution to the field

Marine and coastal areas are complex systems formed by the interaction among the local population, economy, environment and resources and there is an increasing tendency for recent studies in fisheries research to incorporate interdisciplinary methods in their approach. This paper proposes an integrated ecological-economics-social model for evaluating fishing activities and policies to improve fisheries management. The integrated model developed in this research could be applied in developing fishery regions such as in Africa, Asia and Caribbean, and the economy wide value added contribution of fisheries induced by fish harvesting, and its effects on secondary activities such as fish processing, storage, marketing and the indirect impact upon non-fisheries sectors could be evaluated.

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Abstract

Marine and coastal areas are complex systems formed by the interaction among the local population, economy, environment and resources and there is an increasing tendency for recent studies in fisheries research to incorporate interdisciplinary methods in their approach. In this paper, the ECOST model is structured with three modules each of which intends to characterize some relevant aspects of social, economic and ecological systems, respectively. At the heart of the model stands a fisheries economic module describing the fisheries economy; within the model the economic module is extended to the areas of fisheries sociology and biology or ecology where social and ecological aspects of fisheries are modelled following appropriate theory and methodology, respectively.

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1 Introduction

The continued slipping of world-wide fishery resources towards unsustainable direction and the persistent poverty existing in poor fisheries community verify that fisheries management is a complex issue involving social, economic and ecological interactions and in the past sociology, economics and science have walked their own ways in advising fisheries management and policy but couldn't be effective and helpful. Recently, there emerges a new science which integrates multidisciplinary knowledge into a framework to study complex issues from multiple dimensions. A typical method of the science is the integrated assessment modelling, which grows up in study of climate policy and is penetrating into other policy areas but not yet fisheries. Adopting the logic of the Johannesburg Plan of Implementation (JPoI) to restore as much as possible marine ecosystems by 2015 and following the philosophy of the Code of Conduct for Responsible Fisheries (CCRF), this research[1] intends to introduce the integrated assessment method into fishery area for the evaluation of fishing activities and fishing policies in order to contribute to a better management of aquatic resources which affect sustainable development in coastal zones around the world. For the purpose, the present research develops an Integrated Social-Economic-Ecological model for Fisheries management (ECOST model).

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In order to analyse systems with numerous interacting elements such as species interactions in an ecosystem or those between industries and consumers in a socio-economic system economists and ecologists have applied regional fisheries economics models and ecosystem models. Linear models such as Input-output (IO) model and Social Accounting Matric(SAM) are used to analyse the regional economic impacts of fisheries and multispecies and ecosystem modelling approaches such as multispecies production models(MSP) and Ecopath with Ecosim(EwE) have shown remarkable potential for ecosystem modelling (Latour, et al., 2003). The intertwined nature of economy and ecology in the fishery sector leads to economic-ecologic models which combine information and results from each discipline in a single cohesive model. Hoagland et al. (Hoagland, et al., 2003) develop an economic-ecological model via merging the IO model of a coastal economy with a model of marine food web with a case application in New England, USA. Their model simulates the economic impact of changes in primary production in the ecosystem on final demands for fishery products. Steinback et al. (Steinback, et al., 2008) apply the IO to examine the biological and economic impact of reductions in the level of effort for the southern new England lobster fishery. Their results show that reduction in effort could potentially improve the sustainability of lobster resource and stimulate economic growth in the coastal economy. Kaplan and Leonard (Kaplan & Leonard, 2012) combine a fishery ecosystem model with IO model that traces how changes in seafood landing impact the broader economy in the US west coast region under different scenarios. Based on their results each policy option involves trade-offs between economics and conservation of the resources. Fay et al. (Fey, et al., 2019) link the Atlantis ecosystem model to an Input-Output regional economic model and assess the economic impact of change in the fishing effort via different scenarios in the Northeast US. Rybicki et al. (Rybicki, et al., 2020) use a bioeconomic model to understand the response of fleets of northeast Atlantic pelagic fisheries to different scenarios related to quota allocation, disruption in fish and fuel price and changes in recruitment. In another study by (D'Andrea, et al., 2020) a bioeconomic model to capture the dynamics between resources and fishing activities and evaluate the performance of fisheries in terms of catch, and profit is developed.

However one of the shortcomings of these approaches is that these models work in isolation and the dynamic flow of feedback from the ecological system to the socio-economic systems may not be fully captured. The ECOST model proposed in this paper is structured with three modules each of which intends to characterize some relevant aspects of social, economic and ecological systems, respectively. At the heart of the model stands a fisheries economic module describing the fisheries economy; within the model the economic module is extended to the areas of fisheries sociology and biology or ecology where social and ecological aspects of fisheries are modelled following appropriate theory and methodology, respectively; under the model the three modules are interconnected through established links (the so-called hardlinks[2]) so that any changes in a system will automatically affect other systems and also take other systems' reaction into account. In particular, the linkage between social and economic systems is made through income distribution, the linkage between economic and ecological systems is made through changes in fish stock and marine environment, and the linkage between social and ecological systems is made through social response to environmental problems, concerns and states (Failler, et al., 2014). This design enables us to evaluate fisheries management and policies from social, economic and ecological dimensions.

The ECOST model is further extended to measure, monitor, assess, evaluate and analyse consequences of fisheries management and policy intervention with indicators and values. Fisheries impact on the society is obvious and ubiquitous but complex, demanding multi-faceted description. In this aspect various indicators for fisheries performance have been developed in past decade, particularly indicators related to ecology, economy and community (Eggert, et al., 2021). These indicators are designed and organised according to cause-effect chain of Driver-Pressure-State-Impact-Response, ranging from several key indicators or main categories to thousands indices. While they have advantage in characterising various processes, they encounter many problems such as measurability, data availability, selection, aggregation, and judgement. A competing alternative to indicator is valuation, which attempts to measure processes in a unique metric, usually monetary value, and thus provides convenience for policy assessment. However, many ecological and social processes are not possible to be valued. In this research we will not pursue exclusive use of indicators and valuations. Instead, we design a small set of indicators and valuation methods, which are most relevant to the questions in interest and can be generated from the model.

The rest of this paper is organised as follows. Section 2 presents the integrated model. Section 3 and Section 4 discuss the indicators and valuation methods to be used. Section 5 implements an empirical study to explore insights from the model. Finally, Section 6 will conclude the research.

2 The ECOST model

2.1 A structural bioeconomic model of fisheries

There are two strands in the economic modelling of fisheries. One focuses on the bioeconomic relations of fisheries, aiming to maximize fisher's profit by optimally utilizing the resources of commercial species. Its standard bioeconomic model features a fish production function that maps catchability, fishing effort and biomass stock into fish harvest. At steady state the fishing effort can be derived from the balance between harvest and growth of biomass. The other strand is interested in assessment of broad impact of fisheries industry. This strand focuses on the economic structural relations of fisheries, attempting to explore demand or supply stimulus on fisheries and linkage impact of fisheries, with little consideration of interactions between biomass change and fish production. The structural model has traditionally been dominated by input-output models, but recently there emerge SAM and CGE models that allow more comprehensive modelling and analysis (Dixon & Rimmer, 2016). Although linear economic models such as Input-Output can handle a great number of industry sectors, they are unable to capture some key non-linear interactions such as supply and demand for goods and services in the economy and may not be suitable to be used to examine the economic efficiency and welfare and ecosystem changes .

Our interest, however, lies not only in the bioeconomic relations of fisheries that are more oriented towards resource utilization, but also in the economic structural relations of fisheries that are more oriented towards regional economic and social development. Thus, we develop a structural bioeconomic model of fisheries by combining both strands. For this purpose we take a two-step modelling strategy. Firstly, we develop a fisheries input-output model in which structural relations of fish production with other sectors are specified, and with which full impact of fisheries on the economy can be assessed. Secondly, we specify a function of fish production that is determined by both fishing effort and catchability. With the function fishing effort is exogenously given rather than optimally determined, and catchability varies according to changes in biomass stock, which in turn depends on fish production. By this way the fish production follows a non-linear function that relates Catch per Unit Effort (CPUE) to fishing effort in calculating total catch. The innovative advance of the model is that the CPUE is no longer a parameter rather it is a variable, which is subject to biomass change. Therefore, the model establishes connection between the economy and the resource status via the CPUE which acts as an adjustable variable.

2.1.1 The structural relations of fisheries

In the economics literature, input-output analysis was a traditional method to model structural relationships of an economy, probably due to its concise presentation of quantitative interdependence and operational convenience (Seung, Kim, Yi, & Song, 2021). The well-known input-output model is the Leontief demand-driven model and the less well-known is the Ghosh supply-driven model. In the Leontief model, the Leontief production coefficients, $a_{i,j} = \frac{x_{i,j}}{X_j}$, is defined to be the proportion of sector *i*'s product in sector *j*'s total use of production, where $x_{i,j}$ is sector *j*'s production requirement on sector *i*'s product and X_j is sector *j*'s total input of production. In the Ghosh model, the Ghosh allocating coefficients, $b_{j,i} = \frac{x_{j,i}}{X_i}$, is defined to be the share of the sector *i*'s product allocated to sector *j* in total product of sector *i*, where X_i is sector *i*'s total output.

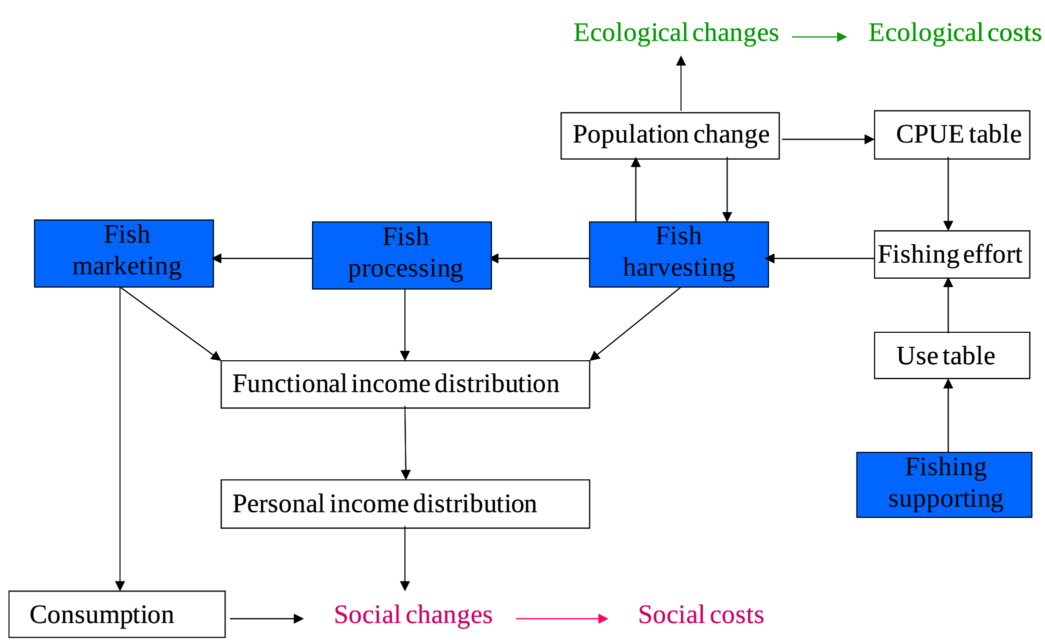
Fish production consumes other sectors' products or services and fish are provided for other sectors' production as well as for consumption. In this sense, fishing sector is backward or forward linked with its upstream or downstream sectors and has impacts that spread out the economy. This structural impact reflects fishing sector's overall economic importance or performance and thus needs to be assessed with disaggregate, structural economic models.

In the literature of fisheries economics, input-output method was conventionally adopted to analyse the contribution of fishing sector to the economy (Seeteram, Bhat, Pierce, Cavasos, &

Die, 2019). The traditional fisheries input-output models were either demand-driven or output supply-driven, not well consistent with modern fisheries regulations. In recognition of the problem, the present research develops a new input-output model that takes fishing effort as the driver of the fisheries economy to assess the economy-wide impact of fishing.

According to the fish production chain, fisheries can be classified into subsectors including not only fishing but also fishing supporting, fish processing and marketing. Figure 1 shows the structural relationships of fishing with other relevant sectors i.e. the fishery production chain and its linkages to social and ecological systems. At the outset it is the variable of fishing effort, which is the principal driver of fishing activity. The fishing supporting sector is backward-driven by fishing sector to service, for example, gear production and maintenance. The fish processing sector is forward-driven by fishing sector, processing raw fish with particular techniques such as frozen, smoking, canned, salted, etc. The fish marketing sector sells raw and processed fisheries products and forward-driven by both fishing and processing sectors. The rest of the economic sectors are the non-fisheries sectors, which are backward-driven by all the fisheries sectors. Within the fishing sector, there are a number of heterogeneous micro fishers that we define as metiers. A fishing metier refers to a particular fleet equipping with a particular gear and targeting a particular species as main catch with other possible species as by-catch. Conventionally, a metier should be related to more than a single target species, indeed. However, one of the fundamental assumptions and also limitations of input-output models is that one type of producer only produces one type of products. Therefore, we have to assume a metier catches a basket of differential species rather than a single species.

Figure 1. A fishery economic model with full production chain and linkages to social and ecological systems



Consider a fisheries economy with a general economic structure that includes a capture fisheries sector (*f*) which consists of *n* metiers, a fish processing sector (*fp*), a fish marketing sector (*fm*), and a non-fisheries sector (*nf*) that includes fishing supporting business. Assume that fishing efforts are represented by the primary inputs or value added in capture fisheries and are exogenously given, the value added generated by the fish processing sector is 'pushed' by the capture fisheries,

$$V_{fp} = c_{fp} \cdot B_{fp,f} \cdot X_f \qquad (1)$$

where the parameter, c_{fp}, is the ratio of value added to total core input in the fish processing sector, representing the effect of per unit core input use on value added generation; $B_{fp,f}$ is a row vector consisting of the Ghosh intermediate allocating coefficients of metiers for the fish processing sector, $b_{fp,f}$. X_f is a column vector of endogenous total inputs of the metiers.

The value added generated by the fish marketing sector is 'pushed' by both the capture fisheries and the fish processing sector,

$$V_{fm} = c_{fm} \cdot \left(B_{fm,f} \cdot X_f + b_{fm,fp} \cdot X_{fp} \right) \qquad (2)$$

where the parameter, c_{fm}, is the ratio of value added to total core input in the fish marketing sector, representing the effect of per unit of core input on value added generation. $B_{fm,f}$ is a row vector consisting of the Ghosh intermediate allocating coefficients of the capture fisheries for the fish marketing sector. $b_{fm,fp}$ is a Ghosh intermediate allocating coefficients of the processing sector for the marketing sector. X_{fp} is endogenous total input of the fish processing sector.

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Assuming that the fisheries sectors' production follows the Ghosh supply-driven model, the balances of fish production are as follows,

$$B_{f,f} \cdot X_f + B_{f,fp} \cdot X_{fp} + B_{f,fm} \cdot X_{fm} + B_{f,nf} \cdot X_{nf} + V_f = X_f, \quad f \in (1, \ldots, n) \qquad (3)$$

where all B represent the Ghosh intermediate allocating coefficients. Among them, $B_{f,f}$ is a square matrix by metier with elements $b_{f,f}$. Normally this matrix contains zeros from the data, since basically there are no interactions among the metiers. X_f is a column vector of total outputs by metier. $B_{f,fp}$ is a column vector by metier for the fish processing sector. $B_{f,fm}$ is a column vector by metier for the fish marketing sector. $B_{f,nf}$ is a column vector by metier for the non-fisheries sector. X_{fm} and X_{nf} are total inputs of the fish marketing and non-fisheries sectors, respectively. V_f is a column vector by metier of exogenous primary inputs (or value added of the metiers).

The primary input of the fish processing sector depends on the amount of fish captured. The more raw and fresh fish that are to be processed, the more primary input that is needed in the fish processing sector. As a result, the production of the fish processing sector will also follow the Ghosh supply-driven model with the following supply and demand balance,

$$B_{fp,f} \cdot X_f + b_{fp,fp} \cdot X_{fp} + b_{fp,fm} \cdot X_{fm} + b_{fp,nf} \cdot X_{nf} + V_{fp} = X_{fp} \qquad (4)$$

where $B_{fp,f}$ is a row vector by metier for the fish processing sector. Its element $b_{fp,f}$ indicates the proportion of metier *f*'s product allocated to the fish processing sector (reflecting the forward linkage effect). $b_{fp,fp}$, $b_{fp,fm}$ and $b_{fp,nf}$ are the Ghosh intermediate allocating coefficients of the processing, marketing and non-fisheries sectors for the fish processing sector, respectively. The primary input (or value added) of the sector V_{fp} is endogenously determined through the 'pushing' effect of capture fisheries.

The primary input of the fish marketing sector depends on both the amount of fish harvested and processed. The more raw or processed fish that needs to be distributed in the market, the more the primary input needed in the fish marketing sector. As a result, the production of the fish marketing sector also follows the Ghosh supply-driven model, with the following supply and demand balance,

$$B_{fm,f} \cdot X_f + b_{fm,fp} \cdot X_{fp} + b_{fm,fm} \cdot X_{fm} + b_{fm,nf} \cdot X_{nf} + V_{fm} = X_{fm} \quad (5)$$

where $B_{fm,f}$ is a row vector by metier for the fish marketing sector. Its element $b_{fm,f}$ indicates the proportion of metier *f*'s product allocated to the fish marketing sector (reflecting the forward linkage effect). $b_{fm,fp}$, $b_{fm,fm}$ and $b_{fm,nf}$ are the Ghosh intermediate allocating coefficients of the processing, marketing and non-fisheries sectors for the fish marketing sector, respectively. The primary input (or value added) of the sector V_{fm} is endogenously determined through the 'pushing' effect of both capture fisheries and fish processing.

Substituting equations (1) and (2) into equations (4) and (5), respectively, we get

$$(1 + c_{fp}) \cdot B_{fp,f} \cdot X_f + b_{fp,fp} \cdot X_{fp} + b_{fp,fm} \cdot X_{fm} + b_{fp,nf} \cdot X_{nf} = X_{fp} \quad (6)$$

and

$$(1 + c_{fm}) \cdot B_{fm,f} \cdot X_f + (1 + c_{fm}) \cdot b_{fm,fp} \cdot X_{fp} + b_{fm,fm} \cdot X_{fm} + b_{fm,nf} \cdot X_{nf} = X_{fm} \quad (7)$$

Contrary to the supply-driven fisheries sectors, the non-fisheries sector follows the Leontief demand-driven model, and has the following product balance:

$$A_{nf,f} \cdot X_f + a_{nf,fp} \cdot X_{fp} + a_{nf,fm} \cdot X_{fm} + a_{nf,nf} \cdot X_{nf} + D_{nf} = X_{nf} \quad (8)$$

where all parameters are the Leontief intermediate use coefficients of the non-fisheries sector. Among them, $A_{nf,f}$ is a row vector the element of which $a_{nf,f}$ indicates the proportion of the non-fisheries sector's product used in capture fisheries sector *f*'s production (reflecting the backward linkage effect). $a_{nf,fp}$, $a_{nf,fm}$ and $a_{nf,nf}$ are the proportions of the non-fisheries sector's product used in processing, marketing and non-fisheries sectors' production (also reflecting the backward linkage effect), respectively. D_{nf} is exogenous final demand for non-fisheries product.

Combining equations (3), (6), (7) and (8), we express them in a matrix format,

$$\tilde{A} \cdot \tilde{X} + \tilde{Y} = \tilde{X} \quad (9)$$

where

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$$\tilde{A} = \begin{bmatrix} B_{f,f} & B_{f,fp} & B_{f,fm} & B_{f,nf} \\ (1+c_{fp})B_{fp,f} & b_{fp,fp} & b_{fp,fm} & b_{fp,nf} \\ (1+c_{fm})B_{fm,f} & (1+c_{fm})b_{fm,fp} & b_{fm,fm} & b_{fm,nf} \\ A_{nf,f} & a_{nf,fp} & a_{nf,fm} & a_{nf,nf} \end{bmatrix}, \ \tilde{X} = \begin{pmatrix} X_f \\ X_{fp} \\ X_{fm} \\ X_{nf} \end{pmatrix} \text{ and } \tilde{Y} = \begin{pmatrix} V_f \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

The solution of this linear equation system can be solved with

$$\tilde{X} = \left(I - \tilde{A}\right)^{-1} \cdot \tilde{Y} \tag{10}$$

where I is unity matrix. Assuming $D_{nf} = 0$, the solution then gives all impact of capture fisheries.

Since non-fisheries production follows the Leontief demand model, its value added will be determined endogenously by total output or input:

$$V_{nf} = v_{nf} \cdot X_{nf} \tag{11}$$

where v_{nf} represents the share of value added in total input in the non-fisheries sector.

Finally all fisheries sectors' value added can be summed into total fisheries value added,

$$V_{fpm} = \sum_f V_f + V_{fp} + V_{fm} \tag{12}$$

Combining the fisheries value added with the non-fisheries value added then produces the economy-wide value added, which is equivalent to the total final demand of society (GDP).

$$V = V_{fpm} + V_{nf} \tag{13}$$

This equation describes an economic system where exogenous primary inputs of capture fisheries (or fishing effort in the terminology of fisheries economics) determines fish production, these act as core inputs to generate value added in the fish processing and marketing sectors (forward linkage sectors), and all fisheries sectors pull non-fisheries sector's production (backward linkage sector).

2.1.2 The bioeconomic relations of fisheries

Fish production uses not only intermediate products and primary factors but also natural aquatic resource. Fishing removes some fish from the sea and thus intervenes into natural production process of fish stock. On the other hand, state of fish stock affects fishing productivity. At this point it is the connection between economic and ecological systems.

The fisheries bioeconomics relates fishing effort with Catch Per Unit of fishing Effort (CPUE) to measure catch of fish in a time interval. CPUE values depend on catchability and fish stock. CPUE coefficient will be high if a fish stock is abundant and will be low if the fish is scarce. Assume a metier's action removes some amounts of multiple species from the biomass stocks and total catch of a species results from all relevant metiers' actions. Let $E_{m,t}$ denote the fishing effort of metier m, $c_{m,s,t}$ the catch of species s by metier m, and $C_{s,t}$ total catch of species s by all metiers at time t, then

$$c_{m,s,t} = CPUE_{m,s,t} \cdot E_{m,t} \tag{14}$$

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Let $q_{m,s,t}$ denote the catchability of species s by metier m, and $BM_{s,t}$ biomass stock of species s at time t, the CPUE coefficient can be transformed into a linear function of biomass stock

$$CPUE_{m,s,t} = q_{m,s} \cdot BM_{s,t} \tag{15}$$

where the catchability is a constant representing the probability of species s being caught by per unit of fishing effort of metier m, and can be calibrated from data at any reference time 0

$$q_{m,s} = \frac{\frac{c_{m,s,0}}{BM_{s,0}}}{E_{m,t,0}} = \frac{c_{m,s,0}}{E_{m,t,0}} \cdot \frac{1}{BM_{s,0}} \tag{16}$$

Substitute equation (16) into (15), then

$$CPUE_{m,s,t} = \frac{c_{m,s,0}}{E_{m,t,0}} \cdot \frac{BM_{s,t}}{BM_{s,0}} = CPUE_{m,s,0} \cdot \frac{BM_{s,t}}{BM_{s,0}} \tag{17}$$

Equation (17) obviously states that CPUE value simply is the adjustment of reference CPUE by change in biomass stock. Substitute this equation into (14), the catch becomes a non-linear function of both fishing effort and biomass stock

$$c_{m,s,t} = CPUE_{m,s,0} \cdot \frac{BM_{s,t}}{BM_{s,0}} \cdot E_{m,t} \tag{18}$$

In the equation， fishing effort, E, plays a key role in calculation. It can be set up on basis of exogenous value, optimisation, simulation or forecast, depending on the questions in interest. In our structural model, since fishing effort is exogenously given and structurally related to total input of fish production, we revise equation (18) by replacing effort with total input into a new formula

$$c_{m,s,t} = CPUO_{m,s,0} \cdot \frac{BM_{s,t}}{BM_{s,0}} \cdot X_{m,t} \tag{19}$$

where $CPUO_{m,s,0}$ measures Catch of species s Per Unit of Output of metier m, its values can be calibrated from the data at reference time 0. Since total output equals to total input, let $C_{m,t}$ denote total catch by metier m, then

$$C_{m,t} = \sum_{s} c_{m,s,t} = X_{m,t} \tag{20}$$

In equation (18)， the biomass stock at present period depends on both the level and growth of biomass stock, and also the catch at previous period

$$BM_{s,t} = \left(1 + BG_{s,t-1}\right) \cdot BM_{s,t-1} - C_{s,t-1} \tag{21}$$

where BG is growth rate of biomass stock, and $C_{s,t-1} = \sum_{m} c_{m,s,t-1}$ is total catch of species s across metiers.

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2.2 The ecological module

The ecological module is an ecological extension of the economic model, focusing on assessment of biomass change. From equation (21) it is clear that catch is a man-made factor of biomass change to be determined in the economic model, and biomass growth is a natural property of biomass change, needing to be simulated with some biological functions such as linear, logistic, exponential, or others (Hilborn & Walters, 1992). Through this way the economic and ecological modules are hard linked to each other, and the interactions between the economic and ecological systems are captured. However, due to the complexity of biological system, biomass change would be better assessed from comprehensive biological model systems where biological interactions are taken into account to a considerable extent. In that situation, a soft (external) link between the economic and ecological modules is needed.

In this research, we assume biomass change follows the logistic curve. Let θ_s and CAP_s denote the intrinsic growth rate and carrying capacity of species s, respectively, then biomass growth of the species is

$$BG_{s,t} = \theta_s \cdot \left(1 - \frac{BM_{t,i}}{CAP_s}\right) \tag{22}$$

Both θ_s and CAP_s are biological parameters that can be estimated or calibrated from biological data.

2.3 The social module

The social module is a social extension of the economic model, focusing on income-based social issues.

Figure 2 shows the linkages among the social, economic and ecological models and the calculation of social, economic and ecological costs. In the figure, ECOSTSM, ECOSTEM and ECOSIM represent social, economic and ecological model, respectively. The economic model is in the middle of the figure, linking the social model by functional incomes and the ecological model by fishing effort. Presently we have not established direct link between the social and ecological model. Based on personal income distribution, the social model can be used to calculate the social cost of fisheries. The economic cost of fisheries is the sum of production costs of all fisheries sectors net of total output, which depends on the catch from the ecological model. The ecological cost is assessed from biomass stock change.

Figure 2 shows the interrelations among fisheries, all the four fishery sectors will use production factors – capital and labor - and generate functional incomes. Once the functional incomes are distributed to the factors, they will be further distributed among fishery-depending households. This comes to the personal income distribution, which is relevant to social issues. Here is the linkage between social and economic systems.

The details of the model are presented in (Wang, et al., 2015). The resource content of fish production is specified and changes in biomass stock are estimated. Thirdly, the feedback of biomass change on fishing productivity or catchability is introduced into fish production. This integration of the bioeconomic and economic structural approaches on fisheries seems to be novel.

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Fish products are raw and fresh fish, part of which will directly go to households for consumption, part of which will go to the fish market for sale, and the rest of which will go to the fish processing sub-sector for processing. In industrial evolutionary theory, a sector's evolution largely depends on its "core inputs", which are produced and provided by the so-called "carrier sectors or branches". According to this view the model regards raw and fresh fish to be the "core inputs" of the fish processing and marketing sub-sectors, and so capture fisheries as the "carrier sectors or branches". Fish processing produces processed fish; part of which will directly go to households for consumption, part of which will go to the fish marketing sub-sector for sale. Finally, raw and/or fresh and/or processed fish can also be supplied direct to the consumers.

It is the economic system that generates income from factor uses. The factor incomes affect the social system through income redistribution among persons. The personal income distribution is thus commonly regarded as one of the main forces determining the social costs and benefits. It is closely related to well-being, poverty, and other income-based social issues. After all, some non-income based social issues are also indirectly related to personal income distribution. The social well-being is discussed in Millennium Ecosystem Assessment (2003) where the social services include five categories, namely basic material needs, health, social relations, personal security, and freedom and choice. The basic material needs generally cover food, water, clothing, shelter, etc. The health concerns body condition, life length, feeling, and living environment. The social relations include social cohesion, respect and help, and gender development. Personal security means safety from natural and social environment. lastly, freedom and choice refers to own control. Clearly, the first two categories are directly related to personal income that is generated from the economy.

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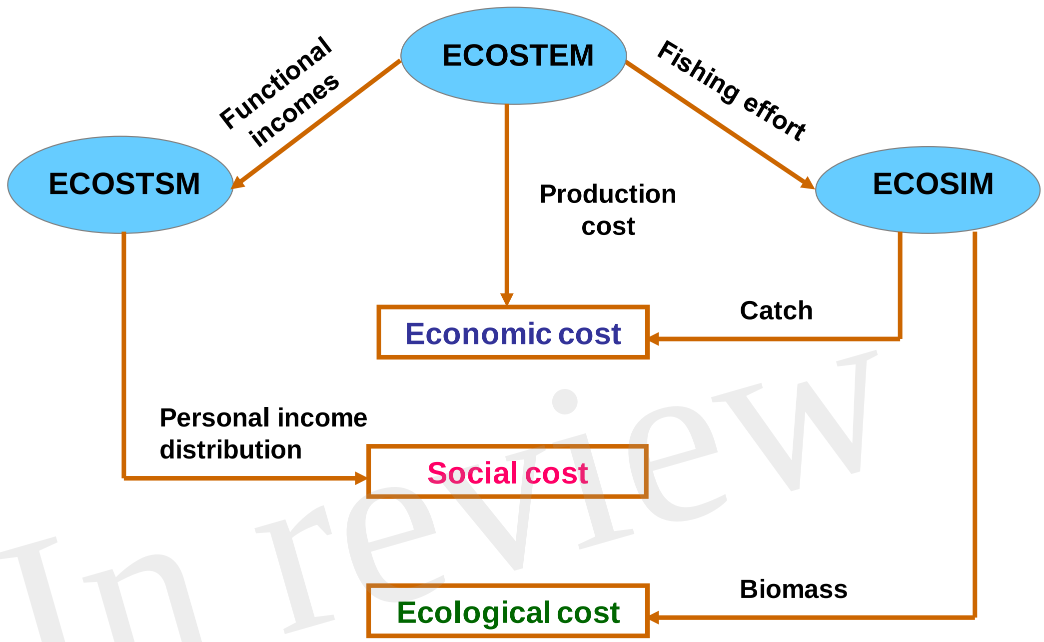
3 The integration model

Figure 2 shows the linkages among the social, economic and ecological models and the calculation of social, economic and ecological costs. In the figure, ECOSTSM, ECOSTEM and ECOSIM represent social, economic and ecological model, respectively. The economic model is in the middle of the figure, linking the social model by functional incomes and the ecological model by fishing effort. Presently we have not established direct link between the social and ecological model. Based on personal income distribution, the social model can be used to calculate the social cost of fisheries. The economic cost of fisheries is the sum of production costs of all fisheries sectors net of total output, which depends on the catch from the ecological model. The ecological cost is assessed from biomass stock change.

Figure 2. The linkages of social, economic and ecological models for cost calculation



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Fisheries have been a traditional primary industry, which not only produce aquatic products for human consumption and industrial uses but also provide employment and generate primary incomes to support the fishery society. In this aspect, the impact of fishing on the society is obvious. However, the impact of fishing activity on social system involves much complexity. Fisheries incomes are relatively low on average particularly in the developing economy and unevenly distributed among earners, causing a number of social problems such as poverty, food insecurity, poor health care, less education, and others. According to Millennium Ecosystem Assessment (2003), social products and services include five categories: basic material needs, health, social relations, personal security, and freedom and choice. While the first two categories are generally classified as income based social well-being, the latter three categories are classified as non-income based social well-being. Because of immaturity in theory and methodology of valuation of the non-income-based social well-being, this research focuses on the income-based social well-being through the changes in income level and distribution induced by fishing activity. We adopt the ideal point method to value the social costs.

Fishing activity means a cost to the ecological system if it removes biomass stock at a scale beyond nature’s ability to recover. As biomass stock declines, catching as same amount of fish as before will require more fishing effort. In this sense, the ecological system in turn induces additional cost to the fishing activity. Both of the two types of costs are related to the ecological system, but they are different by nature. The former measuring the damage to the natural system can be regarded as the ecological cost, while the latter should be taken as the indirect economic cost caused by ecological system. However, if fishing activity does not affect the natural state of biomass stock, the ecological system will offer a net benefit to the activity. There is also indirect impact of fishing on species population or biodiversity. Some fishing methods may damage the environment or ecological system by fishing. As a result, relevant species will be affected inevitably. This research assesses the direct impact on population change by the ecological module and the indirect impact by an associate method.

4 Indicators of fisheries performance

At the central of the ECOST model is the fishery economy which then extends to fishery-related social and ecological systems. The fisheries economic model of the ECOST model considers the full production chain of fisheries, which includes fish harvesting, fishing supporting, fish processing, and fish marketing sectors. The fish harvesting sector consists of a number of micro producers that we define as metiers. A harvesting metier refers to a particular fleet equipping with a particular gear and targeting a particular species as main catch. A metier may capture other species as by-catch. Figure 1 illustrates the fishery production chain and its linkages to social and ecological systems.

4.1 Valuation of fisheries performance

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Our aim in this research is to assess total cost of a metier's fishing activity. As the fishing activity will induce supporting, processing and marketing activities, the economic cost of a metier's fishing activity must include the costs occurred in all relevant fishery sectors. The fishing cost of a metier normally consists of two parts, namely fixed and variable costs. The former normally refers to the maintenance costs that are independent of fishing effort and the latter the running cost including factor and product inputs. In order to assess the full cost of a fishing metier's activity, we extend the fishing metier to include its impact on supporting, processing and marketing sectors. Let *ext*, *har*, *sup*, *pro* and *mak* represent extended metier, harvesting, supporting, processing and marketing sector, respectively, then the full cost of an extended metier then is calculated as follows

$$c_m^{ext} = c_m^{har} + c_m^{\sup} + \sum_{sp} \theta_{m,sp}^{pro} \cdot c_{sp}^{pro} + \sum_{d} \theta_{m,d}^{mak} \cdot c_d^{mak} + \sum_{sp} \sum_{d} \theta_{m,sp}^{pro} \cdot \theta_{sp,d}^{mak} \cdot c_d^{mak} \tag{23}$$

Where

m: metiers

sp: processing firms or processed species

d: distributors

c: cost

$\theta_{m,sp}^{pro}$: the proportion of metier *m*'s products processed by the processor

$\theta_{m,d}^{mar}$: the proportion of metier *m*'s products directly distributed by the distributor *d*

$\theta_{sp,d}^{mar}$: the processor *sp*'s product distributed by the distributor *d*

The proportion variables θ can be either calibrated from data or endogenously determined by maximizing the revenues of processing and marketing sectors. Similarly, the benefit of the extended metier is

$$b_m^{ext} = b_m^{har} + b_m^{\sup} + \sum_{sp} \theta_{m,sp}^{pro} \cdot b_{sp}^{pro} + \sum_{d} \theta_{m,d}^{mak} \cdot b_d^{mak} + \sum_{sp} \sum_{d} \theta_{m,sp}^{pro} \cdot \theta_{sp,d}^{mak} \cdot b_d^{mak} \tag{24}$$

And the net economic cost is

$$nc_{ext,m}^{en} = c_m^{ext} - b_m^{ext} \tag{25}$$

4.2 The ecological costs

Environmental economics has traditionally focused on impact of human activity on ecosystem. Recently a new brand of research mainly generated from ecological economics instead proposes to study impact of ecosystem on human society. Costanza et al. (Constanza, et al., 1997) argue that ecosystem contributes to human society through ecosystem services, which contain some economic value. Once these services are valued, they represent the ecological benefits to human society in monetary term. Millennium Ecosystem Assessment (2003) further extends to social system's services to explore the economic value of social system. Beaumont et al. (Beaumont, et al., 2007) apply the approach of ecosystem goods and services to marine system to study the goods and services that marine provides to human society. They identify 13 types of marine goods and services, which can be classified into five categories, namely, production services, regulation services, cultural services, option use value, and support services. Beaumont et al. (Beaumont, et al., 2008) further attempt to value those marine goods and services, using various valuation methods, in case studies. The result of the research inspires further directions as well as exposes difficulties in valuation of the marine goods and services that are not directly observed in the markets.

The ECOST research basically follows the theory of ecosystem approach to develop a methodology of quantifying and valuing marine goods and services. Instead of studying the full range of marine goods and services, we focus on fish only in this research. The fish perhaps is one of the most important goods and services that marine system provides to human society. The appropriation of the benefit is through fisheries, a direct economic activity. It is the economic system that reduces biomass stock through capture of marine fish and in turn the ecological system affects the fishing productivity due to the scarcity of biomass. If economic capture of marine fish is within the original natural growth of marine resource, the economic activity gains a net value from exploring the marine resource without damaging it. However, if the capture is beyond the original natural growth, the marine resource will only sustain a growth below its original natural growth. As a result, the marine resource may provide less value to the economic system than the marine resource at the original natural state does. In this sense, we say that over-exploration reduces the growing ability of marine resource and causes a loss to the ecological system. It will take time for the marine resource to recover from the new to its original natural state. The recovering process can be viewed as a loss in economic value that the economic system otherwise may subtract from the resource at the original natural state.

We first define landing value of a species of fish as the ecological benefit that the species provides to the fishing activity. Once a certain amount of the species is removed from the marine, the biomass stock of the species reduces to a new, low level, which will grow in next year. We thus define the difference between the landing value and the growth value as the ecological cost.

If the growth value is below the land value, there exists an ecological cost. If the growth value exceeds the land value, the ecological cost is negative, representing a benefit. For example, on an extreme case that the biomass stock will not grow any, the ecological cost equates to the landing value or ecological benefit, the net ecological benefit in fact is zero.

Let *el* refer to ecological system, *X* total removal of a species, the ecological benefit of a species is

$$b_s^{el} = P_s \cdot X_s \tag{26}$$

The potential growth of the biomass stock is

$$GB_s = f(B_{s,t-1}, X_s) \tag{27}$$

Then, the ecological cost of species *s*, is

$$c_s^{el} = P_s \cdot X_s - P_s \cdot GB_s \tag{28}$$

And, the net ecological cost is

$$nc_s^{el} = c_s^{el} - b_s^{el} \tag{29}$$

which in fact is the value of the potential growth of the biomass stock.

Since our aim is to measure social, economic and ecological costs at metier level and the ecological costs are measured for each species, they need to be transformed into the ecological costs by metier. The ecological costs and benefits are associated with not only harvesting fisheries but also processing and distributing fisheries. In each of these fisheries sectors, the ecological benefits are defined to be total production values, which are

$$b_{i,j}^{el} = y_{i,pr}^{j}, \quad i \in (m, sp, d) \; and \; j \in (har, pro, mak) \tag{30}$$

In order to get the ecological costs for fisheries sectors, we first need to know how value output will change correspondingly with the potential growth of the biomass stock of a species. For each of the sector, it is

$$z_{m,pr}^{har} = \sum_s P_s^{raw} \cdot x_{m,s} \cdot \frac{GB_s}{X_s} \tag{31}$$

$$z_{sp,pr}^{pro} = \sum_{sp} P_{sp}^{pro} \cdot x_{sp,sp}^{pro} \cdot \frac{GB_s}{X_s} \tag{32}$$

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$$z_{d,pr}^{mak} = \sum_{s} P_{s}^{mak,raw} \cdot x_{d,s}^{raw} \cdot \frac{GB_s}{X_s} + \sum_{sp} P_{sp}^{mak,pro} \cdot x_{d,sp}^{pro} \cdot \frac{GB_s}{X_s} \tag{33}$$

where z represents the value of potential growth of the biomass stock of a species.

$$c_{i,j}^{el} = z_{i,pr}^{j}, \quad i \in (m, sp, d) \; and \; j \in (har, pro, mak) \tag{34}$$

The ecological benefit of an extended metier is

$$b_{ext,m}^{el} = b_{m,har}^{el} + b_{m,\sup}^{el} + \sum_{sp} \theta_{m,sp}^{pro} \cdot b_{sp,pro}^{el} + \sum_{d} \theta_{m,d}^{mak} \cdot b_{d,mak}^{el} + \sum_{sp} \sum_{d} \theta_{m,sp}^{pro} \cdot \theta_{sp,d}^{mak} \cdot b_{d,mak}^{el} \tag{35}$$

The value of potential growth of an extended metier is

$$z_{ext,m}^{el} = z_{m,har}^{el} + z_{m,\sup}^{el} + \sum_{sp} \theta_{m,sp}^{pro} \cdot z_{sp,pro}^{el} + \sum_{d} \theta_{m,d}^{mak} \cdot z_{d,mak}^{el} + \sum_{sp} \sum_{d} \theta_{m,sp}^{pro} \cdot \theta_{sp,d}^{mak} \cdot z_{d,mak}^{el} \tag{36}$$

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The ecological costs of an extended metier thus is

$$c_{ext,m}^{el} = b_{ext,m}^{el} - z_{ext,m}^{el} \tag{37}$$

And, the net ecological cost of an extended metier is

$$nc_{ext,m}^{el} = c_{ext,m}^{el} - b_{ext,m}^{el} \equiv -z_{ext,m}^{el} \tag{38}$$

4.3 The social costs and benefits

In previous section, we stated that the Millennium Ecosystem Assessment (2003) classifies social products and services into five categories the first two of which are referred to income based social well-being and the latter three are referred to non-income based social well-being. There are rare research that report any valuation of the income based social well-being, needless to say the non-income based ones. In this research, we attempt to develop methods to value the basic material needs and health. To address the social value, we must at first define a society’s economic position. Let us assume that an ideal level of personal income in a society is known. Based on this, ideal levels of spending on basic material needs, health and others can also be derived. Furthermore, based on the current market situation, we can calculate the necessary spending on basic material needs, health and others, respectively. If we define the real spending as social benefit, the difference between the ideal and real situation measures the social cost. For example, if ideal level of spending on basic material needs is \$1000 and real spending is \$600 in a fisheries society. We say that the social benefit of the fisheries is \$600 and the social cost is \$400. If the real spending can reach \$1000, there is no social cost in terms of basic material needs.

In this research, we focus on social costs and benefits of basic material needs and health, and leave all other social services to the other category. Let *BMN*, *HLH* and *OTH* represent basic material needs, health care and other social services, respectively. PIN is person income, and the share of each spending in personal income. Then, the social benefits of each of social services related to each fisheries sector can be calculated as follows

$$b_{i,j}^{sc} = \alpha_i \cdot PIN_j, \quad i \in \left(BMN, HLH, OTH\right) and \;\; j \in \left(m, sp, d\right) \tag{39}$$

The total social benefit of all social services related to each fisheries sector is

$$b_j^{sc} = \sum_i b_{i,j}^{sc}, \quad i \in \left(BMN, HLH, OTH\right) and \;\; j \in \left(m, sp, d\right) \tag{40}$$

In order to calculate the social costs and benefits at métier level, we need to know the number of households depending on the income generated in *j*'s fisheries sector, *NHH*. Then, the social costs related to each fisheries sector can be calculated as follows

$$c_{i,j}^{sc} = IS_i \cdot NHH_j - b_{i,j}^{sc}, \quad i \in \left(BMN, HLH, OTH\right) and \;\; j \in \left(m, sp, d\right) \tag{41}$$

And, the total social cost of all social services related to each fisheries sector is

$$c_j^{sc} = \sum_i c_{i,j}^{sc}, \quad i \in \left(BMN, HLH, OTH\right) and \;\; j \in \left(m, sp, d\right) \tag{42}$$

Finally, we need to transform the social costs and benefits into extended métier level. The social benefit of an extended metier is

$$b_{ext,m}^{sc} = b_{m,cap}^{sc} + \sum_{sp} \theta_{m,sp}^{pro} \cdot b_{sp,pro}^{sc} + \sum_{d} \theta_{m,d}^{mak} \cdot b_{d,mak}^{sc} + \sum_{sp} \sum_{d} \theta_{m,sp}^{pro} \cdot \theta_{sp,d}^{mak} \cdot b_{d,mak}^{sc} \tag{43}$$

The social cost of an extended metier is

$$c_{ext,m}^{sc} = c_{m,cap}^{sc} + \sum_{sp} \theta_{m,sp}^{pro} \cdot c_{sp,pro}^{sc} + \sum_{d} \theta_{m,d}^{mak} \cdot c_{d,mak}^{sc} + \sum_{sp} \sum_{d} \theta_{m,sp}^{pro} \cdot \theta_{sp,d}^{mak} \cdot c_{d,mak}^{sc} \tag{44}$$

And, the net social cost of an extended metier is

$$nc_{ext,m}^{sc} = c_{ext,m}^{sc} - b_{ext,m}^{sc} \tag{45}$$

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4.4 The societal cost

The societal cost is the sum of social, economic and ecological costs. Let *st* indicate the society, then the societal cost of metier *m*'s fishing activity is

$$nc_{ext,m}^{st} = nc_{ext,m}^{en} + nc_{ext,m}^{el} + nc_{ext,m}^{sc} \tag{46}$$

5 Applications of the ECOST model

One of the main application areas of the proposed model is to assess the impacts of fishing policy on fishing activities considering an integrated approach towards the social, economic and ecological aspects in fisheries. Through evaluating the changes in the economic and social indicators and connecting that to an ecosystem module, the model is constructed to investigate how different policies result in different states of the socio-economic and ecosystem structure.

An application of the model is found in the study of (Christensen, et al., 2011) where a case study based on an ecological model of the South China Sea ecosystems is used where the Tuna, Mackarel and Clams value chains are assessed. The trophic ecosystem model is linked to a value chain approach where the flow (amount, revenue and costs) of fish products from sea to the end consumer is tracked. From a management perspective the model shows the impact of interventions such as quota setting and effort regulations, on the ecosystem, economy, the social setting, and the food availability for the consumers. In the study by (Wang, et al., 2016) the ECOST model is applied to assess the implementation of ecosystem based fisheries management in the Pearl River Estuary. The impact on the ecological-economy-social system are examined by varying fishing efforts for four scenarios including status quo management, fishing effort reduction policy, fishing gear switch and summer closure extensions policies. Their results show the the gear switch scenario presents a compormise among the economics, conservation and social metrics and also outperforms other scenarios in terms of biomass at the end of the simulation period. However the fishing effort reduction policy performs better than the summer closure extensions policy in terms of the conservation metrcis but does relatively poorly in economics terms. The model is also used in the study by (Wang, et al., 2020) to investigate how different scenarios of fishing effort and catch management reflecting varying levels of input and output in four fishery management simulations result in different states of the socio-economic and ecosystem structure. The modelling results show that the output control policy has the most positive effect on ecosysytem restoration and can increase over all social welfare.

By providing a useful approach to quantify the trade-offs between ecological and socio-economic systems, the model tends to deal with the multi-objective management of the fisheries sector and reconcile the socio-economic and ecological goals which are inherently conflicting.

6 Conclusions

Marine and coastal area are complex systems formed by the interaction among the local population, economy, environment and resources and there is an increasing tendency for recent studies in fisheries research to incorporate interdisciplinary methods in their approach. This paper proposes an integrated ecological-economics-social model for evaluating fishing activities

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and policies to improve fisheries management. The integrated model developed in this research could be applied in developing fishery regions in Africa, Asia and Caribbean. Data requirements include an aggregate macroeconomic social accounting matrix (SAM) with the fisheries sector particularly identified, detailed microeconomic fisheries data, some social data, and detailed time-series biological data.

The economy wide value added contribution of fisheries induced by fish harvesting, lies also in its effects on secondary activities such as fish processing, storage, marketing and the indirect impact upon non-fisheries sectors. This study would be helpful particularly for developing coastal regions to assess their fisheries industry and make appropriate policy measures to reduce overexploitation of resources while maintaining a healthy economic balance. The comparison of the results among the regions would reveal the current stages of each region's fisheries and policy simulations would provide insights into potential improvement in future practice.

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[1] Being a part of the European international research project in cooperation ECOST (Ecosystems, Societies, Consilience, Precautionary principle: Development of an assessment method of the societal cost for best fishing practices and efficient public policies), formed under the INCO-DEV Priority Research Area A.2.2. (Reconciling multiple demands on coastal zones).

[2] In literature of integrated assessment modeling, a hardlink means different modules are internally linked, whereas a softlink means different models are externally linked each other.