A combined ecosystem and value chain modeling approach for evaluating societal cost and benefit of fishing[1]

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Abstract (max 400)

In this contribution, we describe a combined ecological and economical approach aimed at giving more equal emphasis to both disciplines, while being integrated so that design, analysis, data entry and storage, and result capabilities are developed with emphasis on deriving a user-friendly, easily accessible tool. We have thus developed the approach as an integrated module of the freely available Ecopath with Ecosim scientific software; the world's most widely applied ecological modeling tool. We link the trophic ecosystem model to a value-chain approach where we explicitly and in considerable detail keep track of the flow (amounts, revenue, and costs) of fish products from sea through to the end consumer. We also describe the social aspects of the fish production and trade, by evaluating employment and income diagnostics. This is done with emphasis on distribution income while accounting for gender aspects of the fishing sector, including for dependents. From a management perspective, one of the interesting aspects of the approach we introduce here, is that it opens for direct evaluation of what impact management interventions, e.g., quota settings, effort regulation, or area closures, may have on the ecosystem, the economy and the social setting, as well as on food availability for the consumer.

Introduction

There is an increasing tendency for contemporary studies in fisheries research to strive for interdisciplinarity, and such is almost certainly a requirement if we are to live up to the ambitious agreement of the Johannesburg Plan directing management of fisheries so as to allow ecosystems to be restored by 2015 (United Nations, 2002). As researchers, we tend, however, to build our tools of analysis around what we know best, adding complexity where we from experience know it is required, while giving other areas and disciplines but cursory treatment. We all stand 'guilty as charged' in this respect; we have for instance as ecologists when developing the Ecopath with Ecosim (EwE) approach and software limited the economical aspects to simple ex-vessel cost and benefit considerations (Christensen and Walters, 2004a), even if policy optimization tools with an economic perspective have been added on (Christensen and Walters, 2004b). Similarly, many bioeconomic models have ignored ecological aspects such as caused by trophic interactions, (fish eat fish!), and have typically just applied a simple population growth function to capture fish stock dynamics, (e.g., Failler and Pan, 2007).

In this contribution, we describe a combined ecological and economical approach aimed at giving more equal emphasis to both disciplines, while being integrated so that design, analysis, data entry and storage, and result capabilities are developed with emphasis on deriving a user-friendly, easily accessible tool.

We build on the EwE approach, which is implemented as the world's most widely applied ecological modeling software, and which has been recognized as a flexible and capable tool (Plaganyi, 2007), as expressed by its recognition by the US National and Atmospheric Administration as one of the ten biggest scientific breakthroughs in the organization's 200-year history.

The approach has the Ecopath mass-balance approach as its starting point (Polovina, 1984; Christensen and Pauly, 1992), and involves description and evaluation of the key resources and their trophic interactions as well as of their exploitation. Following, time-dynamics are modeled using the Ecosim model (Walters et al., 1997; 2000), involving a comprehensive scheme for tuning to time-series data in order to replicate time trends in the ecosystem while evaluating fisheries and environmental impact (Christensen and Walters, 2005).

The Ecopath model describes what happens in the oceans with particular emphasis on the food web and on human exploitation. It ends, however, when the ship reaches the port. We have not gone beyond ex-vessel prices when describing bio-economical aspects. Here, we link the trophic model to a value-chain approach where we explicitly and in considerable detail keep track of the flow of fish products from sea through to the end consumer.

Pierre: some background info about value/supply chain approaches here?

We also describe the social aspects of the fish production and trade, by evaluating employment and income diagnostics. This is done with emphasis on distribution income while accounting for gender aspects of the fishing sector, including for dependents.

From a management perspective, one of the interesting aspects of the approach we introduce here, is that it opens for direct evaluation of what impact management interventions, e.g., quota settings, effort regulation, or area closures, may have on the ecosystem, the economy and the social setting, as well as on food availability for the consumer. Likewise the approach, given its capability to evaluate environmental impact (Christensen and Walters, 2005), opens for quantification of how climate impact may impact future harvest from the sea. In this paper, we describe the extended value chain approach, and we demonstrate its use through a hypothetical case study.

We expect that applications of the approach generally will fall in two categories. The first is detailed case studies of the value chain in a given area, typically with focus on fine-scale economical and social indicators, and possibly describing only part of the fishing sector. The second type will be more general descriptions, e.g., at the country-level, used to evaluate the contribution of fisheries overall, e.g., to the Gross Domestic Product and to national employment or for estimation of potential loss through overexploitation (Arnason et al., 2009).

Methods

The ecosystem model

Ecopath is a mass-balance model, originally developed to describe the trophic flows in the French Frigate Shoals ecosystem in the Northwestern Hawaiian Islands, with emphasis on describing all trophic levels in the system and on evaluating how demand by predators could be balanced by production of prey (Polovina, 1984). The approach has been under development for more than 25 years. The computational aspects of the modeling is described in many other publications to which we refer for details, (e.g., Christensen and Walters, 2004a).

The key aspect of the ecological model is that for each functional group (i) in the system we describe the production (P_i),

$$P_i = B_i \cdot \left(F_i + M0_i + NM_i + \Delta B_i\right) + \sum_i Q_j \cdot DC_{ji} \quad (1)$$

where B_i is the biomass of (i) F_i is the fishing mortality rate (catch/biomass), $M0_i$ the unexplained mortality rate, NM_i the net migration rate (immigration – emigration), ΔB_i the biomass accumulation rate, and where the last term describes the predation mortality rate, obtained from summing for all predators (j), the consumption rate (Q) times the proportion (DC) the prey contributes to the predator diet.

We further estimate the consumption (Q_i) for the group as,

$$Q_i = P_i + X_i + R_i \quad (2)$$

where X_i is the combined excretion and egestion rate, and R_i the respiration rate. When parameterizing the model, we typically estimate $M0_i$ in equation (1), and R_i in equation (2) in order to balance the resulting two sets of linear equations. This leaves the total mortality (Z_i

or P_i/B_i), biomass, catches, migration, biomass accumulation, diets, consumption, and excretion/egestion as the parameters for input, all group-specific.

The Ecopath model provides a static description of the ecosystem, with ability to describe the food web in detail as desired. Functional groups may thus consist of multiple species, or they may be detailed age groupings of individual species, depending on what is opportunistic in the individual case (Walters et al., 2008). Fishing operations may similarly be described in details as required.

The time-dynamics are modeled using the Ecosim model (Walters et al., 1997; 2000), which is based on the same equations as above, while estimating time-varying production rates based on changes in predation, prey availability, fishing pressure, and environmental productivity. From a parameterization standpoint, the Ecosim model only requires few additional parameters beyond what is required for the underlying Ecopath model, yet, facilitates modeling of more complex relations such as, e.g., life-history dynamics (Walters et al., 2008), mediation, prey switching, and density-dependent catchability (Walters and Martell, 2004).

For the Ecosim modeling, the most important question is how density-dependence impacts population trends: how may the consumption by a group change when its abundance changes? Should the population double; will it be able to double its food consumption? We model this through a 'vulnerability' parameter, which expresses the maximum factor the predation mortality can increase for a prey given a large increase in the given predator's biomass. The vulnerabilities cannot be estimated directly from observations, and our best approach for estimation involves non-linear fitting to time series data (Christensen and Walters, 2005).

Through the ecosystem modeling we obtain a quantified description of how the fisheries catches change over time, in the past, present as well as into the future through evaluation of alternative management and climate change scenarios (Brown et al., in press).

Value chain modeling

In the value chain modeling (or product flow analysis) we distinguish between producers, processors, distributors, sellers, and consumers, and we describe the flows between these, summing up to estimate overall flow of products, values, and services. We have implemented the value chain approach using an object-oriented programming (OOP) approach in which the enterprises (i.e. excluding the consumers) listed above inherit a suite of joint properties for all enterprises.

We have listed the production and revenue-related parameters in Table 1, the cost parameters in Table 2, and the parameters relating to social aspects in Table 3. A characteristic of the OOP implementation is that it is straightforward to change the parameter structure, including addition of more parameters when this is warranted.

Producers

We start the analysis with the producers, and have defined two alternative starting points, both parameterized from the underlying ecosystem model. We can describe fisheries landings by 'métier', i.e. by fishing fleet and by species or functional group, or we can, for cases where we do not wish to differentiate between fleets, let the landings by functional group provide the starting point. In either case, we extract the fisheries landings by linking directly to the ecosystem model.

The producers can pass the seafood on to any other type of enterprise as well as to the final consumers as desired in the individual case. Revenue and cost structure for the producers follows the general scheme in Table 1 to Table 3, with the note that effort related costs, including observer costs only pertains to the producer category.

Non-extractive uses

Non-extractive uses such as catch and release angling operations, whale watching and dive operations can be treated as producers in the system. Their income is modeled through ticket prices (and subsidies where pertinent), which are assumed to be effort related. The cost structure is likewise likely limited to include only effort-related costs.

Processors

Processors typically receive the raw seafood from the producer and turn it into marketable products. Links from other sources, e.g., from other processors, is, however, also permitted. The processors follow the general revenue and cost scheme, though the agricultural products in Table 1 and costs in Table 2 are used for processors only.

Aquaculture

Aquaculture operations can be treated as either producers or processors in the value chain depending on the circumstances. They will typically receive fish products as input (feeds), which can come from other processors or directly from the producers.

Distributors

Distributors typically serve as intermediates between processors and sellers, with exporters being a common example of distributors.

Sellers

This category includes the intermediate as well as final suppliers to consumers, and as such also restaurants. Wholesale sellers can be distinguished from retailers through the flow patterns.

Consumers

For consumers we keep track of the flow of products to the group, and the only other defined properties are name (i.e. category) and nationality.

Links between enterprises

The fishing fleets serve as the producers in the chain. From the producer, the fish will typically be directed to a processor, on to a distributor, to the seller, and finally to the consumer. This is illustrated schematically in Figure 1. The scheme, as we have defined and implemented it, is very flexible, with only one rule for the flow chart construction: cycles are not permitted. This is illustrated in

Figure 2, where as an example flow from Producer 1 → Processor 1 → Producer 2 → Processor 2 is allowed while flow from Processor 2 → Producer 1 is disallowed as such a flow would cause a cycle, (i.e. Producer 1 → Processor 1 → Processor 2 → Producer 1).

For each link between enterprises we list input parameters in Table 5. For each step we keep track of loss through a dimensionless production/input ratio, which is used for calculation of live weight equivalents (L_c) for a given value enterprise for which the value chain holds enterprises from the first (a producer) to the last element (c), from

$$L_c = W_{p,c} \cdot \prod_{e=1}^{c} \left(W_{i,e} / W_{p,e} \right) \quad (3)$$

where $W_{p,e}$ is the weight of products for a given enterprise (e), and $W_{i,e}$ is the weight of input ('raw material') for the same enterprise. For each link we also store the proportion of the input to the enterprise that is passed through the given chain. Further, we store either the product value for each link between enterprises, or the value ratio (value of product relative to cost of raw material). A flow chain can have any number of links; there are no restrictions in this regard.

Calculations

All calculations are done in an object-oriented manner, where each enterprise has a series of defined properties, and where the calculations are performed and stored independently for each. Units for the parameters below are given in the tables.

Revenue

We calculate the revenue from production (R_p) for each enterprise as $R_p = W_p \cdot (R_a + R_e + R_p + R_s)$, where W_p is the weight of products for the enterprise, and the other symbols are described in Table 1 to Table 3. The agricultural product value (R_a) is used for processors only. Additional revenues from subsidies (U), are $U = W_p \cdot (U_e + U_o)$, where the parameters are described in Table 1 as well. The total revenue (R) is summed up, as $R = R_p + U$. For producers, we assume that the revenue from subsidies is proportional to effort, but we initially parameterize the parameters based on the baseline landed amounts.

The ticket revenue is used for producers only, and is for modeling cases where income is independent of production, e.g., non-extractive uses such as whale watching or guiding operations for angling. We assume that the ticket revenue is proportional to effort (in the time-dynamic simulations), and parameterize the parameter as the total revenue with the baseline effort.

Cost

The cost of input and operation (I) is calculated as $I = W_p \cdot (I_c + I_e + I_i + I_s + C_m + C_l + C_c)$, where the parameters are described in Table 2. We note that certification cost for instance can include cost for Hazard Analysis and Critical Control Points (HAACP, Hamada-Sato et al., 2005) as well as for eco-labeling.

As implemented here (reflecting reality we assume), the costs for management, royalties, and certification will be a linear function of effort, as will the 'other input', which includes capital, energy, industrial, and services costs.

Cost of observers (O) for producers (fishing boats) is calculated as $O = W_p \cdot (C_o \cdot O_r)$ where parameters are listed in Table 2. It is assume that the cost of observers will vary proportionally with effort in the time-dynamic simulations, but the parameter is initialized from the baseline landed amount. We assume that the cost for observers will be a linear function of effort.

Taxation costs (T) are calculated from $T = W_p \cdot (T_e + T_x + T_p + T_v + T_i)$, again with the parameters described in Table 2. Other production costs are the social benefits represented by either wages or shares (typically used for producers), which we calculate separately for workers (P_w) and owners (P_o), summing up later to obtain total costs. We assume that the taxes vary with the landed value, i.e. with production.

If using a wage system, we have for workers, $P_w = W_p \cdot (P_s + P_h)$, or, if based on a share part of the revenue, $P_w = W_p \cdot V_{f,s}(S_s + S_h)$, where $V_{f,s}$ is the value of the product (by fleet and by species) per unit weight. Similarly we have for owners, $P_o = W_p \cdot (P_f + P_m)$. Or, if using a share-distribution system $P_o = W_p \cdot V_{f,s}(S_f + S_m)$, where additional parameters are described in Table 2. From the above the total cost of operation (C) for the given enterprise can be calculated as $C = I + O + T + P_w + P_s$.

We assume that cost for wages (salaries or shares) is a linear function of the landed value, and they will thus not increase any further when effort exceeds the maximum sustainable level.

For calculation of number of jobs and number of people supported by the fishing industry we use the parameters in Table 3 Based on these we calculate the number of jobs for workers (J_w) and owners (J_o), as $J_w = W_p \cdot \left(J_s + J_h\right)$, and $J_o = W_p \cdot \left(J_f + J_m\right)$. From this we get the total number of jobs (J) from the sum of these, $J_w = J_w + J_o$, while the numbers of dependents of workers (D_w) and owners (D_o) is calculated from $D_w = W_p \cdot \left(D_s \cdot J_s + D_h \cdot J_h\right)$ and $D_o = W_p \cdot \left(D_f \cdot J_f + D_m \cdot J_m\right)$, which is next summed up to $D = D_w + D_o$.

For producers we assume that the number of jobs is proportional to effort (while their income depends on the value of the catches). For this we calculate the baseline (unity effort) number of jobs, then scale the number of jobs based on the relative effort over time.

In addition, we sum up to obtain summaries for females and males separately. We further calculate the total production in product weight and live-weight units, based on equation (1) for producers and processors as well as the weight of products available to consumers.

Summaries

The profit (P) for each enterprise is calculated as the difference between total revenue and total costs, or $P = R - C$.

As an expression of the size of the economic sector modeled we calculate the system utility as the sum of all economic flows across the entire sector.

Case study

We here use a case study based on an ecological model of the South China Sea ecosystem (Pauly and Christensen, 1993) to illustrate the approach. The ecological model is distributed as a test model with the Ecopath with Ecosim software (www.ecopath.org), and is therefore easily available. The full model with the linked value chain database can be obtained from the corresponding author.

The ecological model has a total of 10 functional groups, of which one, the tuna, is modeled with two stanza as this notably improves the models capability to incorporate time lags (Walters et al., 2008). The other functional groups are mesopelagics, epipelagics (mackerel, flying fish, a.o.), benthic fish, benthopelagics, benthos (including clams), large and small zooplankton, phytoplankton and detritus. A simplified flow chart of the model is presented in Figure 4, indicating the predator-prey linkages in the system. Only the tuna, mackerel, and clams are exploited, each with a separate fleet fishing for them.

The case study uses a realistic ecosystem model, while we have chosen to use a hypothetical value chain for this contribution. This is done, as the purpose of this paper is to describe an implementation of a value chain methodology, not to report on actual results. The value chain incorporates three product lines coming from tuna, mackerel, and from clams. To illustrate that there can be cross-linkages we have included an example with tuna fleet sending tuna to the canneries, otherwise supplied by the mackerel fleet. We show the outline of the value chain in Figure 6.

We express values in the results below based on a per km^2 basis. It is recommended though, to use the total area of the ecosystem in question in order to scale up to the total economic value.

Equilibrium analysis

The Ecosim time dynamic model is not an equilibrium model, but fully dynamic (Walters et al., 2000). Here we do, however, use a routine in which we set a constant fishing effort, run Ecosim for 25 years, which is enough to reach a steady state balance, read the results, and then repeat with a new fishing effort. In total, we here vary the fishing effort for the tuna fleet from 0 to 4 times the baseline effort in steps of 0.1. This corresponds to moving from no exploitation to vast overexploitation leading toward extinction for the target group.

For each step we evaluate the revenue, cost of fishing, income, and employment for the producers as well as for the entire value chains. We make this separation to illustrate how much value that may be added through the processing and distribution.

Results and discussion

We have noted especially two results from working with the value chain, both foreseeable but most commonly ignored. One is that the full value chain incorporating producers, processors, distributors, and sellers add considerable value to the sector, and that it therefore doesn’t make much sense to manage the fisheries without considering the economics of the processing and distribution parts of the sector. The second result is that there are tradeoffs between fisheries, and an ecological model is required to evaluate those tradeoffs.

When running the equilibrium analysis, varying the fishing effort for the tuna fleet in steps, we obtain the results indicated in

Figure 7. In the plot we included cost for management and observers with the other input, as they all are a function of effort, while taxes and wages are plotted separately as these are a function of landings. One result springs to mind, the total cost of fishing is not a linear function of effort as is otherwise commonly assumed in this form for equilibrium analysis of revenue and cost of fishing (Grafton et al., 2007). This indeed underlines the argument of Christensen (2009) in his critique of how maximum economic yield (MEY) commonly is estimated.

If we evaluate the MEY for the tuna fleet, it is reached when effort is at 90% of the baseline effort, and the yield is above 90% of the fleet-MEY when the relative effort is in the range from 0.55 to 1.2. The maximum sustainable yield (MSY) is, however, reached when the relative effort is at 1.6, i.e. at a considerable higher level than where the fleet-MEY is reached.

If we consider the rest of the supply chain for the tuna fleet as well, i.e. include the processing, distribution, and marketing up to the end consumer; we obtain the results illustrated in Figure 9. We note immediately that we now are dealing with big numbers. The total revenue (summing revenue for each step in the value chain) tops at a level an order of magnitude higher than when only considering the producer part of the fishing industry. While this actual level for how much the revenue increases is very dependent on the economic parameters, the location of the sector-MEY will vary much less because of this. We here find that the sector-MEY is obtained with a relative effort of 1.3, and that it is above 90% in the effort range from 0.8 to 1.8. Overall, this is, as can be expected, considerably higher than for the fleet-MEY.

There is however much less difference in where the MSY (from both an ecological an economical perspective) is obtained. We find that MSY is reached when the relative effort is at 1.5, i.e. slightly below the level for the fleet. Given the discussion of whether it is even reasonable to consider ‘sunken rent’ as an important factor for fisheries management (Bromley, 2009), we stress that we are finding that the MSY-level is very similar whether we are examining the full fisheries sector or only the producer part, and that this level is where the maximum benefits for society, economically and socially, are produced. Overall, this strongly suggests that the traditional fleet-level MEY where cost is assumed proportional to effort is a dubious choice for society, while MSY is the more suitable target reference point for fisheries management (Christensen, 2009).

The simple ecological model we are using includes exploitation of a predator (tuna) as well as one of its preys (mackerel). As can be expected, there are tradeoffs to be considered when managing these fleets. We demonstrate this through the equilibrium analysis, varying the fishing effort for the tuna fleet, and letting the ecological model predict the impact for the other fisheries. We find that there is a clear tradeoff between fishing for tuna and for mackerel (Figure 11).

The number of jobs that is generated in the fishing sector is shown in Figure 13. The number of jobs behaves very similarly to the total revenue (Figure 11) with regards to trends and tradeoffs, with the exception that high effort levels for the tuna fleets results in high employment for the fleet, but very low revenue. The wages generated (not shown, but calculated in software) are therefore extremely low at high tuna effort levels.

When the tuna fleet effort is below the baseline effort, the tuna stocks will increase and they will consume more of their preferred prey, mackerel. This leads to decreased catch opportunities for this group, and the mackerel fleet will experience reduced catches, as their effort is kept constant. In contrast, increased effort, even beyond the sustainable level (1.5) leads to increased catches for mackerel, which as indicated here, has economic benefit for the sector overall. This result is of course dependent on the economic parameters for the two value chains. We have for instance assumed that the off-vessel price per kilogram for tuna is $4.50, and $0.80 for mackerel. If the price difference is bigger there will be less benefit from higher effort for tuna. We note, however, that while the economic parameters we use here are assumed (but reasonable), it is likely that the ecological tradeoff will be real. Exploitation of top predators often have consequences for intermediate predators that are important prey of the top predators (Christensen and Walters, 2005).

For the overall fishing sector, i.e. for the total value chain from producer to consumer, the maximum utility is obtained when tunas are overexploited and we get more mackerel. Whether this is a desired state is something that society should decide – cans of mackerel for sandwiches, or sushi? It is not possible to maximize the yield from all resources concurrently, there are ecosystem tradeoffs (Walters et al., 2005). To consider this, it is important to evaluate potential gains, revenue, and cost from ecological, economic, as well as from social perspectives, and not just base management decisions on the economics of the fleets individually (Christensen and Walters, 2004b; Failler and Pan, 2007).

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Tables

Table 1. Parameters used to quantify production and revenue for all enterprises. The agricultural product revenue is only used for processors. Ticket sales are for producers only, and are assumed to vary proportionally with effort.

Topic	Parameter	Symbol	Units
Identity	Name		
	Nationality		
Products	Agricultural	R_a	\$/t
	Energy	R_c	\$/t
	Industrial	R_i	\$/t
	Services	R_s	\$/t
	Ticket sales	R_t	\$/effort
Subsidies	Energy	U_e	\$/t
	Other	U_o	\$/t

Table 2. Categories used for quantification of cost for enterprises of all types. Shares (S) are in percentage of revenue. The agricultural input cost is only used for processors. For producers, the expenses for input, management, and license costs are assumed to vary proportionally to effort.

Topic	Parameter	Symbol	Units
Pay or share	Worker, female	P_s or S_s	\$/t or %
	Worker, male	P_h or S_h	\$/t or %
	Owner, female	P_f or S_f	\$/t or %
	Owner, male	P_m or S_m	\$/t or %
Input	Agricultural	I_a	\$/t
	Capital cost	I_c	\$/t
	Energy cost	I_e	\$/t
	Industrial cost	I_i	\$/t
	Services cost	I_s	\$/t
Cost	Management	C_m	\$/t
	License	C_l	\$/t

	Certification	C_c	\$/t
	Observers	C_o	\$/t
	Observer rate	O_r	prop.
Taxes	Environmental	T_e	\$/t
	Export	T_x	\$/t
	Import	T_i	\$/t
	Production	T_p	\$/t
	VAT	T_v	\$/t
	Licenses	T_l	\$/t

Table 3. Social parameters used for all enterprises.

Parameter	Symbol	Units
Worker female	J_s	#/t
Worker male	J_h	#/t
Owner female	J_f	#/t
Owner male	J_m	#/t
Female worker dependents	D_s	#/worker
Male worker dependents	D_h	#/worker
Female owner dependents	D_f	#/owner
Male owner dependents	D_m	#/owner

Table 5. Parameters used to describe links between enterprises. Product value can for producers be obtained automatically from the off-vessel price entered in the ecosystem model.

Parameter	Units
Production/input	Prop.
Prop. of input	Prop.
Product value	$/t
Value rate	Prop.

Table 7. Summary table for the baseline value chain calculations in the hypothetical case study. The values are for the three fleets (and value chains) combined. All units are expressed on a unit area (km^{-2}) basis.

Categories	Producer	Processor	Distributor	Market	Total	Unit
Production	0.75	0.45	0.41	0.37	–	t
Production value	985	1890	2916	5079	10870	$
Other production value	0	29	0	0	29	$
Ticket revenue	0	0	0	0	0	$
Subsidies	169	249	186	24	628	$
= Revenue	**1154**	**2168**	**3102**	**5103**	**11527**	**$**
Salaries/shares	421	293	306	613	1607	$
Input (fish)	0	985	1890	2916	5791	$
Input other	481	257	282	312	1324	$
Taxes	65	206	152	352	774	$
Licenses + observers	52	135	31	66	284	$
= Cost	**1018**	**1936**	**2661**	**4258**	**9840**	**$**
= Profit	**135**	**232**	**442**	**845**	**1687**	**$**
= Total utility	**1154**	**2168**	**3102**	**5103**	**11527**	**$**
Jobs, female	0	54	24	23	100	#
Jobs, male	38	14	37	10	99	#
= Jobs, total	**38**	**68**	**60**	**33**	**199**	**#**
Worker dependents	96	184	112	58	450	#
Owner dependents	15	16	9	8	47	#
= Dependents, total	**111**	**200**	**121**	**66**	**498**	**#**

Figure captions

Figure 1. Schematic value chain flow from sea to consumer for a single fish species. The ecosystem parts (diamond-shaped boxes) are modeled in the ecological component, and the enterprises (rectangles) in the coupled value chain. The effort of the producer (fishing fleet) provides feedback to the ecosystem model impacting fish abundance and catches. Aquaculture units can be incorporated as producers or processors as best suited in individual applications. Value chains for other resource sectors can be included by omitting the links to the ecological components.

Figure 2. Partial value chain flow illustrating allowed connections (normal arrows) and disallowed connections (broken-line arrows). A value chain can include any number of enterprises and connectors in any order, as long as there are no cycles in the flows.

Figure 4. Flow chart for the hypothetical case study based on a model of the South China Sea. The tunas, mackerel, and benthos (clams) are the only exploited groups. The arrows indicate predatory flow.

Figure 6. Value chain flow in a hypothetical case study where the Ecopath model includes three exploited groups and three fleets, each with one target group.

Figure 7. Equilibrium analysis for the tuna fleet (producer). Effort (X-axis) is varied from 0 to four times the baseline effort. Revenue, profit, and cost for the fleet is shown, with the cost divided in components; unit is $\$\cdot km^{-2}$. Profit is negative beyond relative effort of 2.2. Maximum utility is at a relative effort of 1.6.

Figure 9. Equilibrium analysis for the value chain starting from the tuna fleet (producer), but including also processing, distribution, and marketing. Total cost includes cost for fish input, other input, wages, taxes and other costs; unit is $\$\cdot km^{-2}$. Profit is negative beyond relative effort of 3.5. Maximum utility is at a relative effort of 1.5.

Figure 11. Total revenue for the combined fishing sector in equilibrium varying only the fishing effort for the tuna fleet. Impact on other fleets is due to predator-prey interactions caused by changes in tuna abundance. The clam supply chain is not affected by tuna fishing, while the mackerel (prey of tuna) shows a strong dependence.

Figure 13. Total number of jobs ($\#\cdot km^{-2}$) in the fishing sector as a function of the effort of the tuna fleet. High occupation for tuna fleet at high effort levels is associated with very low incomes.

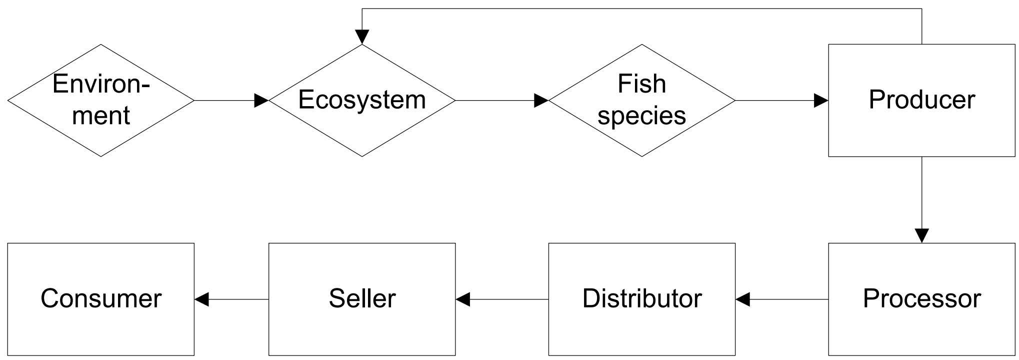

Environ-
ment
Ecosystem
Fish
species
Producer
Consumer
Seller
Distributor
Processor

Figure 1.

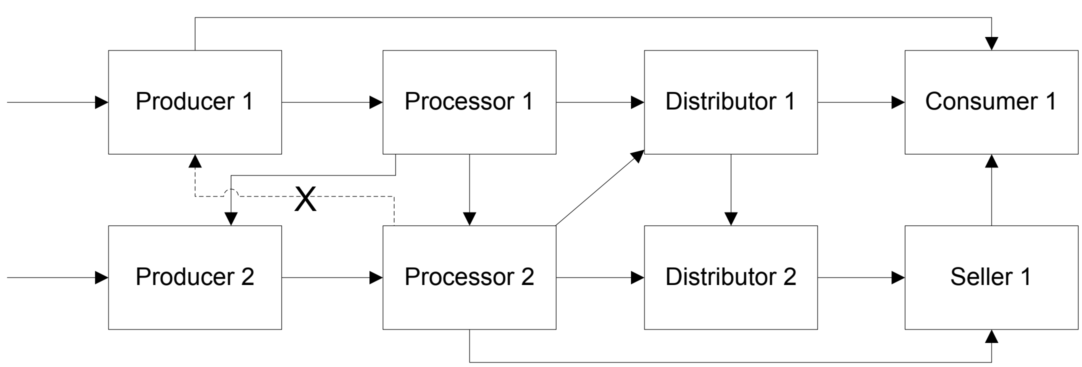

Producer 1
Processor 1
Distributor 1
Consumer 1
X
Producer 2
Processor 2
Distributor 2
Seller 1

Figure 2.

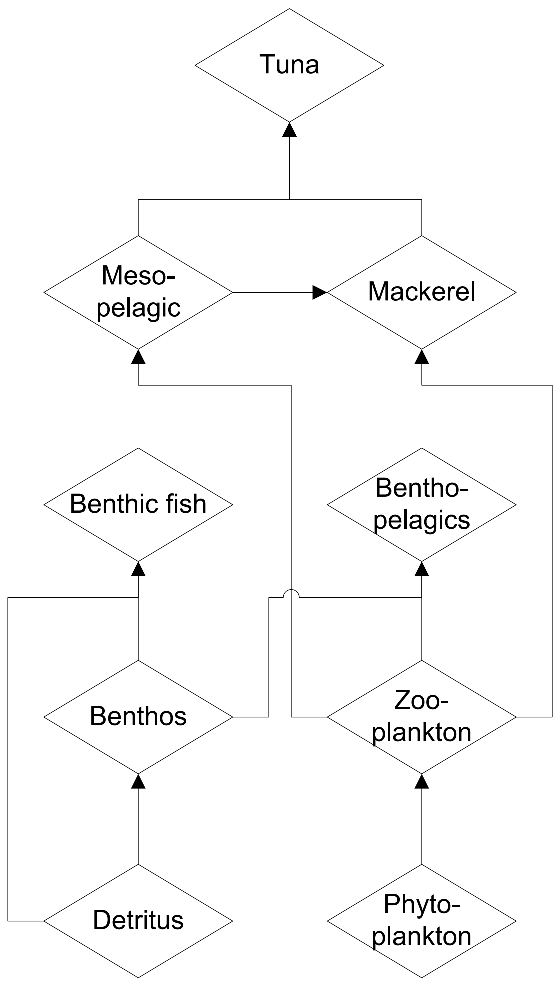


Figure 4.

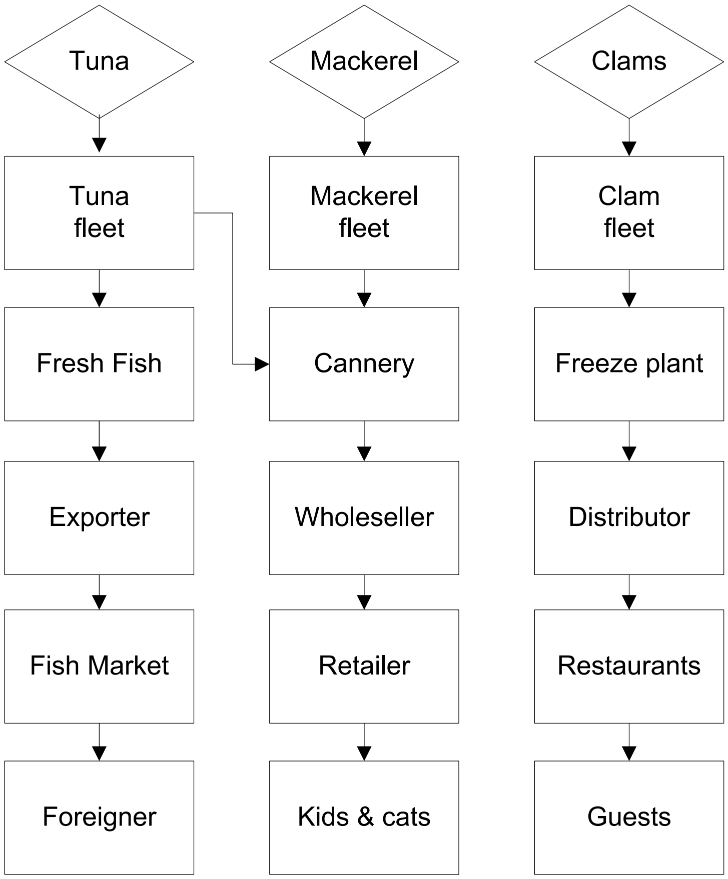

Tuna
Mackerel
Clams
Tuna fleet
Mackerel fleet
Clam fleet
Fresh Fish
Cannery
Freeze plant
Exporter
Wholeseller
Distributor
Fish Market
Retailer
Restaurants
Foreigner
Kids & cats
Guests

Figure 6

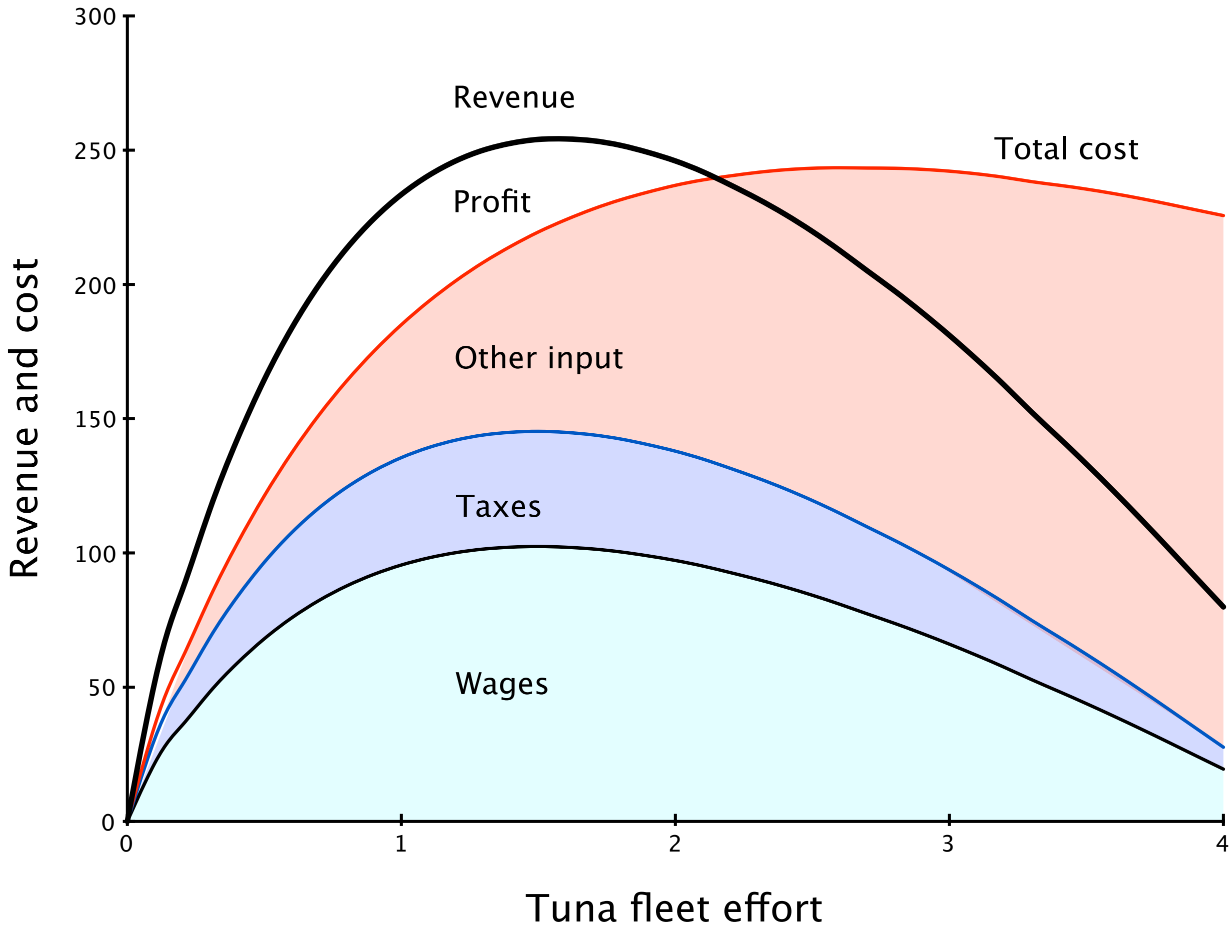

Revenue
Total cost
Profit
Other input
Taxes
Wages
Revenue and cost
Tuna fleet effort
300
250
200
150
100
50
0
0
1
2
3
4

Figure 7

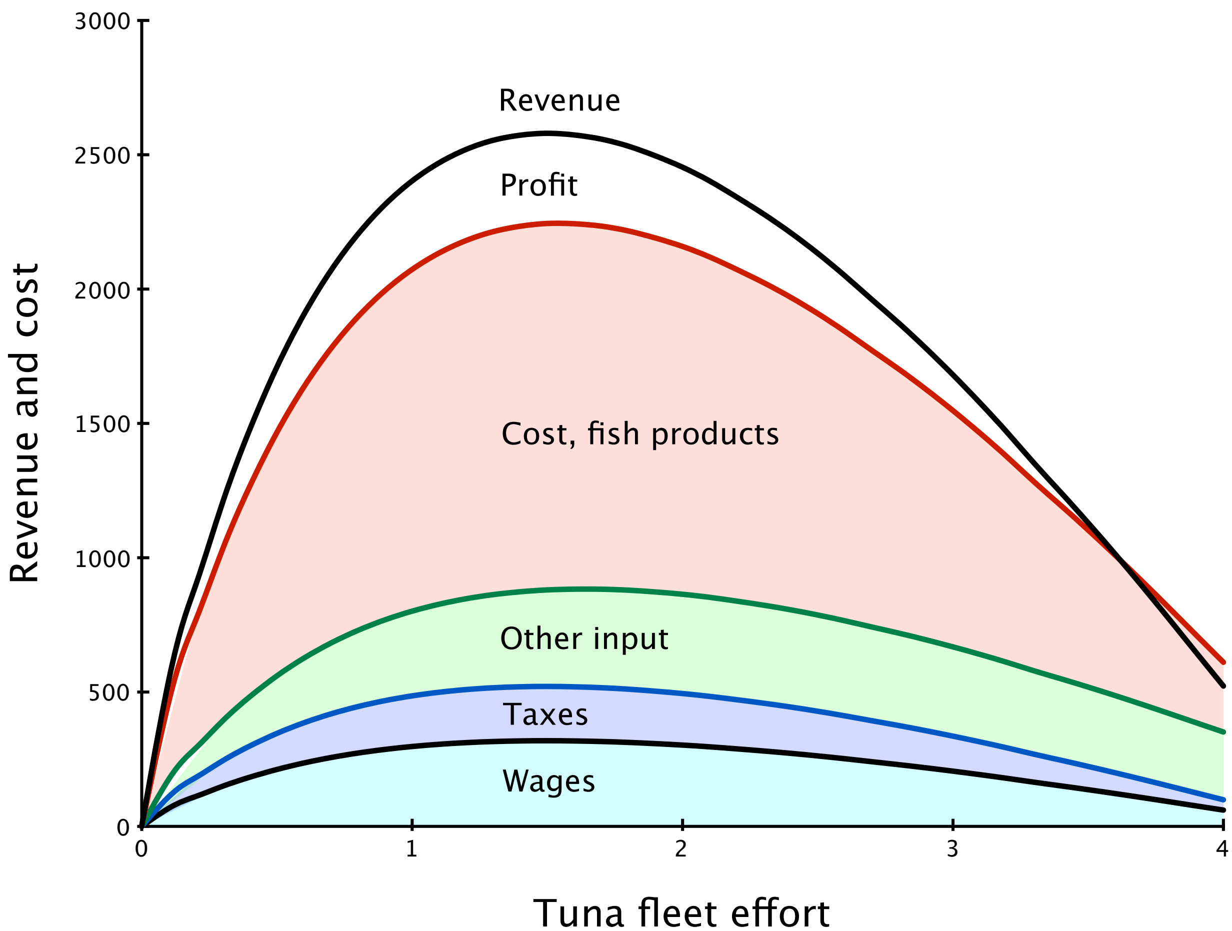

Revenue
Profit
Cost, fish products
Other input
Taxes
Wages
Revenue and cost
Tuna fleet effort
0
500
1000
1500
2000
2500
3000
0
1
2
3
4

Figure 9

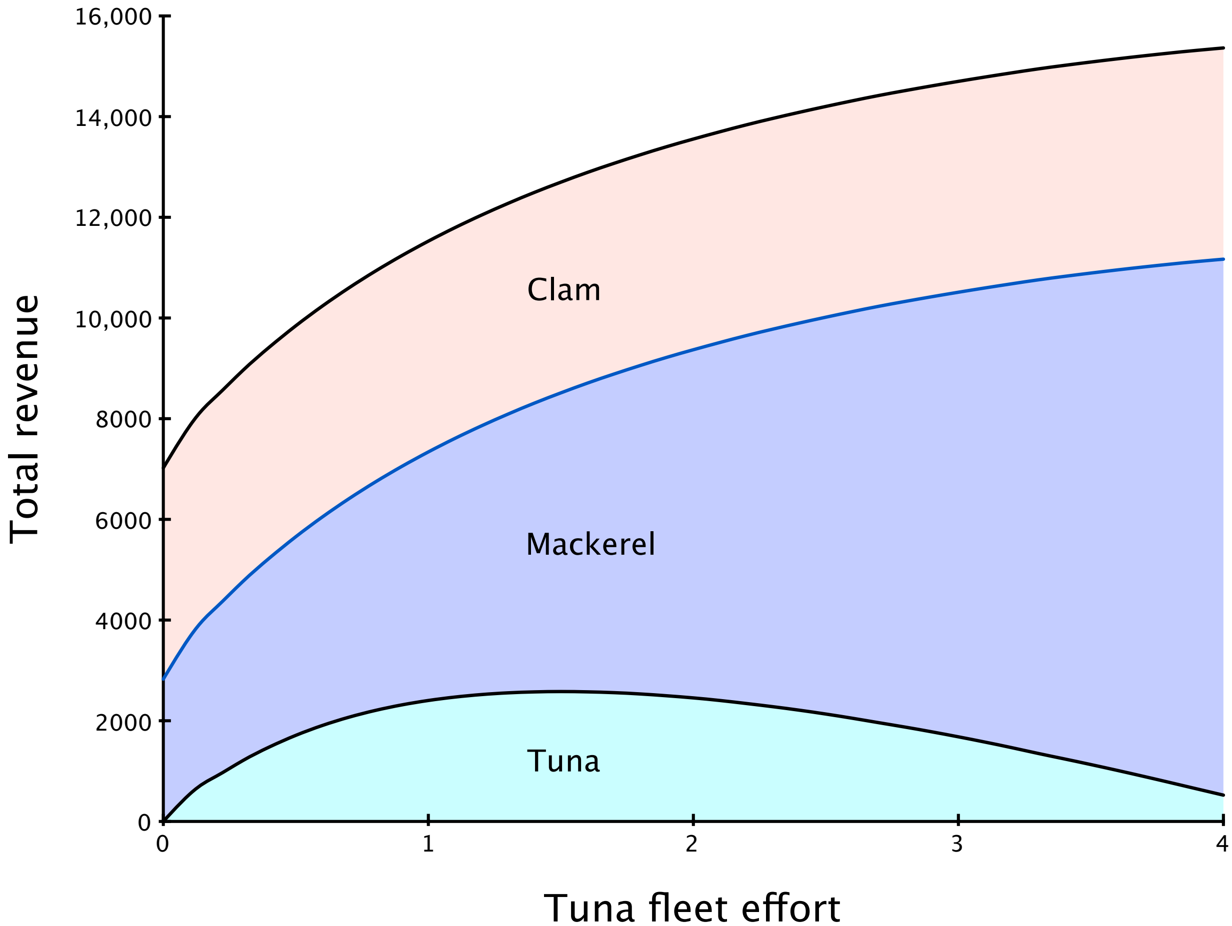
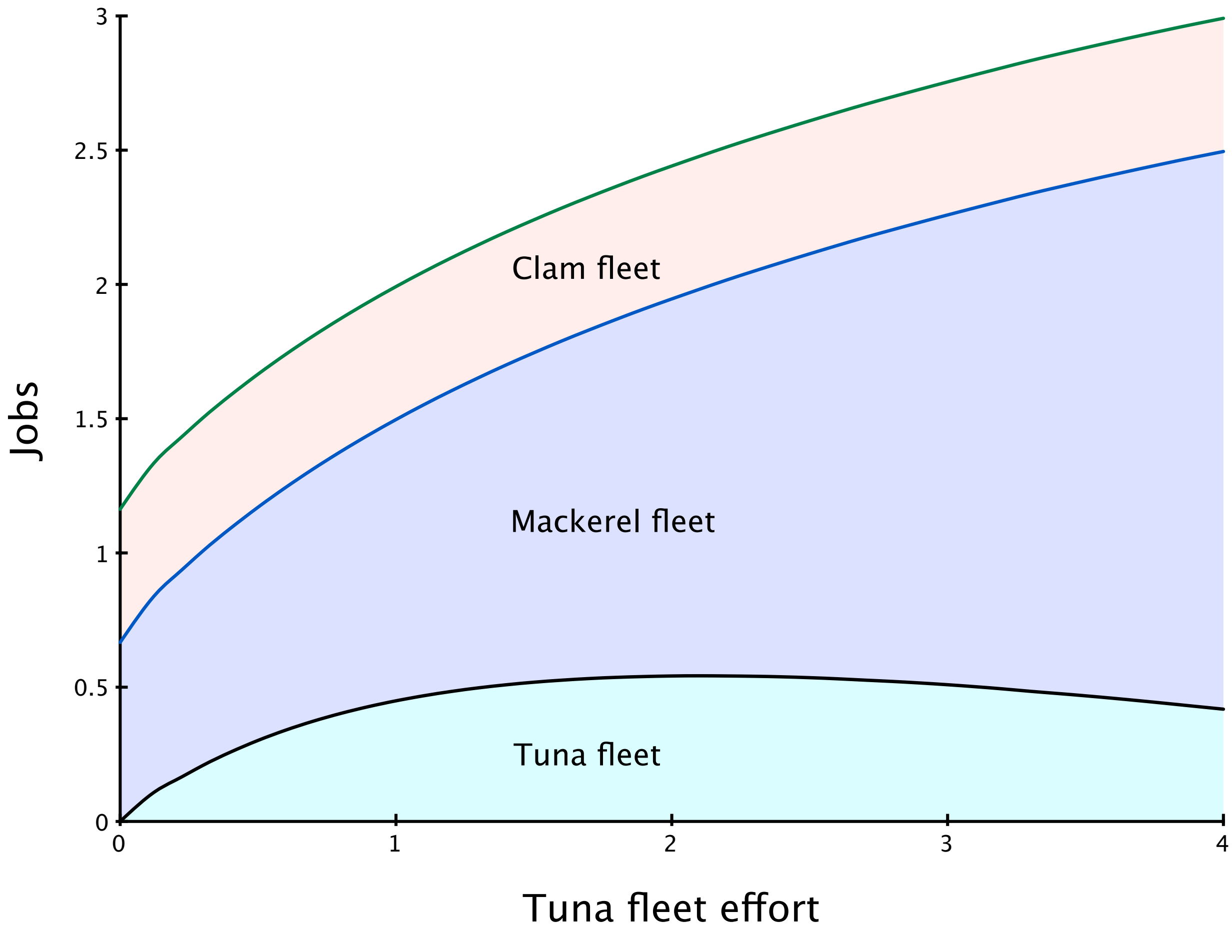

Total revenue
16,000
14,000
12,000
10,000
8000
6000
4000
2000
0
Clam
Mackerel
Tuna
0
1
2
3
4
Tuna fleet effort

Figure 11.



557

558 Figure 13