Available online at www.sciencedirect.com
ScienceDirect
Progress in Natural Science 19 (2009) 1271–1280
Progress in Natural Science
www.elsevier.com/locate/pnsc

Mass-balance ecosystem model of the East China Sea

Jiahua Cheng [a,*], William W.L. Cheung [b], Tony J. Pitcher [b]

[a] East China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Shanghai 200090, China
[b] The Fisheries Centre, University of British Columbia, Vancouver, Canada BC V6T 1Z4

Received 1 August 2008; received in revised form 22 February 2009; accepted 10 March 2009

Abstract

Using the Ecopath mass-balance trophodynamic model, this paper analyzed the trophic levels, flows, food web structure and ecosystem maturity of the East China Sea, and identified ecologically important functional groups in the ecosystem. The model is based on fishery resource surveys of the East China Sea in 2000, studies on diet composition and global databases such as FishBase and the Sea Around Us Project Database. The results showed that trophic levels of the functional groups are between 2.86 and 4.37, with an average of 3.32. Anchocy (*Engraulis japonicus*), small fishes and benthic crustaceans such as shrimps and crabs are important groups in terms of the trophic structure and flow dynamics in the East China Sea. Energy flows of most groups are between specific trophic levels, except file fish (*Thamnaconus* spp.), pomfret (*Pampus* spp.) and cephalopods. Trophic transfer efficiency of levels II, III, IV and more than V are 11.8%, 21.1%, 17.4% and 22.1–22.5%, respectively. Effects of fishery – the largest 'consumer' of the ecosystem – are much stronger than those exerted by biological groups in the system. The model suggests that the current fishery can further reduce the complexity of the ecosystem. Evaluations of the system indices suggest that maturity of the ecosystem is low. The conclusion of this model indicates that it was the overfishing that caused the ecosystem of the East China Sea declined, which should be taken into account as a critical reference for fisheries management in the future.

Keywords: Ecopath; East China Sea; Mass-balance; Fishery; Ecosystem

1. Introduction

The East China Sea (ECS) is situated in the eastern Pacific between the sub-tropical and temperate zones. It has extensive shallow coastal waters, with a total area of 770,000 km^2 in which the continental shelf fishing ground covers 572,900 km^2. The region is biologically diverse, with 727 species of recorded fish, more than 100 shrimps and crabs, and 69 species of cephalopods [1–4]. As a result of the rapid increase in fishing effort, annual catch from the ECS has increased by 400% since the 1980s, from 1.5 million tonnes to 6 million tonnes in recent years. The large fishing pressure and the resulted large annual catch have likely changed the structure of the ESC ecosystem. Numerous traditional commercially important fish such as yellow croaker (*Larimichthys crocea*), Chinese herring (*Illisha elongate*), cuttlefish (*Sepiella maindronide*) have been depleted. Even for species such as hairtail (*Trichiurus japonicus*) and small yellow croaker (*Larimichthys polyactis*) which are relatively more abundant, their age- and size-structures are getting smaller. More than 95% of the catch was age 1 and juvenile fish, while age at sexual maturation and mean trophic level of the system are decreasing [5–7]. Several decades ago, the ecosystem was dominated by high-valued commercial species. Now the ECS is characterized by having a simple trophic structure, fast growth rate, low trophic level and high turnover rate [8]. These have large implications in fishery management and biodiversity conservation.

* Corresponding author. Tel.: +86 21 65803266; fax: +86 21 65680301.
E-mail address: ziyuan@sh163.net (J. Cheng).

1002-0071/$ - see front matter © 2009 National Natural Science Foundation of China and Chinese Academy of Sciences. Published by Elsevier Limited and Science in China Press. All rights reserved.
doi:10.1016/j.pnsc.2009.03.003

This study aims to construct a mass-balance ecosystem model using Ecopath to evaluate the trophodynamics of the ECS. Particularly, it analyzed the ecosystem based on the estimated trophic levels, flows and system indices to understand the impacts of fisheries and their resulted changes on the ecosystem. These should provide useful theoretical bases for fishery management and ecosystem restoration.

2. Materials and methods

2.1. Mass-balance trophodynamic model

The ECS ecosystem was modeled using Ecopath. Ecopath was first developed by Polovina [9] which was applied to model coral reef ecosystem. It was further developed by Christensen and Pauly [10], producing the Ecopath with Ecosim (EwE) software package [11]. EwE has been applied to model marine, estuaries and freshwater ecosystems around the world. This study employed EwE version 5.1 which was available at http://www.Ecopath.org [11].

Ecopath model is based on the mass balance between the inputs into and outputs from the modeled ecosystem. To reduce complexity of the model, species with similar ecology are usually aggregated into a functional group. The model assumes that total amount produced or consumed by a group is equal to the amounts that go out of the group because of predation and fishing mortalities, migrations and biomass accumulations. i.e.

$$B_i \cdot (P/B)_i \cdot EE_i = Y_i + \sum_{j=1}^{n} B_j \cdot (Q/B)_j \cdot DC_{ij} + B_i \cdot BA_i + E_i \tag{1}$$

where B is biomass (usually expressed in t km^{-2} year^{-1}), P the production, EE the ecotrophic efficiency, Y the fishery catch, i and j are prey and predator groups, respectively, Q is consumption, DC the diet composition, BA the biomass accumulation and E the net immigration. The model achieves mass balance by solving Eq. (1) simultaneously for all functional groups in the model. Thus, one of the input parameters (P/B, Q/B or EE) in each functional group should be left to be estimated by the model.

2.2. Structure of the ECS model

We attempted to model the ECS continental shelf ecosystem as of the state in 2000. The model area is 570,000 km^2. We assume that biomass flows within this area is closed. Based on the ecology, economic importance and data availability, species in the ECS were aggregated into 21 functional groups. The groups include marine mammals (e.g. whales, dolphins), elasmobranchs (sharks and rays), hairtails (*Trichiurus* spp.), small yellow croaker (*L. polyactis*), eels (*Muraenesox cinereus*), filefish (*Thamnaconus septentrionalis*), chub mackerels (e.g. *Scomber japonicus*, *Scomber australasicus*), carangids (e.g. *Trachurus japonicus*, *Decapterus maruadsi*), pomfrets (*Pampus argenteus*, *Pampus nozawa*), Spanish mackerels (e.g. *Scomberomorus niphonius*), anchovy (*Engraulis japonicus*), cephalopods (cuttlefish, squids, octopus), other commercial fishes (commercially valuable, but annual catch less than 50,000 tonnes), small fishes (e.g. *Acropoma japonicum*, *Champsodon capensis*, *Benthosema pterotum*), decapods (shrimps and crabs), Acetes (*Acetes* spp.), medium to large jellyfish (e.g. *Stomolophus meleagris*, *Cyanea* sp.), benthos, zooplanktons, phytoplanktons and detritus.

Table 1
Input parameters of the ECS model.

Function groups	Catch yield (t km^{-2})	Biomass (t km^{-2} year^{-1})	P/B (year)	Q/B (year)	Reference
Marine mammals		0.00404	0.050	30.000	[16]
Sharks	0.000880	0.00270	0.500	3.200	[3]
Hailteil	1.597	0.744	2.587	9.000	[17]
Yellow croaker	0.281	0.134	2.392	8.000	[18]
Congers	0.207	0.0963	2.300	8.000	[3]
Filefish	0.100	0.0467	2.500	15.500	[3]
Mackerels	0.251	0.148	2.300	9.400	[7]
Scads	0.307	0.181	2.300	14.900	[3]
Pomfrets	0.395	0.197	2.320	12.500	[3]
Spanish mackerels	0.258	0.129	2.500	9.100	[3]
Anchovy	0.288	0.250	3.000	18.000	[3]
Cephalopods	0.198	0.116	3.000	10.000	[3]
Other commercial fishes	1.097	0.645	2.300	10.000	[3]
Small fishes	0.505	1.371	2.300	24.000	[3]
Shrimps and crabs	1.807	2.008	3.900	15.000	[3]
Acetes	0.507	2.414	7.000	27.000	[3]
Jellyfish	0.175	0.675	5.000	20.000	[19,20]
Benthos		3.660	5.000	20.000	[21]
Zooplankton		6.532	40.000	160.000	[3]
Phytoplankton		16.173	200.000		[11]
Detritus		43.000			Refer to Bohai model

2.3. Data source

Input parameter values for the ECS ecosystem model were based on data from the fishery resources surveys in 2000, fishery statistics, published literature and reports on diet compositions, global databases, such as FishBase (http://www.fishbase.org), the Sea Around Us Project database (http://www.searoundus.org) and experiences from the authors (Table 1). Specifically, biomass of commercial groups was based on survey data and published literature, while P/B was based on estimated total mortality rates. Q/B of fish groups was estimated from empirical equation [12]:

$$\log(Q/B) = 7.964 - 0.204 \cdot \log(W_{\inf}) - 1.965 \cdot T + 0.083 \cdot A + 0.532 \cdot h + 0.532 \cdot h \quad (2)$$

where $W_{\inf}$ is the asymptotic weight, T the average temperature of the inhabited water, A is the aspect ratio, h and d are binary variables indicating the dietary preferences ($h = 1$ indicates herbivores, $h = 0$ indicates detritivores and carnivores, $d = 1$ indicates detritivores, $d = 0$ indicates herbivores and carnivores). For non-fish group, Q/B is based on the published literature (Table 1).

Diet composition matrix of the model is based on survey data, published literature [1,13,14] and unpublished data of diet composition studies in ECS in recent years (Table 2). As diet composition and biomass data are most uncertain among the input parameters, they were adjusted to achieve mass-balance of the model (i.e. $EE < 1$ for all groups).

Catch is based on national statistics of China [15] (Table 1).

Table 2
Diet composition matrix of the ECS model.

No.	Prey/predator	1	2	3	4	5	6	7	8	9	10
1	Marine mammals										
2	Sharks										
3	Hailteil	0.001		0.010	0.002						
4	Yellow croaker	0.001		0.003							
5	Congers	0.001		0.001							
6	Filefish	0.001									
7	Mackerels	0.100	0.050	0.010							
8	Scads	0.050	0.050	0.010							
9	Pomfrets	0.030	0.002	0.005							
10	Spanish mackerels	0.050	0.030	0.005							
11	Anchovy	0.020		0.060							0.040
12	Cephalopods	0.406	0.020	0.005	0.020			0.001			0.020
13	Other commercial fishes	0.050	0.337	0.020	0.005	0.050					
14	Small fishes	0.120	0.510	0.205	0.050	0.050					0.050
15	Shrimps and crabs	0.040		0.200	0.303	0.600	0.144				
16	Acetes	0.030		0.334	0.258	0.100	0.150	0.300	0.300	0.150	0.300
17	Jellyfish						0.150			0.100	
18	Benthos	0.030		0.032	0.200	0.100	0.200				
19	Zooplankton	0.070		0.100	0.162	0.050	0.200	0.699	0.700	0.550	0.590
20	Phytoplankton									0.200	
21	Detritus					0.050	0.156				

No.	Prey/predator	11	12	13	14	15	16	17	18	19
1	Marine mammals									
2	Sharks									
3	Hailteil			0.010						
4	Yellow croaker			0.001						
5	Congers			0.001						
6	Filefish			0.001						
7	Mackerels			0.001						
8	Scads			0.002						
9	Pomfrets			0.001						
10	Spanish mackerels			0.001						
11	Anchovy			0.001						
12	Cephalopods			0.002						
13	Other commercial fishes			0.025						
14	Small fishes		0.100	0.154						
15	Shrimps and crabs			0.300	0.050					
16	Acetes	0.100	0.213	0.250	0.250	0.039				
17	Jellyfish				0.020					
18	Benthos		0.050	0.100	0.150	0.623				
19	Zooplankton	0.800	0.500	0.100	0.400	0.335	0.900	0.850	0.100	
20	Phytoplankton	0.100	0.087		0.050	0.003	0.050	0.100	0.100	0.900
21	Detritus		0.050	0.050	0.080		0.050	0.050	0.800	0.100

2.4. Sensitivity analysis

Sensitivity of the model was evaluated by systematically varying each input parameter value by ±50% (increment of 10%). Input values of biomass, *P*/*B*, *Q*/*B* and *EE* were varied in this analysis. The proportional changes to the estimated parameters (*B*, *P*/*B*, *Q*/*B* and *EE*) of the model were recorded.

3. Results

Based on the input parameters, the model estimated the trophic levels, mortality rates (fishing, predation and others), ecotrophic efficiency, omnivory index and other system indices (Table 3).

3.1. Trophic level

As diversity in ECS is high, the predator-prey relationship in the ecosystem is particularly complex (Fig. 1). Currently, trophic levels of the major commercial groups in ECS are between 2.86 and 4.37, with an average of 3.32. Groups of trophic level 3 or above represent about 4.86% of the total biomass in ECS.

3.2. Mortalities

The model indicates the relative importance of fishing and predation mortalities of each functional group. Estimated fishing mortalities of major commercial groups from the model, such as small yellow croaker, eels, filefish, hairtails, pomfrets, Spanish mackerel, are the highest among all the groups in the ecosystem. Fishing mortalities of these groups generally represent more than 80% of their total mortality rates, indicating that these groups were severely over exploited. Predation mortalities are relatively high in anchovy, cephalopods, small fishes and benthic crustaceans (shrimps and crabs), representing more than 40% of their total mortalities.

Ecotrophic efficiency represents the proportion of total output from group that is explained by fishing, predation, migration and biomass accumulation. In ECS, besides the top predators such as marine mammals, and the lower trophic level groups such as zooplanktons and jellyfish, *EE* of most groups is high, generally over 0.9. As the model assumed no migration (assuming a closed system) and biomass accumulation, high *EE* suggested that productions of most groups go directly to their predators or to the fisheries as catch.

3.3. Trophic structure

The ECS ecosystem is dominated by low trophic level groups (Fig. 2). Biomass of groups in 1–2 represents more than 90% of the total biomass in the ecosystem. Biomass of groups with trophic level great than 4, which is composed of top predators such as sharks and marine mammals, is very small relative to the total system biomass.

Biomass flows into functional groups of the ECS ecosystem was aggregated into seven trophic levels (Table 4). Trophic level I represents flows of detritus and phytoplanktons, while zooplanktons and benthos dominated the flows in trophic level II (>90%). About 70% of the flows in trophic level III are from jellyfish, acetes, benthic crustaceans, anchovy, chub mackerels and carangids. Trophic level IV and above consist mainly of flows from elasmobranchs,

Table 3
Estimated parameters from the ECS model.

Function groups	Biomass ($t\ km^{-2}\ year^{-1}$)	Trophic level	*P*/*B* (year)	Fishing mortality	Predation mortality	Ecotrophic efficiency	Omnivory index
Marine mammals	0.00404	4.08	0.050	0.000	0.000	0.000	0.149
Sharks	0.00270	4.37	0.500	0.326	0.000	0.652	0.059
Hailteil	0.744	3.88	2.587	2.146	0.188	0.902	0.146
Yellow croaker	0.134	3.61	2.392	2.097	0.199	0.960	0.185
Congers	0.0963	3.71	2.300	2.150	0.138	0.994	0.286
Filefish	0.0467	3.25	2.500	2.141	0.141	0.913	0.432
Mackerels	0.148	3.27	2.300	1.696	0.581	0.990	0.171
Scads	0.181	3.27	2.300	1.696	0.477	0.945	0.170
Pomfrets	0.197	3.02	2.320	2.005	0.221	0.960	0.393
Spanish mackerels	0.129	3.40	2.500	2.000	0.359	0.943	0.233
Anchovy	0.250	2.99	3.000	1.152	1.830	0.994	0.181
Cephalopods	0.116	3.18	3.000	1.707	1.225	0.977	0.416
Other commercial fishes	0.645	3.70	2.300	1.701	0.540	0.974	0.325
Small fishes	1.371	3.17	2.300	0.368	1.930	0.999	0.357
Shrimps and crabs	2.008	2.86	3.900	0.900	2.896	0.973	0.219
Acetes	2.414	2.90	7.000	0.210	6.777	0.998	0.090
Jellyfish	0.675	2.85	5.000	0.259	1.501	0.352	0.128
Benthos	3.660	2.10	5.000	0.000	4.377	0.875	0.090
Zooplankton	6.532	2.00	40.000	0.000	17.527	0.438	0.000
Phytoplankton	16.173	1.00	200.000	0.000	59.069	0.295	0.000
Detritus	43.000	1.00				0.066	0.166

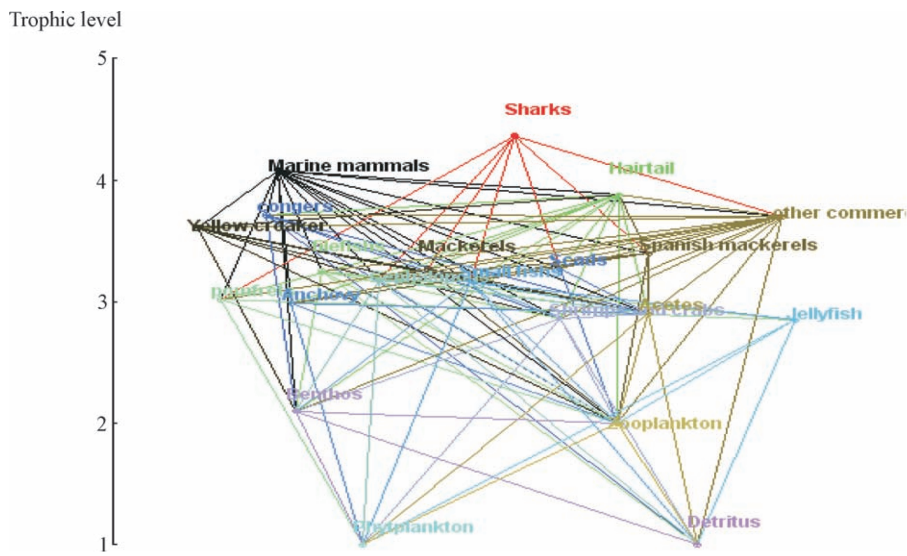

Fig. 1. Trophic relationships of functional groups in the ECS ecosystem.

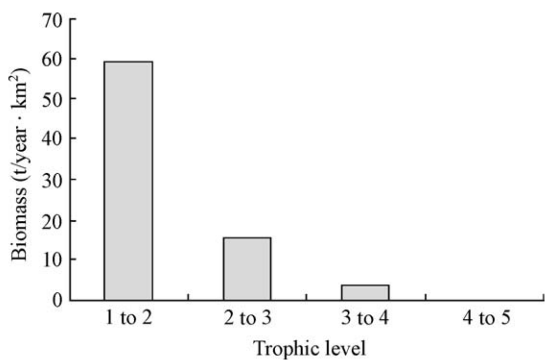

Fig. 2. Total biomass by trophic levels in the ECS ecosystem.

hairtails, small yellow croakers, eels, and other commercial fishes (>50% of the flows). Filefish, pomfrets, cephalopods and other small fishes which are omnivores and have diverse diet preference (omnivory indices >0.35), their flows spread across all the trophic levels.

3.4. Trophic transfer

The basic origins of flows in the ECS are from primary producers (phytoplanktons) and detritus. Total throughput of these two groups (i.e. sum of all flows into and out of a group) is 7,210 t km^{-2} $year^{-1}$ in which phytoplankton contributed about 60% (Table 5). Trophic transfer efficiency

Table 4
Trophic aggregations showing the proportion of flows from each trophic aggregation to the functional groups.

Group	Trophic aggregations						
	I	II	III	IV	V	VI	VII
Marine mammals			0.190	0.554	0.237	0.018	
Sharks			0.087	0.500	0.383	0.029	0.001
Hailteil			0.241	0.654	0.102	0.003	
Yellow croaker			0.442	0.517	0.040	0.001	
Congers		0.050	0.281	0.582	0.083	0.004	
Filefish		0.156	0.447	0.388	0.010		
Mackerels			0.729	0.271			
Scads		0.000	0.730	0.270			
Pomfrets		0.200	0.580	0.220			
Spanish mackerels			0.633	0.341	0.025	0.001	
Anchovy		0.100	0.810	0.090			
Cephalopods		0.137	0.579	0.254	0.029		
Other commercial fishes		0.051	0.305	0.566	0.076	0.002	
Small fishes		0.130	0.573	0.293	0.003		
Shrimps and crabs		0.203	0.730	0.067			
Acetes		0.100	0.900				
Jellyfish		0.150	0.850				
Benthos		0.900	0.100				
Zooplankton		1.000					
Phytoplankton	1.000						
Detritus	1.000						

Table 5
Disaggregation of biomass flows from different source and trophic aggregations.

The origin of flows	Trophic level/flow	Consumption by predator	Export	Flow to detritus	Respiration	Throughput
Primary producers	VI	0.001	0.007	0.005	0.02	0.031
	V	0.031	0.25	0.185	0.806	1.273
	IV	1.272	2.085	3.358	12.853	19.569
	III	19.567	2.95	22.664	60.593	105.774
	II	105.776	0.199	323.529	525.813	955.316
	I	955.316	0	2279.284	0	3234.6
Detritus	VI	0	0.001	0.001	0.003	0.005
	V	0.005	0.041	0.03	0.128	0.205
	IV	0.205	0.556	0.646	2.687	4.094
	III	4.094	1.357	5.336	15.74	26.526
	II	26.527	0.528	51.831	97.308	176.194
	I	176.194	2510.676	0	0	2686.87
Primary producers and detritus	VI	0.001	0.007	0.005	0.023	0.036
	V	0.036	0.291	0.216	0.935	1.478
	IV	1.477	2.641	4.004	15.54	23.663
	III	23.66	4.307	28	76.333	132.3
	II	132.302	0.727	375.36	623.12	1131.51
	I	1131.51	2510.676	2279.284	0	5921.47
Sum		1288.986	2518.649	2686.87	715.951	7210.456

for levels II, III, IV and more than V are 11.8%, 21.1%, 17.4% and 22.1–22.5%, respectively (Table 6). Transfer efficiency is calculated as the ratio between the sum of all the exports plus the flow that is transferred from one trophic level to the next, and the throughput on the trophic level. The averaged transfer efficiency between levels II and IV is 16.3%, which is within the theoretical range of values of 10–20% [22–23]. However, transfer efficiency of level II is low, which is mainly a result of the relatively higher respiration rate and flows to detritus of these trophic levels.

3.5. Ecosystem attributes

Properties of the ECS ecosystem were reflected by the estimated system indices (Table 7). Total system throughput is about 7,210 t km^{-2} year^{-1}. The put of the lagoon of Taiwan's coastal waters was about 21 times of it [24], and that of the inshore Gulf of West of Scotland was a little bit more than one time of it [25]. It indicates that the activity of material and energy exchange in ECS ecosystem is less than that of inshore area. Sum of all production is 3,549 t km^{-2} year^{-1}, of which 91% comes from primary production. It indicates that the productional contribution of detritus to the ECS ecosystem is less than that of the inshore area. Gross efficiency, measured as the ratio of total catch to net primary production, is about 0.25%, and average trophic level of the catch is 3.32, which is a little bit lower than that of the inshore Gulf of West of Scotland, of which the values are 0.3% and 3.5, respectively, and pretty less than that of the lagoon of Taiwan's coastal waters, of which the values are 1.8% and 3.4, respectively. The comparison indicates that the gross efficiency of the ECS ecosystem is less than that of inshore area.

Table 6
Trophic transfer efficiency of the ECS model.*

Source	TL					
	II	III	IV	V	VI	VII
Producer	11.1	21.3	17.2	22.1	22.5	
Detritus	15.4	20.5	18.6	22.5	22.4	
All flows	11.8	21.1	17.4	22.1	22.5	22.5

Transfer efficiencies (calculated as geometric mean for TL II–IV).
From primary producers: 15.9%.
From detritus: 18.0%.
Total: 16.3%.
* Proportion of total flow originating from detritus: 0.4.

3.6. Mixed trophic impacts

Based on the results from mixed trophic impact analysis [10,26], hairtails and the fisheries exerted major trophic impacts on most groups in the system (Fig. 3). Mixed

Table 7
System indices of the ECS model.

Sum of all consumption	1289.249 t km^{-2} year^{-1}
Sum of all exports	2518.649 t km^{-2} year^{-1}
Sum of all respiratory flows	715.951 t km^{-2} year^{-1}
Sum of all flows into detritus	2686.87 t km^{-2} year^{-1}
Total system throughput	7211 t km^{-2} year^{-1}
Sum of all production	3549 t km^{-2} year^{-1}
Mean trophic level of the catch	3.32
Gross efficiency (catch/net p.p.)	0.002465
Calculated total net primary production	3234.6 t km^{-2} year^{-1}
Total primary production/total respiration	4.518
Net system production	2518.649 t km^{-2} year^{-1}
Total primary production/total biomass	91.047
Total biomass/total throughput	0.005
Total catches	7.973 t km^{-2} year^{-1}
Total biomass (excluding detritus)	35.527 t km^{-2}

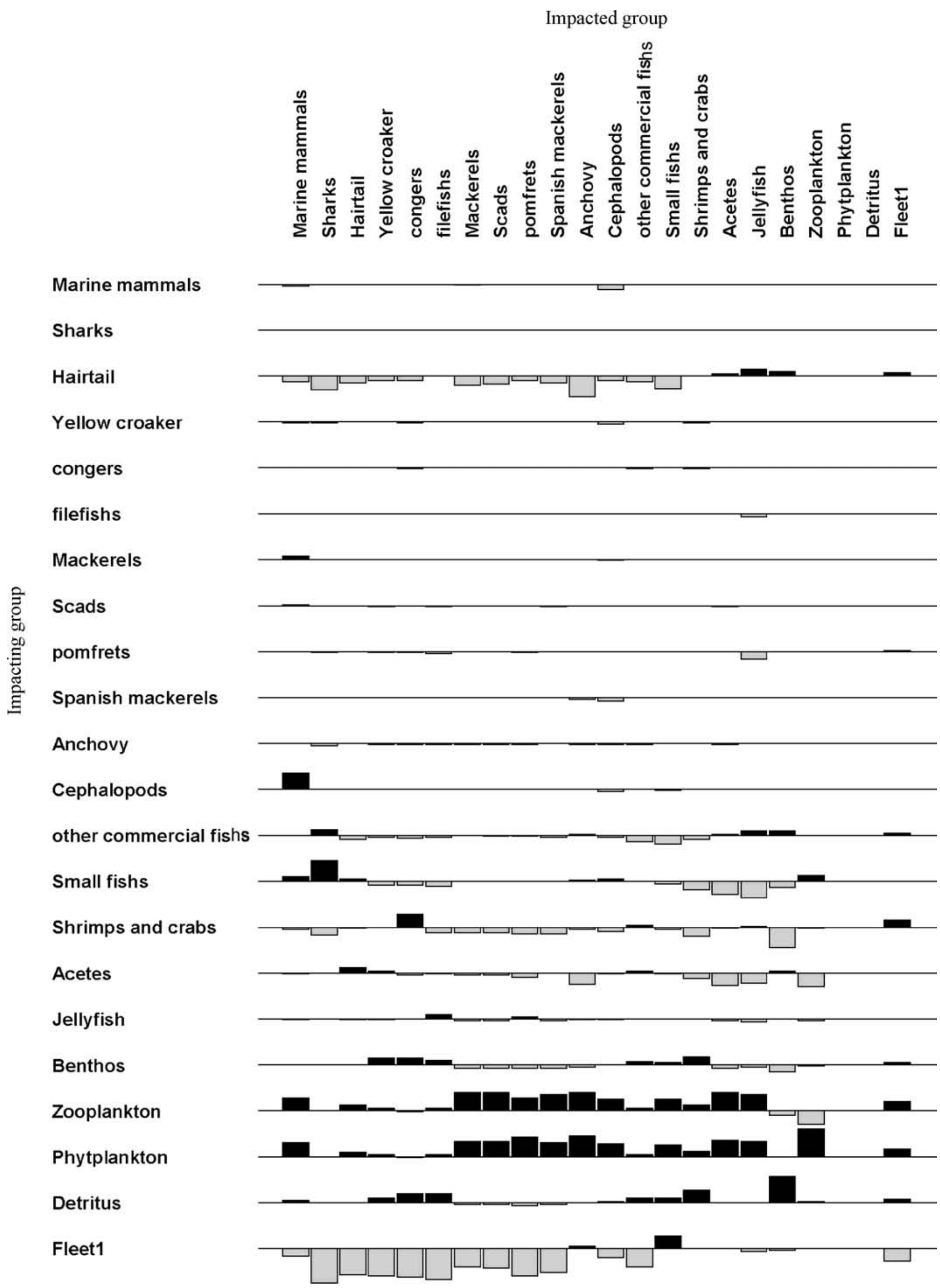

Fig. 3. Mixed trophic impact assessment of the ECS ecosystem.

trophic impact is a measure of relative impact of one group on the other through direct or indirect trophic effects. For instance, increase in biomass in a predator may increase predation on its prey, which results in reduction in the prey's biomass. This is indicated by a negative trophic impact exerted by the predator to the prey [10,25]. In the ECS model, increase in biomass of hairtail would reduce the abundance of small fish, anchovy, eels and Spanish mackerels. Moreover, as expected, if fishing effort increases, biomasses of most groups decline except small fishes of which increase in fishing mortalities is offset by reduced predation mortalities from over exploitation of their predators. The negative impacts are more prominent in higher trophic level groups.

3.7. Sensitivity analysis

The estimated parameters from the model are relatively insensitive to large variations in the most input parameter values. When input parameters were changed by 50%, sensitivities of output parameters to varying input values mostly change less than 10% from the original estimated values. However, output parameters are slightly more sensitive to input values of hairtails (resulted in 21–27% change of outputs), other commercial fishes (about 16%), small fishes (15–28%), crabs and shrimps (30%), acetes (26%), and zooplanktons (49%) (absolute percentage changes of output are 26.9% and 21.8%, respectively).

4. Discussion

4.1. Trophic impacts

Most functional groups in the ECS ecosystem were heavily exploited. Mortalities of commercially important groups that have a high trophic level, such as haritails, eels, small yellow croaker are mainly attributed to fishing. Although groups lower in the trophic level (e.g. shrimps and crabs, anchovy, small fish, etc.) generally have a higher proportion of predation mortalities (>40% of total mortality), their fishing mortalities are also high. For instance, anchovy, shrimps and crabs are currently being over exploited [27,28]. As these lower trophic level groups play an important ecological role as food sources for the predatory groups, their over exploitation may negatively affects the conservation and restoration of the ECS ecosystem. Thus, future fishery management policy should account for these lower trophic level species, instead of focusing on the targeted species only.

The importance of considering trophic dynamics in managing the fisheries is further indicated by the strong trophic impacts between functional groups. Particularly, hairtails seem to play an important role in shaping the ecosystem. Biomass of most groups is sensitive to increase in abundance of hairtails because of both direct and indirect trophic effects. For instance, hairtails are major predators of small fishes and anchovy, and thus hairtails exert negative trophic impacts on the latter groups. On the other hand, small yellow croakers, eels and mackerels compete with hairtails on food. Because of the large biomass of hairtails, relative change in their abundance indirectly affects the biomasses of their competitors. Such interactions should be considered when managing the fisheries in the ECS.

4.2. Trophic level of major commercial groups

Trophic level of commercial groups may have declined between the mid-1980s and 2000. The trophic levels of commercial groups from these studies generally agree with similar estimates from Bohai – north of ECS [13,14]. However, based on diet composition data, Yang showed that the trophic levels of small yellow croaker, Spanish mackerels and eels in Bohai had declined from 4.3, 4.6 and 4.6 in 1985 to 3.61, 3.41 and 3.61 in 2000, respectively [14]. Two factors that may explain the observed changes: (1) increase in overfishing resulted in the domination of juvenile fish in the age structure of these groups; thus, their average trophic levels declined, (2) abundance of prey groups declined because of over exploitation. This might have changed the proportion of diet of the predators; with an increase in dominance of the lower trophic level groups which are more abundant and less exploited. The fishing effort in the ECS increased to 6.66×10^6 kw quickly from 1.78×10^6 kw in 1985. Given the rapid development of the fisheries [3] and severe depletion of traditional commercial groups in ECS, similar decline in trophic level in the species is likely to have occurred in our modeled area. For instance, the small yellow croaker (*L. polyactis*) is seriously over exploited, which resulted in increased dominance of young fish [5]. Such changes in trophic levels imply that the ECS ecosystem may have changed considerably over the past few decades. Understanding the structure of the past ecosystem and comparisons with the present day should gain useful insights into fishery and ecosystem management [29].

4.3. Ecosystem maturity

Maturity of the ECS ecosystem [30] in 2000 seems to be low, as suggested from various system indices (Table 7). For instance, the primary production to respiration ratio (P_p/R) in mature ecosystem tends to be in unity. However, P_p/R in the ECS is much higher than 1. Net system production is large (mature system is close to zero). As fishery resources in ECS changed from under exploited in the 1950s–1960s, to fully exploited in the 1970s and over exploited in the 1990s, biomass of most long-lived predatory species has been greatly depleted. As a result, maturity of the ECS ecosystem reduced from the 1950s to now. These agree with other theoretical and empirical studies that suggested the deteriorations of the ECS ecosystem [6,18,31].

A mature ecosystem tends to be more stable and have stronger resistance to perturbations. Also, as a stable ecosystem usually has ecotrophic efficiency less than 0.5 [32], so the high ecotrophic efficiency of the current ECS ecosystem further suggests the instability of the system. Thus, the reduced maturity and stability of the present ECS ecosystem may increase its volatility under environmental perturbations. Such volatility may result in large fluctuations of stock abundance, and therefore, the fishery catches. As some of the species in the region are already severely depleted [3], the increased volatility or reduced stability may greatly affect the restoration and conservation of these species. These also have large socio-economic implications in the communities that depend on the resources.

4.4. Model sensitivity and uncertainty

The current ECS model is associated with both parameter and structural uncertainties. Some of the input parameters are uncertain as they are based on practical experiences of researchers in the region or data from other ecosystems that are similar to the ECS. Particularly, parameters of primary productivity and detritus biomass are based on data from other ecosystems. Improved data quality for these parameters, particularly on the groups from which estimated parameters are most sensitive to (e.g. hairtails, zooplankons, etc.), should improve the certainty of the model. On the other hand, as output parameters are relatively insensitive to the input parameters, we believe that the current ECS model is generally robust for the analyses of this paper. Moreover, because of the constraint on data availability, species in the ECS were only broadly aggregated into 21 functional groups. When more detailed data on the major species are available, further segregations of the model into more ecological sound functional groupings may improve the performance and resolution of the model. For instance, in the study, most commercially less important fish groups were aggregated into small fishes and other commercial fish groups. Future attempts to improve the ECS model may need to segregate this group into finer aggregations.

4.5. Towards ecosystem-based management

This study indicates that a holistic approach in analyzing fishery problems and management policies is needed to effectively achieve sustainable fisheries in the ECS. The ECS ecosystem is severely over exploited which is mainly caused by the over capacity of the fisheries. Currently, the Chinese authorities have initiated a series of policies to restore the fishery resources such as marine protected areas (e.g. trawl-prohibition zones, hairtail spawning and small yellow croaker protected areas, etc.), seasonal fishing moratorium, licensing system, reduction of fishing capacity, mesh-size control. However, besides the problem of ineffective implementation, many of these management measures are mainly species based. Our analysis suggests that there are strong interactions between functional groups in the ECS ecosystem. Such interactions may likely result in trade-offs between restorations of ecosystem groups or between fishery sectors which targeted different trophic levels in the ecosystem (e.g. restoration of predators vs. preys groups, benefits of fishery targeting lower trophic level species vs. those that target predatory species etc.). Thus when evaluating fishery management policies, instead of focusing only on limiting the productions of targeted species, we should also consider the interactions of and effects on other ecosystem groups. Future studies using dynamic ecosystem simulation models such as Ecosim [33] may help to gain useful insights into the effects of various management policies and the possible trade-offs at the system level.

Acknowledgments

We thank the Back to the Future team of the Fisheries Centre, University of British Columbia for their advice and help. Specifically, we are grateful to Cameron Ainsworth for the valuable suggestions on model validations and analyses. This study was conducted under the auspices of the National Science and Technology Support Plan (2007BAD43B01) and the Chinese Ministry of Agriculture Assessment of Marine Fisheries Resources Programme.

References

[1] Zhao CY. Survey and division of fishery resource in East China Sea. Shanghai: Huadong Normal University Press; 1986 (in Chinese).
[2] Zhao CY. Marine fishery resource of China. Hangzhou: Zhejiang Science and Technology Press; 1990 (in Chinese).
[3] Zheng YJ, Chen XZ, Cheng JH. Fisheries resource and environment of continental shelf in East China Sea. Shanghai: Shanghai Science and Technology Press; 2003 (in Chinese).
[4] Li SF, Cheng JH. The spatial pattern of the fish assemblage structure in the mid-southern East China Sea. Acta Oceanol Sin 2005;27(3):110–8 (in Chinese).
[5] Ling JZ, Cheng JH. Relationships between main physical characters and individual fecundities of hairtail *Trichiurus japonicus* in the East China Sea. J Fish Sci China 2004:11116–20 (in Chinese).
[6] Lin LS, Cheng JH. Analysis of population biology of small yellow croaker (*Pseudosciaena polyactis*) in the East China Sea region. J Fish Sci China 2004;11:333–8 (in Chinese).
[7] Cheng JH, Lin LS. Study on the dynamic characteristic of fishery biology of common mackerel in the East China Sea region. Mar Fish 2004;26(4):1–5 (in Chinese).
[8] Cheng JH, Chen XZ. Analysis on character of marine fisheries resource and its fisheries structure in East China Sea region. Chin Aquacult 2000;292(3):44–5 (in Chinese).
[9] Polovina JJ. Model of a coral reef ecosystem I. The ECOPATH model and its application to French Frigate Shoals. Coral Reefs 1984;3:1–11.
[10] Christensen V, Pauly D. ECOPATH II – a software for balancing steady-state ecosystem models and calculating network characteristics. Ecol Model 1992;61:169–85.
[11] Christensen V, Walters CJ, Pauly D. Ecopath with Ecosim: a user's guide. Fish Centre Res Rep 2004;12(4):8–18.
[12] Pauly D. A simple method for estimating the food consumption of fish populations from growth data of food conversion experiments. US Fish Bull 1986;84(4):827–40.
[13] Yang JM. A study on food and trophic levels of Bohai invertebrates. Mod Fish Inform 2001;16(9):8–16 (in Chinese).
[14] Yang JM. A study on food and trophic levels of Baohai Fish. Mod Fish Inform 2001;16(10):10–9 (in Chinese).
[15] Shen ZZ. Annual of China fisheries. Chinese Agriculture Press; 2001 (in Chinese).
[16] Cheng JH. The quantity and distribution character of whales and dolphins in East China Sea and Yellow Sea. In: Proceeding of international whales and dolphins conference; 2001. p. 57–61 (in Chinese).
[17] Xu HX, Liu ZF, Zhou YD. A elementary study on quota catch of hairtail, *Trichiurus haumela* in the East China Sea. J Zhejiang Ocean Univ (Nat Sci) 2003;22(1):1–6 (in Chinese).
[18] Cheng JH, Lin LS. Effects of summer close reason and rational utilization on redlip croaker resource in East China Sea region. J Fish Sci China 2004;11:554–60 (in Chinese).
[19] Cheng JH, Ding FY. A study on the quantity distribution of macro-jellyfish and its relationship to seawater temperature and salinity in the East China Sea region. Acta Ecol Sin 2005;25:440–5 (in Chinese).
[20] Cheng JH, Li SF. Primary analysis on the jellyfish blooms and its cause in the East China Sea and the Yellow Sea. Mod Fish Inform 2004;19(5):10–2 (in Chinese).
[21] Zhang ZN, Mu FH. Abundance and biomass of the *Benthic Mejofauna* in the spawning ground of anchovy in the southern Yellow Sea, China. J Ocean Univ Qingdao 2002;32:251–8 (in Chinese).

[22] Odum EP. Fundamentals of ecology. 3rd ed. Philadelphia (PA): W.B. Saunders; 1971.
[23] Barnes RSF, Hughes RN. An introduction to marine ecology. 2nd ed. Oxford: Blackwell Scientific Publications; 1988.
[24] Lin HJ, Shao KT, Kuo SR, et al. A trophic model of a sandy barrier lagoon at Chiku in southwestern Taiwan. Estuar Coast Shelf Sci 1999;48:575–88.
[25] Morissette L, Pitcher T. Ecosystem simulation model of Scotland's west coast and sealochs. Fish Center Res Rep 2005;13(4):30–40.
[26] Ulanowicz RE, Puccia CJ. Mixed trophic impacts in ecosystems. Coenoses 1990;5:7–16.
[27] Jin X, Hamre J, Zhao X, et al. Study on the quota management of anchovy (*EngrauIis japonicus*) in the Yellow Sea. J Fish Sci China 2001;8(3):27–30 (in Chinese).
[28] Cheng JH, Ling JZ. The discussion on commercial shrimps resource management in East China Sea. Chin Aquacult 2003;326(1):74–5 (in Chinese).
[29] Pitcher TJ. Fisheries managed to rebuild ecosystems. Reconstructing the past to salvage the future. Ecol Appl 2001;11:601–17.
[30] Odum EP. The strategy of ecosystem development. Science 1969;164:262–70.
[31] Horikawa H. Biological and ecological characters of the commercial fisheries resource in East China Sea and Yellow Sea. Seikai National Fisheries Research Institute, Fisheries Research Agency; 2001.
[32] Dickie LM. Food chains and fish production. ICNAF Spec Publ; 1972.
[33] Christensen V, Walters CJ. Trade-offs in ecosystem-scale optimization of fisheries management policies. Bull Mar Sci 2004;74(3): 549–62.