

Fisheries Impact on the South China Sea Large Marine Ecosystem: A Preliminary Analysis using Spatially-Explicit Methodology*

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Abstract

A multiple regression model is derived, based on biomass estimates in 16 mass-balance food web (Ecopath) models, which explains 68 % of the variation in the data at hand, and shows that the abundance of fish with trophic levels of 3.0 or more in the South China Sea area had declined, by 2000, to less than half its value in 1960. This is worrisome, as this generalizes to the entire region declining trends observed in local areas within the South China Sea. Moreover this estimate is almost surely too conservative, given the method we used. This declining trend is compatible however with the fishing 'down marine food webs', reported from well studied parts of the South China Sea, notably the Gulf of Thailand, where the mean trophic levels of landings have declined, indicating gradual replacement in the underlying ecosystems of large, long lived, high-trophic level fishes by small, short-lived, low trophic level species often described as 'trashfish'. The only exception to these trends is Brunei, whose offshore oilrigs have led to regulations precluding trawling across much of the shelf, thus in effect creating a marine reserve. We conclude by pointing out that marine reserves are indeed one approach that will have to be used if the present declining trends are to be reversed, along with a rollback of excessive fishing effort.

Introduction

Fisheries impact not only on the stocks they exploit,

but also the ecosystems in which the stocks are embedded (Gislason et al. 2000; Hall 1998). This is particularly true for demersal trawl fisheries, which

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are non-selective and also impact on the habitat on which the fish depend. Indeed, contrary to a still widely spread perception, fisheries are causing the major impact on marine ecosystems, far outweighing effects such as pollution and environmental changes. This is particularly true in Southeast Asia where regime shifts such as are observed in the North Pacific do not appear to occur, and hence where fisheries operate in an almost pure 'experimental' setting (Christensen 1998; Pauly and Chuenpagdee 2003).

We investigate here the impact of fisheries on the South China Sea system using a subset of the data collected and models constructed during the ADB-RETA 5766 project (Sustainable Management of Coastal Fish Stocks in Asia), and a spatially-explicit methodology developed for analyzing fisheries impact on marine ecosystems (Christensen et al. 2003).

Materials and Methods

Materials

Table 1 summarizes the major characteristics of the mass-balance food web (Ecopath) models, used here as starting point for this analysis.

The spatially explicit primary production data used here originated as SeaWiFS data, as processed by the European Union's Joint Research Center, in Ispra, Italy (Hoepffner et al. unpublished data), based on a model that incorporates estimated chlorophyll, photosynthetically active radiation, and sea surface temperature patterns (Behrenfeld and Falkowski 1997). The data are average values for 1998.

Depth information by $\frac{1}{2}$ by $\frac{1}{2}$ degrees of latitude/longitude was obtained from the ETOPO5 data-set available on the U.S. National Geophysical Data Center's Global Relief Data CD (www.ngdc.noaa.gov/products/ngdc_products.html).

Table 1. Overview of ecosystem models used for estimating abundance patterns of fish biomasses around the South China Sea.

Area covered	Year(s)	Spatial cells	Functional groups	Reference
Gulf of Thailand	1963, 1973, 1980	45	29, 40, 29	Christensen (1998), Vibunpant et al. (this vol)
Peninsular Malaysia, west coast	1970, 1990	48	15	Alias M. (this vol.)
Peninsular Malaysia, east coast	1972	63	15	see Annex A (this paper)
Sabah	1972	17	29	Garces et al. (this vol.)
Sarawak	1972	81	29	Garces et al. (this vol.)
Central Java, north coast	1979	15	27	Nurhakim (this vol.)
Deep South China Sea (50 - 200 m)	1980	160	13	Pauly and Christensen (1993)
Ocean part, South China Sea (> 200 m)	1980	509	10	Pauly and Christensen (1993)
Vietnam, coast (< 50 m)	1980	44	13	Pauly and Christensen (1993)
Brunei Darussalam	1989	19	13	Silvestre et al. (1993)
San Miguel Bay, Philippines	1993	1	16	Bundy (1997); Bundy and Pauly (2001)
San Pedro Bay, Philippines	1994	8	16	Campos (this vol.)
Vietnam, southwest	1994	63	15	see Annex B (this paper)

Methods

The methodology we have used to predict the biomass of fish in the South China Sea draws on a combination of ecosystem modeling, information from hydrographic databases, statistical analysis, and GIS modeling (Christensen et al. 2003). The mapping of biomass changes was performed using a series of steps as follows:

1. The 16 models of Table 1 were re-expressed on a spatial basis (again using $\frac{1}{2}$ by $\frac{1}{2}$ degree cells, corresponding to 30 by 30 miles at the Equator) using the spatial model Ecospace, with particular attention to the rapid decline in biomass of demersal fish with depth that is known to occur in South East Asia (Pauly 1989). For each of the spatial models, the cells were distributed between habitats based on depth only. The following depth strata were used for all models: (1) < 10 m, (2) 11 - 50 m, (3) 51 - 100 m, (4) 101 - 200 m, (5) 201 - 1000 m, and (6) > 1000 m. These yielded estimates of biomass by Ecopath functional groups for each of the spatial cells covered by each model, which ranged from 1 to 509 cells (see Table 1).
2. The biomass of different functional fish-groups were re-expressed as a single value representing all fish with a trophic level of 3.0 or higher, (excluding, however the unexploited meso- and bathypelagics and deep-sea benthic fish in the model representing the deepest, central part of the South China Sea; see Table 1).
3. Regression analyses were performed using multiple linear regression in S-Plus 6. We used the software's additive and variance stabilizing transformation, (AVAS) to decide how individual variables are best transformed to obtain linearity.
4. A multiple regression was identified which predicted the fish biomass based on the year for which the biomass was estimated (expressed as $\log(\text{year} - 1959)$), primary production in each half-degree cell (\log transform), and the mean depth of each cell (\log transform). To prevent the records from models covering large areas from overwhelming those from other models, each of the records was weighted in the regression analysis by the inverse of the square root of the number of non-land cells in the model to which it belonged. As data material we extracted 1 158 records based on the $\frac{1}{2}$ by $\frac{1}{2}$ degree spatial cells of the 16 ecosystem models in Table 1. Each of the records included estimates of fish biomass (trophic level ≥ 3.0), depth, primary production, and year of the model.
5. Following a first run of regression in Step 4, and an examination of the residuals, it was clear that the biomass values for the 1989 Brunei-model were higher than the model predicted. This is expected as fishing is very limited in Brunei, due to offshore oil rigs which fishing vessels may not approach (Cruz-Trinidad et al. 1997; Pauly et al. 1997). Thus a dummy variable was used to indicate whether a cell belonged to the EEZ of Brunei or not.
6. Using the regression the biomass for each cell represented was predicted and plotted for 1960 and 2000, representing the extremes for the period covered.

Results and Discussion

Based on the data in Table 2, we conclude that the multiple regression we derived is adequate in that it explains the major part of the variance in the data-set ($R^2 = 0.68$), and the partial regression coefficients (slopes) all have the expected signs. The t-values in Table 2 indicate the internal 'ranking' of the parameters, i.e. they identify those that matter most (or where the probability of exceeding the t-value by chance is smallest). However, due to co-variation between variables the 'rankings' should be treated with extreme caution. We note that the highest t-value is associated with the depth parameter, followed by the year, then primary production. The intercept is estimated least reliably, which is the reason why we abstain from presenting absolute biomass estimates obtained through the multiple regression.

Table 2. Parameter estimates and associated test statistics for multiple linear regression to predict the biomass ($\log, \text{g}\cdot\text{m}^{-2}$) for fishes ($\text{TL} > 3.0$) in the South China Sea during the period from early 1960s to late 1990s. The variables are arranged by t-value (value relative to standard error, given) corresponding to adjusted partial slopes (Blalock 1972). All parameters are highly significant.

Variable (Unit)	Value	Std. error	t-value	Pr(> t)	Transformation
Depth (m)	-0.293	0.013	-22.7	0.000 000 0	Logarithmic
Year (year - 1959)	-0.760	0.043	17.6	0.000 000 0	Logarithmic
Brunei (0 or 1)	1.167	0.132	8.84	0.000 000 0	None
Primary production ($\text{gC}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$)	0.407	0.073	5.61	0.000 000 0	Logarithmic
(Intercept)	2.045	0.438	4.68	0.000 003 3	–

Figure 1 shows the transformation required to obtain linearity in the models. Based on this, log transformations were deemed suitable for all parameters apart from the dummy variable identifying the Brunei-variable. Further, Figure 2 shows the distribution of predicted versus observed values. There is no obvious pattern suggesting the model failed to linearize, or to include a key variable.

Figure 3 contrasts the maps of biomass distribution from the multiple regression model for 1960 against that for 2000. The high fish concentrations originally occurring in the Malacca Strait, the Gulf of Thailand, along the northern coast of Kalimantan and in other productive areas around the South China Sea, had completely disappeared by 2000, with the exception of the waters off Brunei, where fishing is forbidden around offshore oil rigs, a theme to which we return below. As estimated by the multiple regression and illustrated in Figure 3, fish biomass has strongly declined over the last 40 years, with present biomass generally less than half their values in 1960. This decline is most probably underestimated, as the catch per unit of effort of research trawlers in the Gulf of Thailand decreased from over $400 \text{ kg}\cdot\text{hour}^{-1}$ in 1961 to around $30 \text{ kg}\cdot\text{hour}^{-1}$ in the 1990s (Eiamsa-ard and Amornchairojkul 1997; Pauly 1979), with similar declines reported elsewhere.

This underestimation is a feature of the approach used here, which leads to conservative estimates. A similar conservative result was obtained in an earlier application of the above methodology to the North Atlantic, where individual species have declined far more sharply than estimated by the multiple regression used for biomass prediction (Christensen et al. 2003).

We also note that the decline of trawlable biomass documented here accompanied strong changes in species composition, noted by various authors as early as the 1960s (Pauly 1979; Pope 1979), a feature that can be straightforwardly reproduced by simulation modelling.

Figure 4 illustrates this through the example of the Gulf of Thailand, whose catches have stagnated since the 1970s, in spite of a massive increase in fishing effort, and a strong decline in the mean trophic level of the catch. These changes imply the loss (or at least disproportional decline) of large, long-lived high-trophic level species in the system, and their partial replacement with small short-lived, low trophic level species, used as duck and fish feed in the case of the Gulf of Thailand (Pauly and Chuenpagdee 2003).

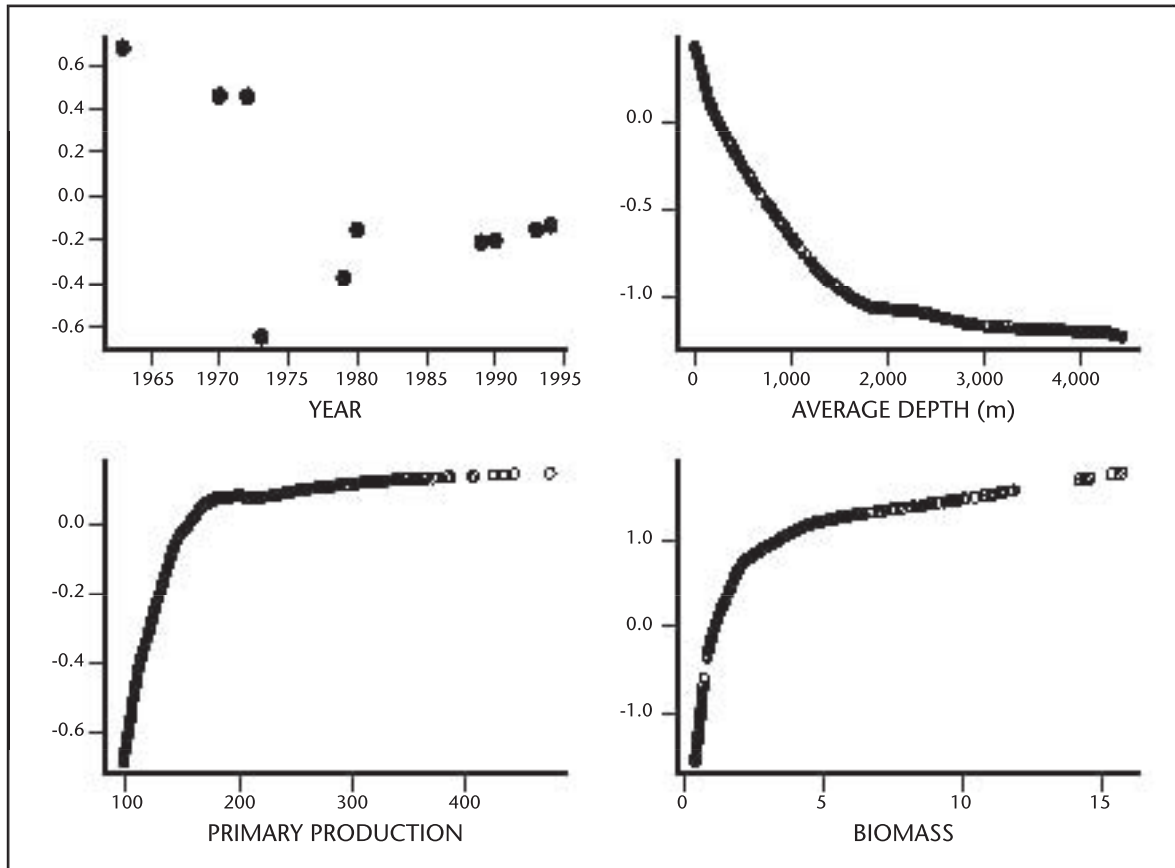


Fig. 1. AVAS transformations indicating how parameters (X-axis) should be transformed (Y-axis indicate biomass, linear scale) to linearize the individual parameters while considering their joint effects. These results indicate that logarithmic transformations are reasonable for year, depth, and primary production.

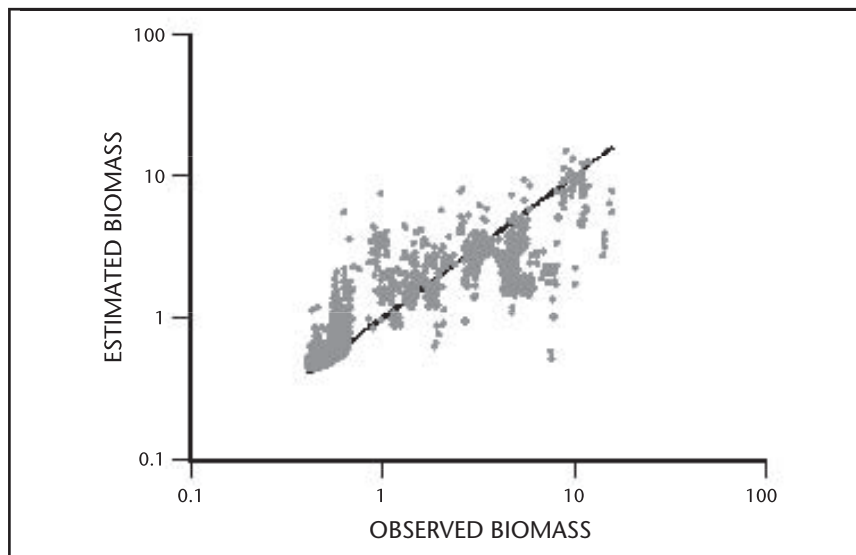


Fig. 2. Plot of predicted versus observed biomass ($\text{g}\cdot\text{m}^{-2}$). The predicted values are from the regression in Table 2, the 'observed' values from the spatialization of Ecopath models described in the Methods section.

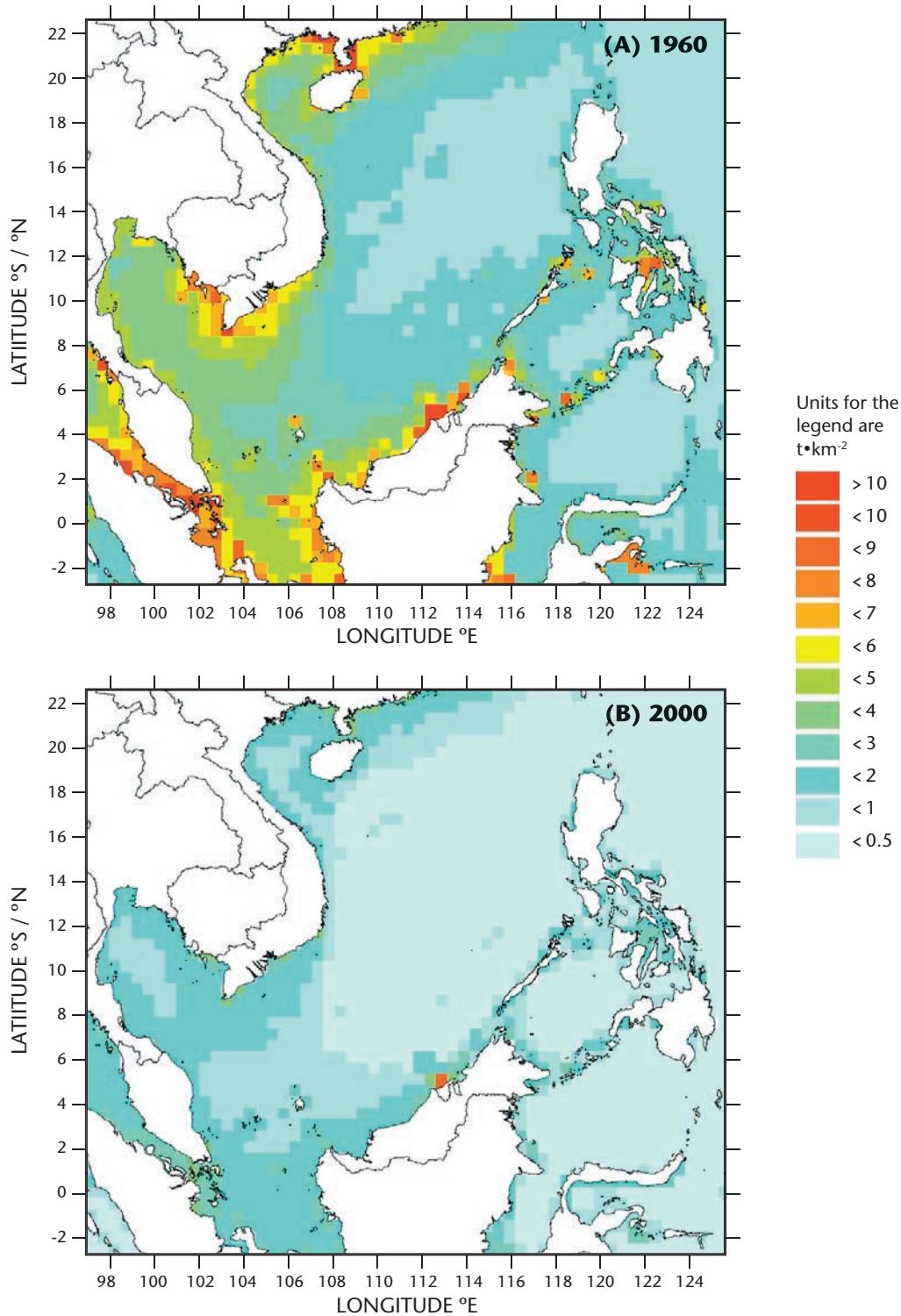


Fig. 3. Biomass distributions for fishes (trophic level ≥ 3.0) in the South China Sea large marine ecosystem in (A) 1960, and (B) 2000. The distributions are predicted from linear regressions based on log-transforms of depth, year, and primary production. Note that the high coastal concentrations in the early period have nearly completely disappeared - except for the Exclusive Economic Zone of Brunei.

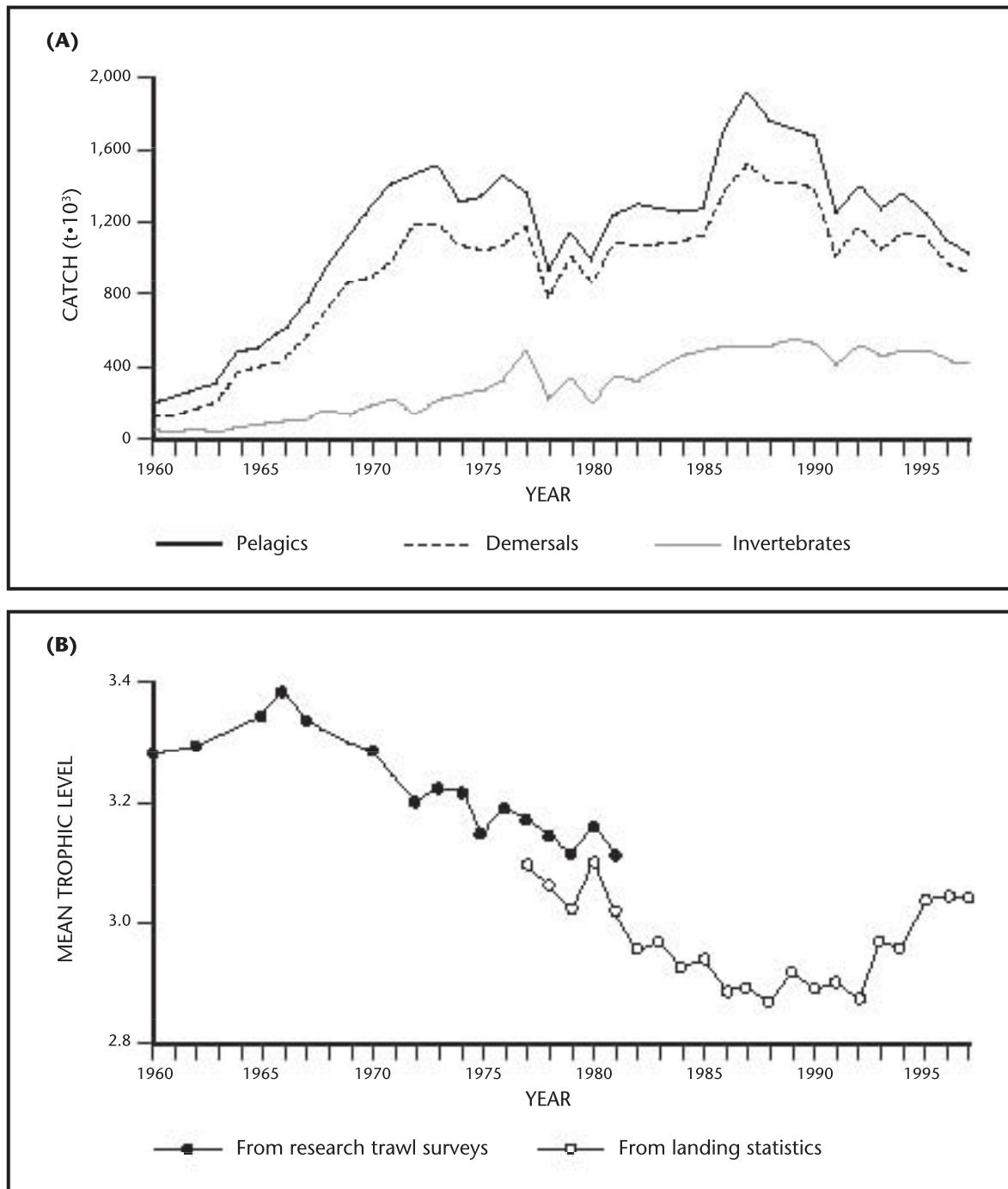


Fig. 4. Impact of fishing on the Gulf of Thailand ecosystem, an example of trends in the South China Sea:
(A) Catches, by major species groups (excluding tuna and other large pelagics). Note stagnation and decline of demersal catches, following their rapid increase in the 1960s and 1970s. Also note increasing contribution of small and medium pelagics, and overall decline in the 1990s.
(B) Trophic level (TL) trends in the catch of research trawlers (reflecting relative abundances in the ecosystems), and in the total landings (both series excluding large pelagics). Lower TL's in 1977 to 1997 series are due to inclusion of small pelagics and other low-TL organisms caught by gear other than trawl (adapted from Pauly and Chuenpagdee 2003)

The methodology deployed here thus diagnoses the same problems for the South China Sea that occur throughout the world, notably a complete absence of sustainability (Pauly et al. 2002). Indeed, if present trends are not reversed, fisheries are heading for a collapse of their underlying resource base, and of the ecosystems on which the fisheries depends (Pauly et al. 2002). At the same time, this study gives a pointer toward an important component of a solution for the over-fishing problem in South East Asia as well as elsewhere, through the example of Brunei - the only country in the region that has a significant part of its shelf effectively closed to fishing due to the presence of offshore oil rigs, around which fishing is not permitted. This has limited the Brunei trawl fishery to a small area near Muara, the only industrial port. While the small exploited area near Muara exhibits the same signs of over-fishing as the rest of South East Asia (Pauly 1989), a significant part of the biomass on the rest of the Brunei shelf has been retained, thus allowing for export of larvae and other live stages to adjacent areas, and the maintenance of functioning ecosystems.

It is hard to conceive how the depleted demersal stocks of the other areas of the South China Sea could be replenished without closing areas to fishing, or at least to trawling. The 1980 trawling ban in Indonesia might be instructive here as well (Sardjono 1980), though it is quite evident that the gain that could have been realized through the closure has been quickly dissipated, at least in the Java Sea by an enormous expansion of small scale fisheries and of an industrial pelagic fishery.

Thus, we cannot but reiterate that capping, and ultimately reducing fishing effort, including that of small scale fisheries is the only long term solution to halting, and reversing the worrying trends described here.

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Annex A.
Notes on the construction of the Ecopath model for the east coast of Peninsular Malaysia (1970).

In constructing the 1970 Ecopath model, the 1990 mass-balance trophic model constructed for the coastal fisheries ecosystem of the west coast of Peninsular Malaysia (see Alias, this vol.) was used. The ecosystem is partitioned into 15 trophic groups with biomasses for selected groups (e.g. large zoobenthos feeders) obtained from research (trawl) surveys conducted in the area in 1970. Biomass values were calculated using stock density estimates from Talib et al. (this vol.) ~ 5.092 5 t·km², and species composition from the trawl surveys (Jothy et al. 1975).

Total landings for each species/group were obtained from catch statistics of the Department of Fisheries for 1970. The 1970 P/B (=Z) values of the all-fished

groups were calculated using the following equations:

$$Z_{70} = [Z_{90} (F_{70} + M)] / (F_{90} + M) \quad (\text{Eqn. 1})$$

where: Z₉₀ is the 1990 total mortality values, F₉₀ the estimated fishing mortality (1990); F₇₀ the estimated fishing mortality (1970); M is the natural mortality and was assumed to be the same in 1970 and 1990. F₇₀ was estimated:

$$F_{70} = (F_{90} \times C_{70}) / C_{90} \quad (\text{Eqn. 2})$$

where: F₇₀ is the fishing mortality (1970); F₉₀ is the estimated fishing mortality (1990); C₇₀ is the total catch for the species/group in 1970; and C₉₀ is the total catch for the species/group in 1990.

Table A1 presents the basic input and output parameter values used in modeling the coastal fisheries ecosystem off the west coast of Peninsular Malaysia.

Table A1. Basic input and output (in parenthesis) parameter values used in modeling the coastal fisheries ecosystem off the west coast of Peninsular Malaysia.

Ecological group	Biomass (t·km ²)	P/B (year ⁻¹)	Q/B (year ⁻¹)	EE	Catch (t·km ² ·year ⁻¹)
Mammals	0.02	0.05	30.00	(0.00)	–
Large predators	(0.02)	2.86	7.30	(0.69)	0.02
Large pelagics	(0.17)	3.93	9.55	0.95	0.17
Medium pelagics	(0.15)	2.43	10.00	0.95	0.05
Large zoobenthos feeders	0.25	3.90	7.85	0.95	0.02
Intermediate predators	(0.78)	7.49	15.00	(0.12)	0.42
Small demersal species	2.54	(0.21)	23.74	0.95	0.43
Small pelagics	(0.62)	3.75	12.9	0.95	0.86
Crustaceans (excl. plankton)	(6.55)	5.11	21.81	0.95	0.07
Misc. invertebrates	(5.96)	5.51	11.02	0.95	–
Squids	(4.40)	4.10	10.51	0.95	0.05
Turtles	0.02	1.50	3.50	(0.00)	–
Zooplankton	(2.66)	67.00	280.00	0.95	0.03
Aquatic plants	(14.08)	71.15	–	0.50	–
Detritus	100.0	–	–	(0.38)	–

Note: P/B = Production/Biomass ratio, Q/B = Consumption/Biomass ratio, EE = Ecotrophic efficiency.

Annex B.
Notes on the construction of the Ecopath model for the southwest coast of Vietnam (1994).

The primary source of quantitative information (i.e. biomass) in determining the input data for the model were obtained from results of the trawl surveys conducted in southwest Vietnam between 1993 to 1995. Other sources of information on the study area include (Khoi et al. 1995) for plankton studies, and (Chung and Ho 1995) for zoobenthos fauna. Only the biomasses estimated from the trawl surveys in southwest Vietnam were used as input values for demersal groups i.e. demersal predators, Leiognathids and other small demersals. Biomass values for zoobenthos were taken from results of

a zoobenthos study in the seawaters of Vietnam (Chung and Ho 1995).

The food web model consists of 15 functional groups, i.e. 13 consumer groups, a producer (phytoplankton) group and a detritus group (see Table B1). The species composition and biomass data from the trawl surveys were used to determine the ecological groups. The aggregation process for this model was performed based on similarities in habitat, body size, growth and mortality rates and diet composition, after the method proscribed by (Christensen and Pauly 1996; Pauly and Christensen 1993). Such information (notably for fish) was mainly obtained from the FishBase database (www.fishbase.org). Table B2 summarizes the basic input and output parameter values used in modeling the coastal fisheries of southwest Vietnam.

Table B1. Species composition for the 15 functional groups of the southwest Vietnam Ecopath model^a

Ecological Groups	Species/taxa included
Large predators	Sharks (Carcharinidae), Scombridae
Tuna	Scombridae (<i>Scomberomorus</i> spp., <i>Auxis</i> spp., <i>Euthynnus</i> spp., <i>Thunnus</i> spp.)
Medium pelagics (except Tuna)	Carangidae, Trichiuridae, Stromateidae
Small pelagics	Clupeidae and Engraulidae
Other pelagics	Carangidae, Caesionidae, Scombridae (<i>Rastrelliger</i> spp.)
Cephalopods	Includes squids (<i>Loligo</i> spp.), cuttlefish (<i>Sepia</i> spp.) and octopus (<i>Octopus</i> spp.)
Demersal predators	Apogonidae, Ariidae, Cepolidae, Cynoglossidae, Drepanidae, Fistularidae, Gobiidae, Holocentridae, Meneidae, Monacanthidae, Nemipteridae, Muraenidae, Ostraciidae, Paralichthyidae, Pegasidae, Platycephalidae, Plotosidae, Polynemidae, Priacanthidae, Rhinobathidae, Sciaenidae, Syngnathidae, Synodontidae, Tetraodontidae, Lethrinidae, Serranidae, Scorpaenidae
Reef fish	Chaetodontidae, Labridae, Pomacentridae
Leiognathids	<i>Gazza minuta</i> , <i>Leiognathus</i> spp., and <i>Secutor</i> spp.
Other small demersals	Bothidae, Cynoglossidae, Gerreidae, Haemulidae, Mullidae, Nemipteridae, Psettodidae, Siganidae, Sillaginidae, Soleidae, Sparidae, Teraponidae Sciaenidae
Crustaceans (crabs & shrimps)	Portunidae, Palinuridae, Scyllaridae, Penaeidae
Zoobenthos	Crustacea, Polychaeta, Coelenterata Echinodermata, Porifera (Chung and Ho 1995)
Zooplankton	Copepoda, Chaetognatha (Khoi et al. 1995)
Phytoplankton	
Detritus	Comprised of particulate and dissolved organic matter

^a Fish groups are only listed as families, complete species list can be found in the species composition of trawl surveys (Thouc and Dat 2000).

Table B2. Basic input and output (in parenthesis) parameter values used in modeling the coastal fisheries ecosystem off the southwest coast of Vietnam.

Ecological group	Biomass (t·km⁻²)	P/B (year⁻¹)	Q/B (year⁻¹)	EE	Catch (t·km⁻²·year⁻¹)
Large predators	(0.01)	1.20	15.00	0.50	0.003
Tuna	(0.02)	0.80	(4.00)	0.95	0.004
Medium pelagics	(0.05)	1.50	(7.50)	0.95	0.015
Small pelagics	(0.21)	3.35	17.60	0.95	0.025
Other pelagics	(0.12)	3.00	(12.00)	0.90	0.048
Cephalopods	(0.08)	3.10	16.00	0.95	0.000
Demersal predators	1.21	3.00	12.00	(0.27)	0.151
Reef fish	(0.10)	2.00	12.00	0.70	0.021
Leiognathids	0.49	3.00	17.50	(0.60)	0.061
Other small demersals	0.21	(3.70)	18.50	(0.70)	0.026
Crustaceans	(2.85)	4.00	21.90	0.95	0.003
Zoobenthos	20.00	6.57	27.40	(0.64)	–
Zooplankton	(4.26)	50.00	200.00	0.90	–
Phytoplankton	(6.87)	120.00	–	0.90	–
Detritus	120.00	–	–	0.53	–

Note: P/B = Production/Biomass ratio, Q/B = Consumption/Biomass ratio, EE = Ecotrophic efficiency.