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# Selective harvesting by small-scale fisheries: ecosystem analysis of San Miguel Bay, Philippines

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## Abstract

San Miguel Bay is a large embayment along the Pacific coast of southeast Luzon, Philippines. The estuarine ecosystem therein is described through a mass-balance model that includes 16 functional groups (state variables), representing over 200 exploited fish and commercial invertebrate species, the energy (feeding) fluxes among them, and the multispecies catch of the fisheries, which pit artisanal fishers, using a wide range of gear, against trawl operators. The parameterization of the model is described in some detail, as are the implications of the ecological and fisheries interactions thus described. The discussion emphasizes the need for regulating the competition between the two sectors of the fisheries, whose present trajectories tend toward further degradation of the San Miguel Bay ecosystem. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* Mass-balance ecosystem analysis; Fisheries interactions; Species interactions

## 1. Introduction

About 60% of the world's fish catch is taken from fisheries in developing countries, yet the dynamics of these predominantly tropical resources have been studied only sporadically (see e.g. contributions in Saila and Roedel (1980), Agüero (1992) and Gallucci et al. (1995)). The fisheries are typically multispecies, with over a 100 or more species landed for immediate consumption, trade, fishmeal and other animal food or fish sauce (Pauly, 1996). This is especially true in southeast Asia, where marine biodiversity is at its

global peak (Eckman, 1967), and where the fisheries are also extremely diverse (Pauly, 1988). These multi-species fisheries are usually exploited by a heterogeneous small-scale fishery sector, and, in many cases, a competing large-scale fishery sector. Increased population growth, development of fishing technologies and demand for fish have placed enormous pressure on fish stocks. Patterns of exploitation have expanded and large-scale, capital intensive fisheries have long since moved into areas, and targeted species, traditionally exploited by small-scale fisheries (Pauly, 1979, 1997; Smith, 1983; Marr, 1982; Gulland, 1982). Massive overfishing of coastal resources has been one of the major results (Pauly and Chua, 1988).

At the same time, and rather surprisingly, there has been little research aimed specifically at the ecological assessment, impact and management of multispecies, multigear fisheries, particularly for the fisheries of the developing world (Christensen, 1996; Larkin, 1996).

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Indeed, the problems of managing these fisheries on an ecological basis are still being addressed in the relatively data-rich developed world, as shown by the description in Murawski (1991) of issues and problems in the multispecies, multigear demersal fishery of the Gulf of Maine, USA. Yet, there is arguably a greater demand and challenge to resolve these problems in tropical multispecies fisheries, where ecological and fisheries data are sparse.

Due to this paucity of ecological and fisheries data in tropical ecosystems, sophisticated assessment methods such as multispecies Virtual Population Analysis (Magnusson, 1995; Sparre, 1991) that are used in temperate fisheries, are not readily applicable to tropical settings. This constraint also applies to other multispecies approaches (see reviews in Daan and Sissenwine (1991), Mercer (1982) and Pauly and Murphy (1982)). The limited nature of data in tropical ecosystems demands a method that is less parameter intensive and that can be readily parameterized.

Fishing takes place within an ecosystem. Fish do not live in isolation from each other, they interact biologically, and different fishing gears have different impacts on the ecosystem. Fishing has been described as structuring ecosystems from the top-down (Larkin, 1996; Pauly, 1979). However, fishing also directly exploits species at lower trophic levels. Therefore, when examining the effects of fishing in a multispecies context, both the direct effect of fishing and its indirect effects, mediated through food webs, need to be taken into consideration.

The ecosystem effects of fishing can be examined with the mass-balance ecosystem model Ecopath (Christensen and Pauly, 1992a,b). This method has relatively limited data requirements, yet provides an ecological perspective to the assessment and management of multispecies, multigear fisheries. The aim of this paper is to examine the effects of fishing on the ecosystem, using a case study from San Miguel Bay, Philippines (Fig. 1). In particular, the relative effects of large-scale and small-scale fishing gears on the ecosystem are examined. Large-scale fishing gears are generally considered to have a greater impact on the resource than small-scale fishing gears. This assumption is tested by directly comparing the impact of the different types of fishing gear used in San Miguel Bay.

## 2. Methods

### 2.1. Model methodology

Ecopath is a mass-balance description of trophic interactions and has been applied widely to aquatic systems (see contributions in Christensen and Pauly (1993)). It has been used to describe and examine the energy flows in ecosystems (e.g. Jarre-Teichmann et al., 1995; Christensen, 1994, 1995) and as a diagnostic tool (e.g. Pauly et al., 1998; Pauly and Christensen, 1995, 1996). Ecopath is also a means to collate data about a system in a coherent form, enabling a better understanding of the entire system. It is a mass-balance ecosystem model, determined largely by trophic interactions and fishery removals, which enables analysis of ecosystem structure and function.

Ecopath was originally conceived by Polovina (1984) and further developed by Christensen and Pauly (1992a,b). The basic premise of the model is that, over the time period of the model, total production is equivalent to total loss, i.e., mass-balance occurs. That is, for each group “*i*” in the model

$$\begin{aligned} \text{Production by } (i) = & \text{all predation on } (i) \\ & + \text{non-predation losses of } (i) \\ & + \text{catch } (i) + \text{export of } (i) \end{aligned}$$

or

$$\begin{aligned} B_i \left( \frac{P}{B_i} \right) = \sum_j B_j \left( \frac{Q}{B_j} \right) DC_{ji} + \left( \frac{P}{B_i} \right) B_i (1 - EE_i) \\ + FX_i + EX_i \end{aligned} \quad (1)$$

where  $B_i$  = biomass of (*i*),  $P/B_i$  = production/biomass of (*i*),  $EE_i$  = ecotrophic efficiency of (*i*), (i.e., the proportion of the production that is exported or consumed by the predators in the system),  $Q/B_i$  = consumption/biomass ratio of (*i*),  $DC_{ji}$  = fraction of prey (*i*) in the average diet of predator (*j*),  $FX_i$  = catch of (*i*), and  $EX_i$  = export of (*i*) (Christensen and Pauly, 1992a).

The ecosystem is modeled using a set of simultaneous linear equations: each group in the model is represented by one balanced equation and requires six input parameters. The export and the diet composition of each group must be entered. Of the four other parameters,  $B$ ,  $P/B$ ,  $Q/B$ , and  $EE$ , three must be entered for each group. Since the linear equations

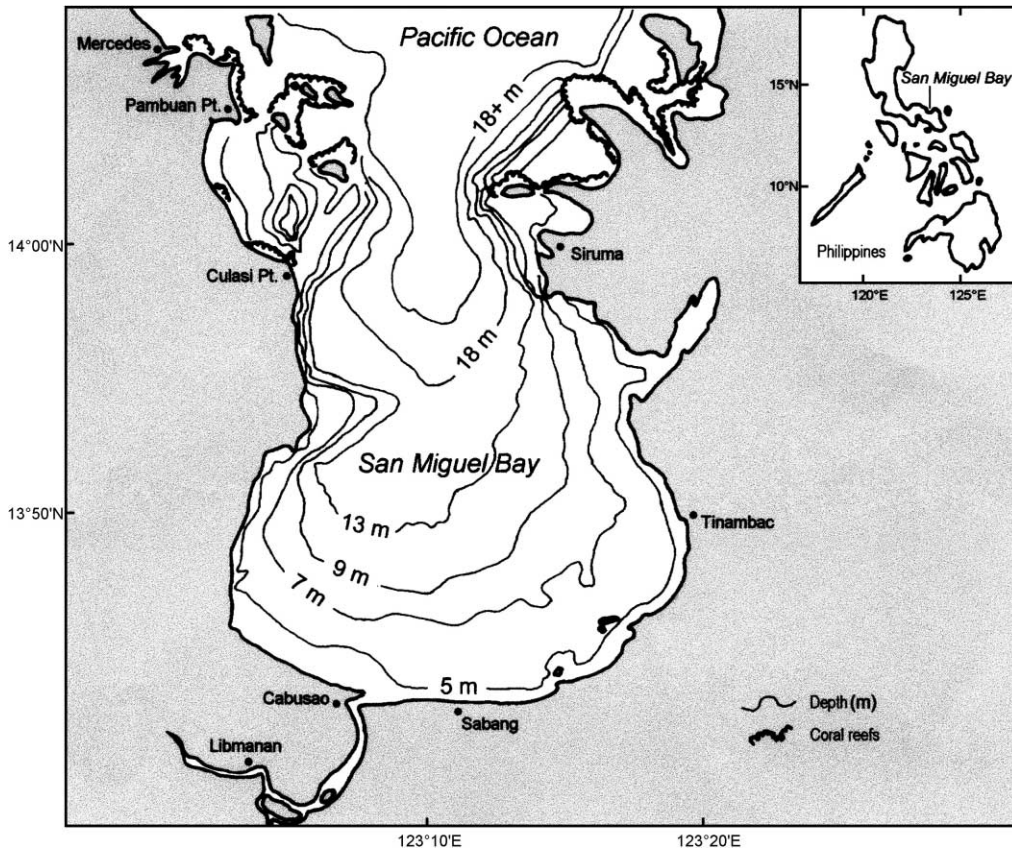


Fig. 1. Map of San Miguel Bay, inset shows location in Philippines, bathymetry of the Bay is shown in fathoms.

represent a balanced system, they can be solved for the unknown parameters. For further information, see Christensen and Pauly (1992a,b).

## 2.2. The case study

The study system, San Miguel Bay, Philippines (Fig. 1) covers an area of 1115 km<sup>2</sup>. The Bay is wide and shallow, and soft sediments dominate 95% of the bottom (Garces et al., 1995). It is, by definition, open to the ocean and there are coral reefs at its mouth. Suspended materials may be carried into San Miguel Bay by tidal currents, although Villanoy et al. (1995) reported that there is no net transport into or out of the Bay. Pauly (1982) speculated that fish spawn outside of the Bay and that larvae are carried into the Bay on tidal currents. Mangroves fringe the coast of San Miguel Bay and several rivers flow into the Bay. These

factors may have a modifying effect on the Bay. However, they are not included in the model and it is assumed that there are greater intra- and inter-species interactions within the model area than there are between species within and outside the model area.

San Miguel Bay is an ecosystem under stress due to excess fishing pressure from both large- and small-scale fishery sectors, a repeated pattern in the developing world. Three types of trawlers operate regularly in San Miguel Bay, alongside a diverse range of small-scale gears, including handlines, gillnets, and fish corrals. There is a history of resource competition in the Bay dating from the 1940s, when there was a trawl fishery for shrimp (Warfel and Manacop, 1950).

Fisheries statistics from San Miguel Bay have never been collected on a regular basis. However, two comprehensive studies of the fishery were conducted, during 1980–1981 (Smith et al., 1983), and

1992–1994 (ICLARM/BFAR/FSP, 1995). In these studies, the following types of surveys were conducted: trawl survey, landings survey, and fishing gear inventory. These provided data on species composition, trawlable biomass, length and weight of fish, fish landings, fishing effort, and use and number of fishing gear. Both studies concluded that the fishery is over-exploited, and both provided specific management recommendations.

The data from the 1992 to 1994 survey were used to construct an Ecopath model of San Miguel Bay representing the time period 1992–1994. Ecopath was first used to describe the interactions between different components within the ecosystem. In this way, the major energy flows and pathways in the ecosystem, upon which the fishery is based, were identified. A second model was then built incorporating the fishery, including the large- and small-scale fishery sectors, as predators within the model. In this way, it was possible to directly examine the impacts of fishing gears on the ecosystem.

### 2.3. The input parameters

Species groups were defined from over 200 species of fish and invertebrates that have been recorded in San Miguel Bay (Pauly, 1982; ICLARM/BFAR/FSP, 1995). Following Sugihara et al. (1984), these species were aggregated into functional groups, according to similarities in habitat, body size, diet, and co-occurrence in the catches of specific fishing gear. The functional groups are defined in Tables 1 and 2. There are 16 groups in total, eight fish groups representing predatory fish, demersal fish and pelagic fish, three invertebrate groups, two benthos groups, zooplankton, phytoplankton and detritus. Catch was estimated from landing survey data (Silvestre et al., 1995). Biomass was estimated as trawlable biomass for groups with survey data. *P/B*, *Q/B*, and the diet composition were estimated from empirical data where possible or taken from the literature on comparative tropical shallow marine ecosystems. Table 2 lists the input parameters, Table 3 a mater list of abbreviations for the functional groups, and Table 4 the diet composition used here. Further details are provided in Bundy (1997), and in [www.ecopath.org](http://www.ecopath.org), where a self-documenting file of the Ecopath model of San Miguel Bay may be accessed.

Table 1  
Functional groups of species in the San Miguel Bay Ecopath model

Ecopath group	Family/species	Relative abundance (%)
Sergestid shrimp		
Penaeid shrimp		5.30
Large crustaceans		0.80
	Portunid crabs	
	Stomatopods	
Demersal feeders		16.86
	Mullidae	
	Nemipteridae	
	Haemulidae	
	Priacanthidae	
	Theraponidae	
	Tetraodontidae	
	Bothidae	
	Apogonidae	
	Lethrinidae	
	Sparidae	
	Silliganidae	
	Gobiidae	
	Mugilidae	
	Siganidae	
	Cynoglossidae	
	Polynemidae	
	Platycephalidae	
	Tricantidae	
	Soleidae	
	Lactariidae	
Leiognathids		37.85
	<i>L. splendens</i>	
	<i>L. elongatus</i>	
	<i>L. equulus</i>	
	<i>L. bindus</i>	
	<i>Gazza minuta</i>	
	<i>Secutor ruconius</i>	
	<i>S. insidiator</i>	
Engraulids		6.13
	<i>Stolephorus commersonii</i>	
	<i>Stolephorus indicus</i>	
	<i>Thryssa setirostris</i>	
Pelagics		8.24
	Clupeidae	
	Dussumieria	
	Carangidae	
	Chirocentridae	
	Scombridae	
	Loligo	
Sciaenids		7.02
	<i>Otolithes ruber</i>	
	<i>Dendrophysa russelli</i>	
	<i>Pennahia macrophthalmus</i>	
	<i>Pennahia</i> sp.	

Table 1 (Continued)

Ecopath group	Family/species	Relative abundance (%)
Medium predators		11.11
	Arridae	
	Synodontidae	
	Trichiuridae	
	Muranaesocidae	
	Sphyracnidae	
	Formionidae	
	Muraenidae	
	Plotosidae	
	Serranidae	
	Psettodidae	
	Lutjanidae	
	Fistularidae	
	Opichthidae	
Large zoobenthos feeders		2.32
	Rays	
	Ephippidae	
Large predators		0.31
	<i>Carcharhinus melanopterus</i>	
	<i>Lates calcifer</i>	

Table 3

Master list of abbreviations for Table 4 and Figs. 2–7

Abbreviation	Full name
Ph/P	Phytoplankton
ZP	Zooplankton
Meiob	Meiobenthos
Macrob	Macrobenthos
Serg	Sergestids
Pen	Penaeids
LC	Large crustaceans
DF	Demersal feeders
Leiogn	Leiognathids
Engr	Engraulids
Pel	Pelagics
Sciae	Sciaenids
MP	Medium predators
LZB	Large zoobenthos feeders
LP	Large predators
B	Biomass
QB	Consumption to biomass ratio
GE	Gross food conversion efficiency
EE	Ecotrophic efficiency

#### 2.4. Balancing the model

The parameters estimated as described above specified a top heavy, unbalanced model: there was insufficient biomass or production at the lower trophic

levels to support the consumption by higher trophic levels. Consequently, some EE's were greater than unity. In addition, some of the gross conversion efficiencies ( $GE = P/Q$ ), were unrealistically high. Essentially, the biomass was too low to support the catches being removed from the ecosystem.

Table 2

Input parameters for the Ecopath model of San Miguel Bay

Ecopath group	$P/B$ ( $\text{yr}^{-1}$ )	$Q/B$ ( $\text{yr}^{-1}$ )	Biomass ( $\text{t km}^{-2}$ )	Export/catch ( $\text{t km}^{-2}$ )	EE
Phytoplankton	200	NA	– <sup>a</sup>	NA	0.95
Zooplankton	67	192	–	NA	0.95
Meiobenthos	10	50	–	NA	0.95
Macrobenthos	6.8	25.9	0.107	0.036	0.95
Sergestid shrimp	62	506	–	2.403	0.95
Penaeid shrimp	6.48	31.4	0.144	1.677	0.95
Large crustaceans	2.8	13.9	0.022	0.854	0.95
Demersal feeders	6	24.5	0.458	1.273	0.95
Leiognathids	9.42	26	1.03	1.434	0.95
Engraulids	6	24	0.167	1.071	0.95
Pelagics	5.45	28.9	0.224	1.149	0.95
Sciaenids	4.39	11.3	0.191	3.388	0.95
Medium predators	2.5	7.6	0.302	1.090	0.95
Large zoobenthos feeders	1.3	11.7	0.063	0.309	0.95
Large predators	2	11.9	0.008	0.131	0.95
Detritus	NA	NA	19.8	NA	

<sup>a</sup> Indicates parameters to be estimated by the model.

Table 4  
Diet composition for the Ecopath model<sup>a</sup>

Ecopath group	ZP	Meiob	Macrob	Serg	Pen	LC	DF	Leio gn	Engr	Pel	Sciae	MP	LZB	LP
Zooplankton	0.05			0.40	0.05	(0.10) <i>0.04</i>	0.10	0.275	0.40	0.50	0.10	(0.10) <i>0.09</i>		(0.10) <i>0.00</i>
Meiobenthos		0.1	0.05		0.10	<i>0.13</i>	0.05	0.050			0.05			
Macrobenthos			0.05		0.40	(0.30) <i>0.38</i>	0.45	0.425	0.15	0.10	0.30	(0.19) <i>0.14</i>	0.9	(0.10) <i>0.04</i>
Sergestid shrimp						(0.15) <i>0.04</i>	0.10	0.150	0.25	0.05	0.25	0.15		
Penaeid shrimp						(0.05) <i>0.04</i>	0.05		0.15	0.1	0.15	(0.10) <i>0.09</i>	0.05	
Large crustaceans						(0.00) <i>0.01</i>				0.05	0.10			
Demersal feeders												0.10		(0.15) <i>0.13</i>
Leio gnathids												(0.11) <i>0.18</i>		(0.10) <i>0.14</i>
Engraulids										(0.20) <i>0.00</i>	0.03	0.10		(0.15) <i>0.16</i>
Pelagics												0.10		(0.15) <i>0.20</i>
Sciaenids											0.02	(0.05) <i>0.03</i>		(0.15) <i>0.20</i>
Medium predators												(0.00) <i>0.03</i>		(0.10) <i>0.13</i>
Large zoobenthos feeders														
Large predators														
Phytoplankton	0.70		0.05	0.50	0.05	(0.00) <i>0.00</i>		0.050		(0.00) <i>0.20</i>				
Detritus	0.25	0.9	0.85	0.10	0.40	(0.40) <i>0.36</i>	0.25	0.050	0.05				0.05	

<sup>a</sup> Figures in brackets were changed during the balancing process. Figures in italics are the new values. Units are proportions of 1. Some values are rounded to two figures, thus not all columns add up to 1.

This problem was addressed by allowing the model to estimate biomass for all groups other than the large predators and detritus. Consequently, all other biomasses were left as unknowns, and default values of 0.95 entered for the EE. This is a valid approach since the original biomass estimates were based on trawlable biomass estimates. The large predator biomass scales the system, since Ecopath is a top-down model and scales all flows to the food required to maintain the biomass at the top of the food web. For a description of other adjustments for model constraints, see Bundy (1997).

### 2.5. Sensitivity analysis

The uncertainty of the parameter estimates was explored using a simple sensitivity analysis routine. Each parameter is varied by  $-50$  to  $+50\%$  of the original value, in steps of  $10\%$ . The impact of this on the estimated parameters is calculated as

$$\frac{\text{estimated parameter} - \text{original parameter}}{\text{original parameter}}$$

Since biomass is estimated for all groups, other than the large predators and detritus, the analysis describes the sensitivity of these biomass estimates to the  $P/B$  and  $Q/B$  estimates, and the default assumption for EE. The  $P/B$ s and  $Q/B$ s were estimated from empirical data or taken from the literature (see above), and the sensitivity analysis explores the impact of the uncertainty of this data on the mass-balance model.

### 2.6. Impacts of species interactions

The impacts of species interactions were explored using the Ecopath “trophic impact routine”. The method is derived from economic input/output theory, which was adapted to ecology by Hannon (1973) and Hannon and Joiris (1989). Ulanowicz and Puccia (1990) used a similar approach, and their methodology was incorporated into Ecopath, as the trophic impact routine (Christensen and Pauly, 1992b). Essentially, the trophic impact routine estimates the difference between the positive and negative effects that functional groups have on each other, either directly, or indirectly. Thus it is possible to qualitatively assess the impact on the ecosystem of a small biomass increase in one part of the ecosystem.

The trophic impact results are comparable within Ecopath models, but not between models.

### 2.7. Interactions between the fish and fishery

In order to include the fisheries explicitly in the Ecopath model as “predators”, certain assumptions were made concerning the input parameters of the fisheries. First, their biomass was arbitrarily designated to be 1 (this is valid since biomass simply operates as a multiplier in the linear system of equations), and their consumption equated to the catch. Unassimilated food was equated with discards, and thus flow to detritus, and respiration, the energy required by the system, equated with fish consumed aboard the vessel. The diet composition of the “fishery predators” is equivalent to their catch composition. The technique of forcing the software to treat the fisheries as if they were predators does not affect the computation of flows.

Two fishing predators were considered: one large-scale fishery sector (LS), and a small-scale fishery sector (SS). The large-scale fishery sector predator includes the large, medium, and small trawlers, while the small-scale fishery sector predator includes all the other fishing gears in San Miguel Bay, such as gillnets, longlines, fish corral, and fish traps. This is denoted as the “LS–SS sector” model.

The small-scale fishery sector is composed of many gear types, each designed to target certain fish or crustacean groups. Different fishing gears would therefore be expected to have different impacts on the ecosystem. In order to examine the impacts of the small-scale fishery sector in greater detail, the small-scale fishery sector predator was subdivided into eight small-scale gear groups (“LS–SS gears” model). This model consisted of one large-scale fishery sector predator and eight small-scale fishery sector predators.

Comparisons of trophic level and omnivory indices were made between the large- and small-scale fishery sectors. The omnivory index is a measure of the variability in the trophic level at which the functional groups feed (Christensen and Pauly, 1992a). A value of 0 indicates complete specialization in prey selection. The impact of the large- and small-scale fishery sectors on the ecosystem were compared using the trophic impact routine. The impact of an

increase in effort (biomass) is simulated as described above.

### 3. Results

The San Miguel Bay ecosystem spans four trophic levels. Fig. 2 is a flow diagram that shows the relationships between functional groups, their trophic position and the size of the flows between them. The ecosystem modeled is more dependent on its detritus–benthic components than the pelagic components of the ecosystem. Of the total flow in the ecosystem, 56% originates from the detritus and 44% from primary producers.

The large predators occupy a trophic level of 4.1 (Table 5) and the fishery operates at an average trophic level of 4.0. Thus the large predators occupy a marginally higher trophic level than the fishery. Most of the functional groups occur at a trophic level between 2.5

and 3.5. Of these, the engraulids and pelagics are mainly dependent on the pelagic side of the food web. Others, such as the sciaenids, leiognathids, demersal feeders, large zoobenthos feeders, large crustaceans, and penaeids are dependent on the detritus side of the food web. Given the large number of groups occurring at a similar trophic level, there is likely to be strong competitive, (i.e., horizontal) interactions between groups, in addition to the more “vertical” predator–prey relationships.

The Ecopath model estimated the total biomass of functional groups sampled by the trawl survey at 5.78 t km<sup>-2</sup>, about twice the trawl survey estimate. This was derived from a large predator biomass of 0.095 t km<sup>-2</sup>, and is within the confidence limits of the trawl survey estimate (Bundy, 1997).

However, the relative abundance of the functional groups in the trawl survey and the Ecopath model show considerable discrepancies (Fig. 3). These are likely due to two factors. First, each functional group

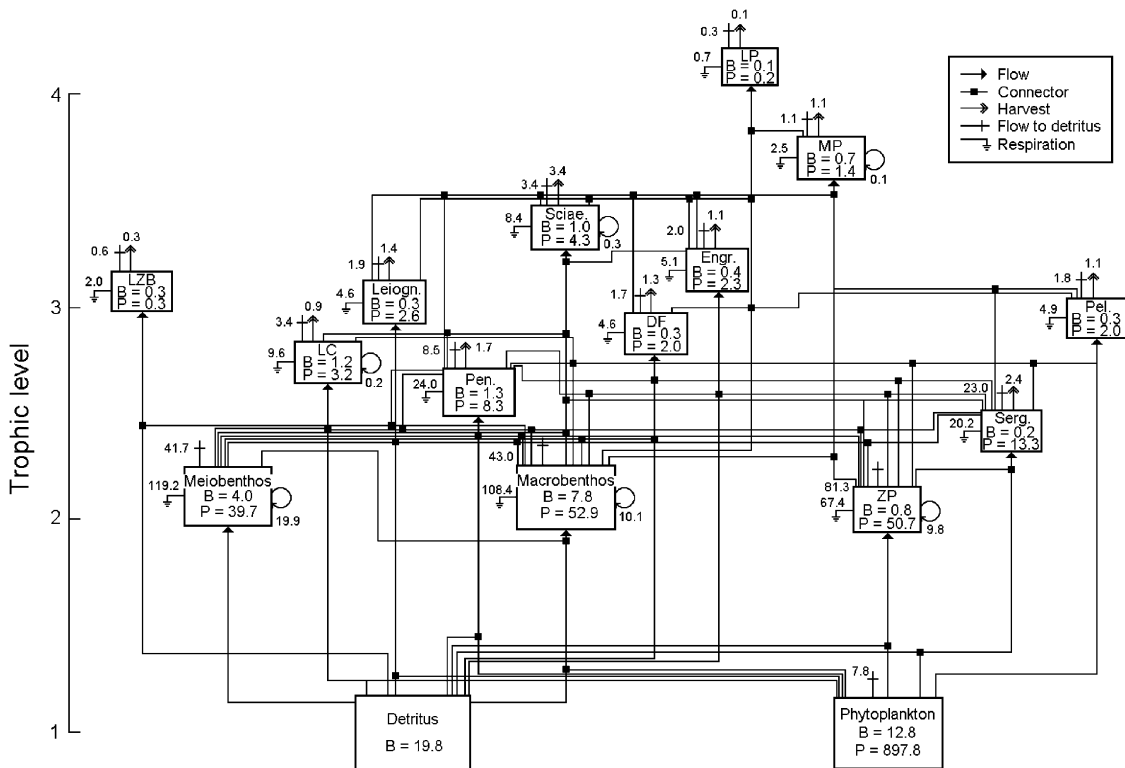


Fig. 2. Flow diagram of the San Miguel Bay ecosystem. See Table 3 for abbreviations.

Table 5  
Selected results from the San Miguel Bay ECOPATH model<sup>a</sup>

	Biomass (t km <sup>-2</sup> )	Trophic level	Omnivory index
Zooplankton	<i>0.757</i>	<i>2.05</i>	<i>0.053</i>
Meiobenthos	<i>3.973</i>	<i>2.11</i>	<i>0.111</i>
Macrobenthos	<i>7.786</i>	<i>2.11</i>	<i>0.111</i>
Sergestids	<i>0.215</i>	<i>2.42</i>	<i>0.266</i>
Penaeids	<i>1.286</i>	<i>2.60</i>	<i>0.303</i>
Large crustaceans	<i>1.154</i>	<i>2.75</i>	<i>0.332</i>
Demersal feeders	<i>0.336</i>	<i>2.88</i>	<i>0.279</i>
Leiognathids	<i>0.348</i>	<i>3.03</i>	<i>0.132</i>
Engraulids	<i>0.39</i>	<i>3.18</i>	<i>0.119</i>
Pelagics	<i>0.296</i>	<i>2.96</i>	<i>0.274</i>
Sciaenids	<i>0.972</i>	<i>3.38</i>	<i>0.097</i>
Medium predators	<i>0.651</i>	<i>3.70</i>	<i>0.188</i>
Large zoobenthos feeders	<i>0.250</i>	<i>3.08</i>	<i>0.073</i>
Large predators	<i>0.095</i>	<i>4.14</i>	<i>0.112</i>
Phytoplankton	<i>12.825</i>	<i>1</i>	<i>0</i>
Detritus	<i>19.800</i>	<i>1</i>	<i>0.283</i>

<sup>a</sup> Figures not in italics are input parameters.

is differentially available to the trawl gear used in the survey. A survey performed with one type of gear cannot sample all species with an equal catchability. Therefore some species will be under, and others will be over-represented in the trawl survey catches. Secondly, Ecopath uses catch estimates to estimate biomass. That is, Ecopath calculates the biomass required to support a given catch (and predator consumption): the greater the catch, the greater the biomass estimate. The catch estimates in San Miguel Bay are derived from the landings of over 20 different types of fishing gear, all targeting different groups. These catches have a composition quite different from the relative abundance in the trawl survey. The large crustaceans, e.g., are hardly represented in the trawl survey, while they have a large catch, mostly by the crab gillnet. Similarly, the large predators are poorly represented in the trawl survey, but are caught in relatively large numbers by the set longline gear. Given these kinds of differences, it seems unlikely that Ecopath could reproduce the relative abundance of a trawl survey from catch-derived biomass estimates.

### 3.1. Sensitivity analysis

The functional groups are most sensitive to their own input parameters. Fig. 4a, for example, shows the

sensitivity of the sciaenid biomass estimate to the sciaenid input parameters, *P/B* and *EE*. A 50% reduction in the input parameter results in a 118% increase in the sciaenid biomass estimate. The other functional groups, are similarly sensitive to their own *P/B* and *EE* parameters. In addition, the meiobenthos is sensitive to its *Q/B* parameter.

The sensitivity of other functional groups to the sciaenid parameters is also shown in Fig. 4a. The biomass of the large crustaceans, meiobenthos, macrobenthos, sergestids, and penaeids undergo a 45–65% increase when the *P/B* or *EE* of the sciaenids is reduced by 50%. Fig. 4b illustrates the sensitivity of these groups to the sciaenid *Q/B* input parameter. All groups are less sensitive to this parameter.

The model is most sensitive to the sciaenids and medium predators. These affect the greatest number of other functional groups. With the exception of the sensitivity of large crustaceans to sciaenids, the magnitude of the change in the estimated parameter is less than the magnitude of the change in the input parameter. There are some greater sensitivities to other functional groups, however: phytoplankton is very sensitive to zooplankton and sensitive to sergestids; meiobenthos is very sensitive to macrobenthos; and zooplankton is sensitive to sergestids. In general, the model is not very sensitive to the other functional groups.

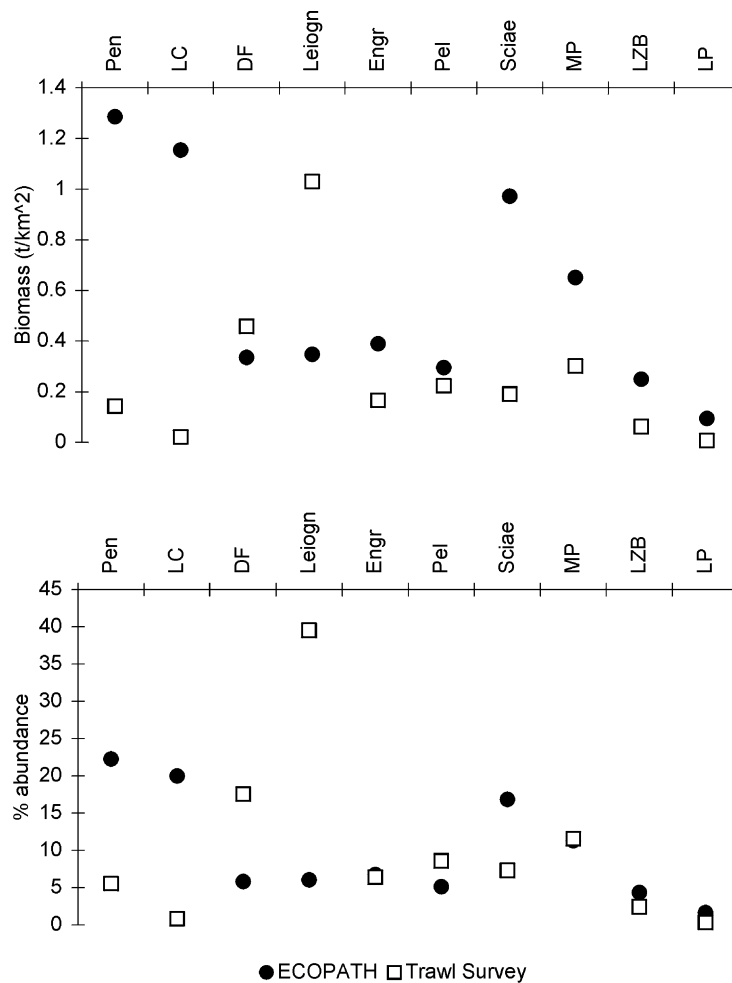


Fig. 3. Comparison of (A) biomass estimates from the Ecopath model and (B) relative abundance estimates from the San Miguel Bay 1992–1994 trawl survey.

### 3.2. Impacts of species interactions

The functional groups with the greatest impact on the fishery groups in the model are the groups at the bottom of the food web, such as phytoplankton, zooplankton, and macrobenthos. This is evidence of bottom-up control (Hunter and Price, 1992; Hall et al., 1970), where an increase in productivity at the bottom of the food web leads to an increase in productivity and abundance at higher trophic levels. The increase in phytoplankton biomass, e.g., leads to a positive increase in the biomass of zooplankton, sergestids, leiognathids, engraulids, pelagics, sciaenids, medium

predators, and large predators (Fig. 5). Similar positive responses by these functional groups are observed when the biomass of other lower trophic levels, such as detritus, zooplankton, and macrobenthos are increased.

Phenomenon of top-down predator–prey interactions and trophic cascade (Carpenter et al., 1985) can be seen in the model results. An increase in the biomass of the large predators produces a small decrease in the biomass of all fish groups and a small increase in the three crustacean groups (Fig. 5). An increase in the biomass of the medium predators leads to a small increase in the large predators, a decrease in

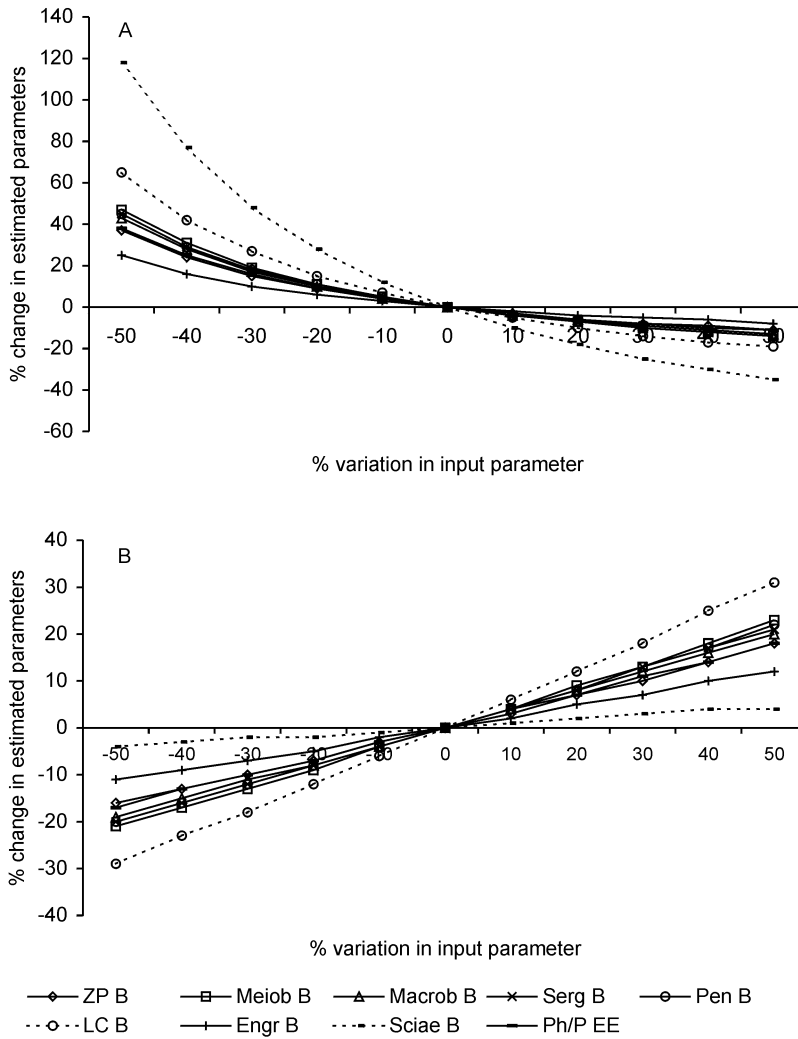


Fig. 4. Sensitivity analysis of the model to the Sciaenids' input parameters: (A) PB and EE; (B) QB. See Table 3 for abbreviations.

most of the other functional groups and a small increase in the large crustaceans, macrobenthos and zooplankton. An increase in the fishery has a negative impact on most of the functional groups that are fished, with the exception of the penaeids and sergestids, which increase.

There is also evidence for competition between functional groups. The three crustacean groups, the sergestids, penaeids and large crustaceans each decrease in response to an increase in the biomass of the other two crustaceans, indicating competitive interactions (Fig. 5).

More complex interactions, with both predator-prey and competitive interactions may also occur. Fig. 2 showed that many of the functional groups are clustered around trophic level 3. An increase in the biomass of any of these groups leads to competitive decrease in the biomass of the other functional groups at this trophic level. An increase in the leiognathid biomass, e.g. (Fig. 5) produces a decrease in the biomass of the demersal feeders, leiognathids, engraulids, and pelagics. Meanwhile, the biomass of their predators, the medium predators and the large predators, increases. However, the sciaenids and the

penaeids, which are not prey of the leiofnathids, also decrease. These groups may decrease through the combined effects of predation by the large and medium predators and competition between trophic

level 3 groups. All functional groups respond negatively to an increase in their own biomass, due to increased resource competition within the functional group.

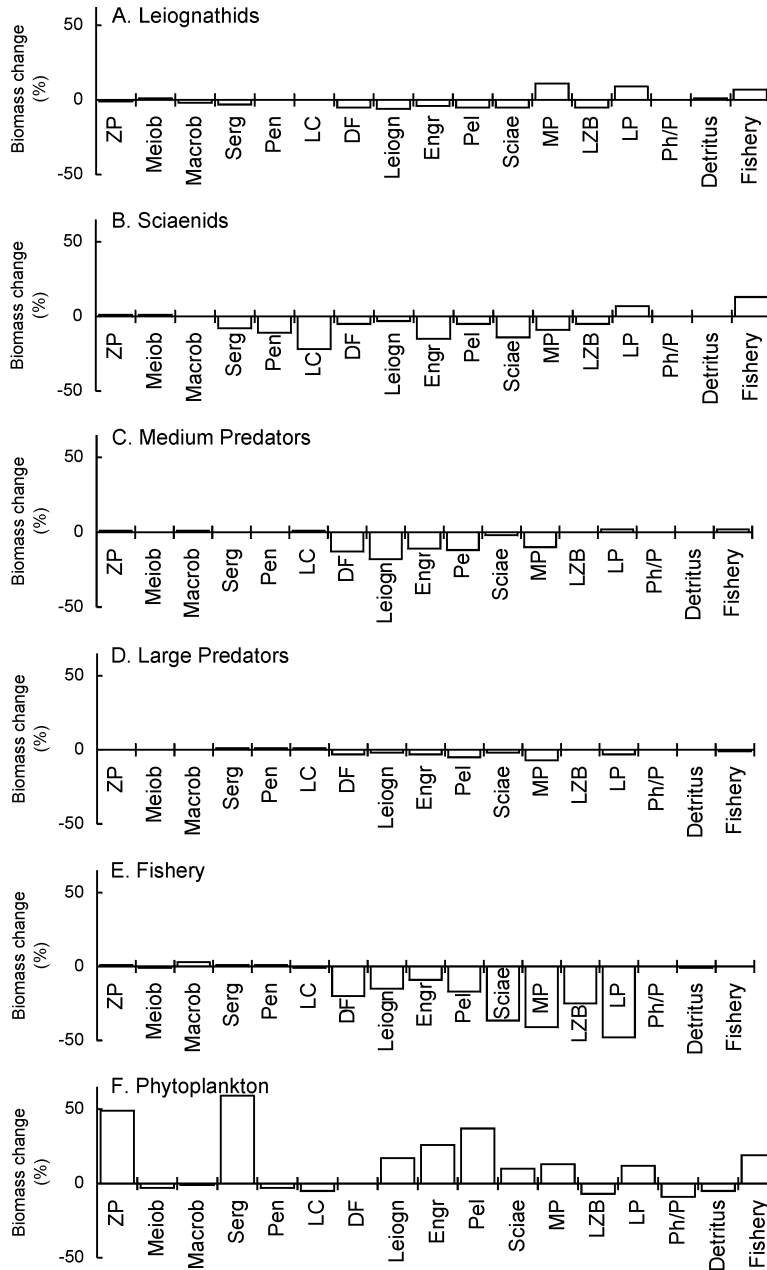


Fig. 5. Results of the trophic impact routine. Each figure, (A)–(J), shows the predicted change in biomass of all functional groups in response to an increase in the biomass of groups (A)–(J).

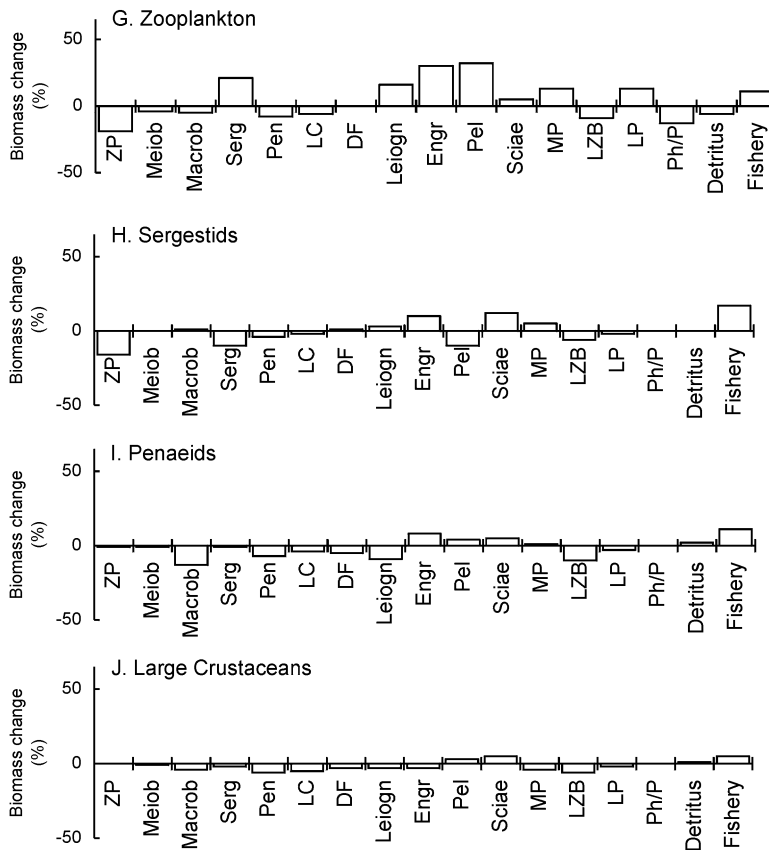


Fig. 5. (Continued).

### 3.3. Interactions between the fish and fishery

The general Ecopath analysis results for the “fishery predators”, the “LS–SS sector” and “LS–SS gears”, are shown in Table 6. Each fishery predator is assigned biological parameters such as trophic level and omnivory index since it is treated as though it is a natural predator within the ecosystem.

The average trophic levels of the large- and small-scale fishery sectors fish are very similar. The large-scale fishery sector has a trophic level of 4.09 and the small-scale fishery sector collectively has a trophic level of 3.98. However, the individual small-scale fishing gears operate at variable trophic levels. The ordinary and hunting gillnets fish at the highest trophic levels while the mini-trawler and fine meshed gears fish at the lowest trophic levels. The former targets

sciaenids, whereas the latter targets sergestids and penaeids.

The “fishery predators” have low omnivory indices compared to the biological functional groups (Table 5), indicating that they do not exploit many trophic levels. Among small-scale gears, the highest omnivory index occurs in the “other gear”, as may be expected since it is a composite group of gears, including handlines, beach seines and spear guns. Collectively, the small-scale fishery sector has a much higher omnivory index than the large-scale fishery sector. Thus, the small-scale fishery sector fishes at a wider range of trophic levels than the large-scale fishery sector.

The results of the trophic impact routine indicate that an increase in the small-scale fishery sector has a far greater impact on the ecosystem than an increase in the large-scale fishery sector (Fig. 6). Indeed, the

Table 6  
Input parameters and results for the two “fishery predator” ECOPATH models, “LS–SS sector” and “LS–SS gears”

Fishing gear <sup>a</sup>	Input parameters							Results	
	Biomass (t km <sup>-2</sup> )	P/B (yr <sup>-1</sup> )	Q/B (yr <sup>-1</sup> )	Export (t km <sup>-2</sup> yr <sup>-1</sup> )	Harvest (t km <sup>-2</sup> yr <sup>-1</sup> )	EE <sup>b</sup>	GE <sup>b</sup>	Trophic level	Omnivory index
Other gear	1	0.68	0.68	0.68	0.68	1	1	4.20	0.164
Fixed gear	1	1.23	1.23	1.23	1.23	1	1	4.05	0.024
Crab gear	1	0.66	0.66	0.66	0.66	1	1	3.75	0.002
Fine mesh gear	1	1.83	1.83	1.83	1.83	1	1	3.58	0.112
Other gillnets	1	2.75	2.75	2.75	2.75	1	1	4.00	0.116
Ordinary gillnet	1	2.37	2.37	2.37	2.37	1	1	4.31	0.088
Hunting gillnet	1	1.51	1.51	1.51	1.51	1	1	4.33	0.040
Mini-trawler	1	1.56	1.56	1.56	1.56	1	1	3.54	0.070
Large-scale	1	2.23	2.23	2.23	2.23	1	1	4.09	0.095
Small-scale	1	12.59	12.59	12.59	12.59	1	1	3.98	0.172

<sup>a</sup> Other gear: set longline, handline, fish trap, ring net, pull net, fish weir, beach seine, spear gun; fixed gear: lift net, fish corral; crab gear: crab gillnet, crab liftnet; fine mesh gear: filter net, scissor net; other gillnets: shrimp gillnet, bottom-set gillnet, surface gillnet, shark gillnet, “other gillnets”; large-scale: large trawlers, medium trawlers, small trawlers; small-scale: all small-scale gear, including mini-trawlers.

<sup>b</sup> EE and GE are 1 since “consumption” and “production” are here equivalent and there is no respiration.

small-scale fishery sector has a larger impact on all the functional groups with the exception of the leionathids and the engraulids. The small-scale fishery sector also impacts some non-fished groups, including zooplankton and macrobenthos.

The trophic impact routine results for the “LS–SS gears” model illustrate both the diversity of the small-scale fishery sector and the selectivity of the small-scale gears, and their impacts (Fig. 7). There is a clear

differential response by the functional groups to increased fishing by the different small-scale gears. The results demonstrate that the effects of fishing are far more widespread than the targeted fish species. The ordinary gillnet and hunting gillnet, e.g., target sciaenids and medium predators. Both functional groups decrease in response to increased fishing effort by the two gears. However, the functional groups below them, with the exception of the pelagics, increase,

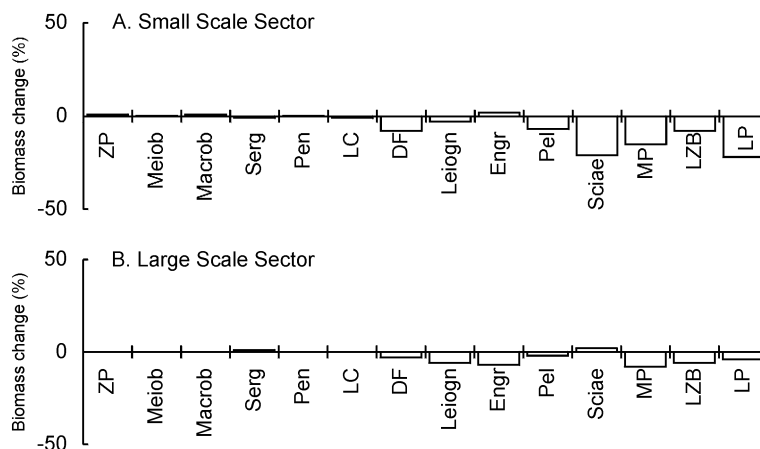


Fig. 6. Results of the trophic impact routine for: (A) the small-scale fishery sector; (B) the large-scale fishery sector. Figures (A) and (B) show the predicted change in biomass of functional groups in response to an increase in fishing effort by each fishing sector.

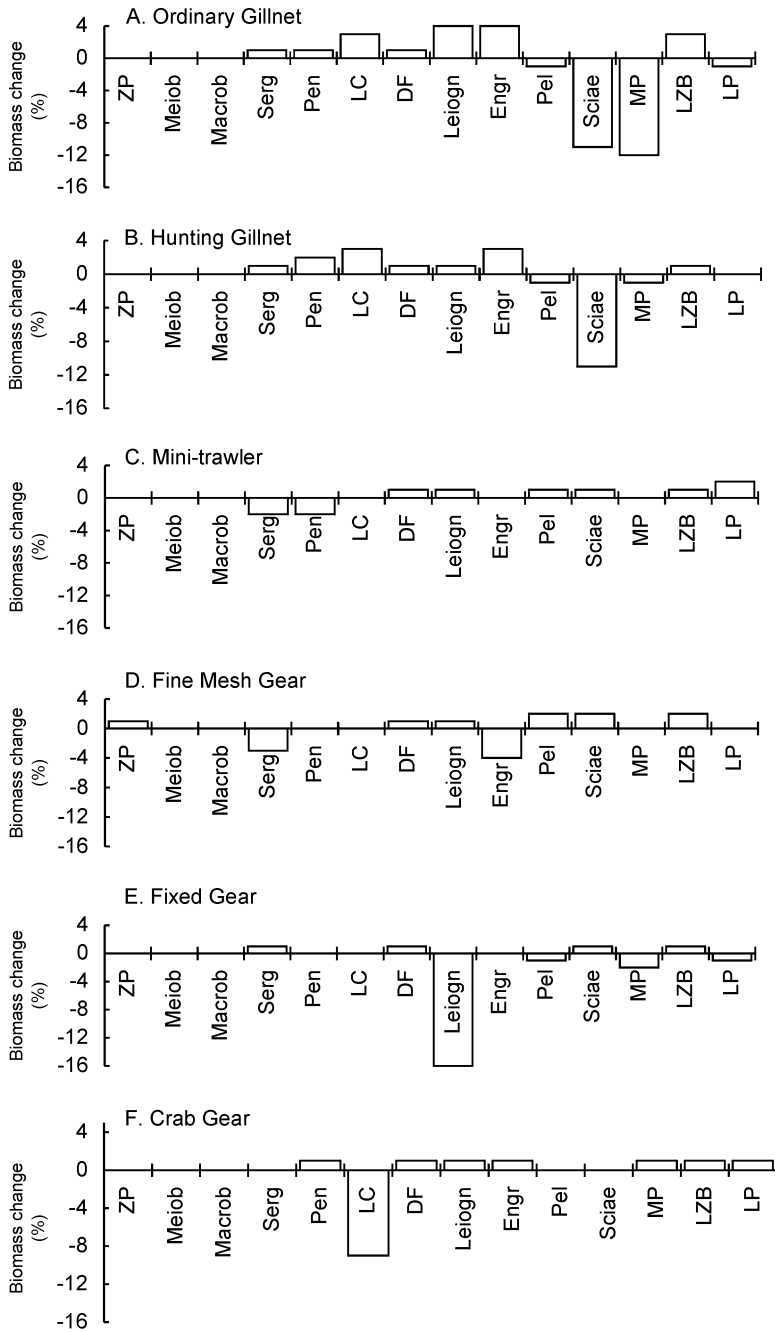


Fig. 7. Detailed results of the trophic impact routine for the small-scale fishery sector. Figures (A)–(F) show the predicted change in biomass of functional groups in response to an increase in fishing effort by each fishing gear, (A)–(F).

even though some, such as penaeids and engraulids, are caught by the ordinary and hunting gillnets. Similarly, crab gear targets large crustaceans, but also has a wider impact. An increase in fishing by crab gear produces a large decrease in the large crustaceans while other functional groups such as engraulids and medium predators, which are not fished by crab gear, increase. This effect is also observed for the fine meshed gear which exploits a wide range of functional groups, notably sergestids and, to a lesser extent, engraulids. The impact of an increase in this gear is that engraulids and sergestids decrease. Again, several of the other functional groups are impacted. Some, such as the demersal feeders and leiognathids increase although they are caught by the fine meshed gear. This gear does not catch other functional groups such as sciaenids, large zoobenthos feeders or zooplankton, and yet the biomass of these groups also increases. Similar wide-ranging impacts on the ecosystem are observed for the mini-trawler, fixed gear and “other gillnets”.

#### 4. Discussion

Mass-balance models were used to analyse the San Miguel Bay fishery and to examine species interactions and the impacts of fishing on this ecosystem. Directly incorporating the fishery into the model as predators allowed its impact on fishing to be examined. The results of the “LS–SS sector” and “LS–SS gears” predator models gave insight into the effects of fishing on species interactions. They demonstrate that the small-scale fishery sector has a greater impact on the ecosystem than the large-scale fishery sector.

The model estimated the biomass of all groups other than the large predators. The total fished biomass was greater than the trawlable biomass estimate but within the confidence limits of the survey estimate. It indicates an average trawl survey catchability of around 0.25–0.3, not far from values previously assumed or estimated for southeast Asian trawlers (Pauly, 1980). Moreover, this total fished biomass estimate is within the range of estimates from other areas, i.e., the Gulf of Thailand (9.35 t km<sup>-2</sup>; Pauly and Christensen, 1993) and the coast of Terengganu, Malaysia (4.02 t km<sup>-2</sup>; Liew and Chan, unpublished).

There are four trophic levels in the ecosystem. Many of the species are grouped around trophic level 3, where competition between functional groups is likely to be strongest. The trophic impact regime demonstrated that there is both predation and competition occurring among functional groups at all trophic levels. However, it also indicated that the fishery and the functional groups at the lowest trophic levels have the greatest impact on the system. This is reasonable since the fishery has reduced the biomass of the top predators (Bundy, 1997; ICLARM/BFAR/FSP, 1995), and thus there is little predator biomass to exert top-down control.

A sensitivity analysis showed that, in general, the model is robust. However, the parameters used in the model have mixed origins and only some were estimated directly from empirical data for San Miguel Bay (some *P/B* values, most *Q/B* estimates, and some diet compositions). The model was most sensitive to the *P/B* ratio and the EE. The *P/B* ratios estimated from San Miguel Bay data were comparable with other ecosystems, particularly the Gulf of Thailand. As far as possible, the empirically derived parameters were not altered in the balancing of the model, thus ensuring that the model was fitted to the local data. The model would, however, be improved with more empirical data from San Miguel Bay.

This mass-balance analysis demonstrates the complexity of the interactions that occur between the effects of fishing mortality, predation mortality, and competition. In some cases it is possible to separate and understand these inter-related effects. An increase in crab gear, e.g., led to a decrease in crabs and an increase in the biomass of other functional groups. This can be compared to the results of the trophic impact routine for crabs (Fig. 4). When crab biomass was increased, functional groups such as demersal feeders, engraulids, and leiognathids decreased. When crab biomass was decreased, due to increased fishing effort, the biomass of these same groups increased. Since crabs do not prey on these groups, these increases in biomass are likely due to a reduction in competition with the large crustaceans for resources.

The inter-related effects of fishing, predation, and competition can also be discerned in the impact of the ordinary gillnet gear on the ecosystem. An increase in effort of this gear led to a decrease in its main target groups, the medium predators and the sciaenids

(Fig. 7). However, other functional groups also caught by this gear, such as penaeids and engraulids, increased. The trophic impact analysis showed that the engraulids decreased when sciaenid and medium predator biomass was increased and that the penaeids decreased when sciaenid biomass was increased. Thus, it is likely that the release from predation pressure on engraulids and penaeids, by sciaenids and medium predators, was greater than the increase in fishing pressure, and caused the increase in their biomass.

However, for other gears, such as the mini-trawler the possible interactions of competition, predation and fishing were too complex to interpret. The main target groups, sergestids and penaeids decreased when fishing effort is increased, whilst other groups that are also caught by the gear, increased (Fig. 7). In this case, the trophic impact results do not provide insight into the causes of these changes.

Other gears such as the “other gillnets” and “other gear” are mixed gear groups, and have mixed impacts. It is not possible to determine which responses are due to the different gears and which are due to interactions between the functional groups. These mixed groups should be split.

This analysis suggests that the small-scale fishery sector has a larger and more wide-ranging impact on San Miguel Bay than the large-scale fishery sector. The large-scale fishery sector is non-selective and, although there are preferred catches, it catches a large range of species. When taken as a whole, the small-scale fishery sector also catches a large range of species. In addition, it fishes a greater range of trophic levels. Some of the individual gears, such as the mini-trawler and the ordinary gillnet, catch as many different species as the large-scale fishery sector. However, there is a fundamental difference. Almost all of the small-scale gears specifically and effectively target certain species or groups. Small-scale gears are more versatile than large-scale gears. In effect, the small-scale gears can and do fish any species in San Miguel Bay, in any niche, at any trophic level, anywhere. The result is that while the large-scale fishery sector mass harvests non-selectively, selective harvesting by the small-scale fishery sector has a greater, and more damaging, impact on San Miguel Bay.

The model suggests there is little refuge from fishing for species in San Miguel Bay. The small-scale

sector has the versatility to target species in response to changing resource abundance. In addition, the small-scale sector has diversified since the early 1980s. This diversification has increased the potential of the small-scale gear to target fish. The hunting gillnet, e.g., was apparently not present in the 1980s. It uses scaring devices to drive sciaenids into the net and is likely that this was developed as an adaptation to scarcer resources. As a consequence of this versatility, there has been species succession in San Miguel Bay: the preferred larger “K” strategists, such as groupers (medium predator), have been replaced by smaller “r” strategists such as penaeids and possibly sergestid shrimp and large crustaceans (ICLARM/BFAR/FSP, 1995 and Bundy, 1997).

The common and perhaps entrenched view is that the large-scale fishery sector has a negative impact and the small-scale fishery sector does not, is benign and creates livelihoods for a greater number of fishers. The results of this analysis indicate that the apparent benign nature of the small-scale fishery sector should be evaluated. The small-scale fishery sector in San Miguel Bay has the ability to fish at all trophic levels and to impact beyond the target species. The small-scale fishery sector can impose a greater fishing mortality than the large-scale fishery sector on every functional group, except the engraulids. Recent management actions in San Miguel Bay have been aimed at banning the large-scale fishery sector (San Miguel Bay Integrated Coastal Fisheries Management Plan, unpublished). In effect, large-scale fishing effort may have been reduced (Mike Pido, ICLARM, pers. comm.). However, this analysis suggests that this may not be sufficient; both large- and small-scale sectors of the fishery must be assessed and managed, and their impact on the ecosystem reduced.

### Acknowledgements

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been published as a CD-ROM. The results presented here represent an independent analysis of the database, kindly made available to the authors, and the use of published results were appropriate. We thank the two anonymous referees and the editors for thoughtful and helpful comments.

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