

## **BASS WORKSHOP ON THE DEVELOPMENT OF A CONCEPTUAL MODEL OF THE SUBARCTIC PACIFIC BASIN ECOSYSTEMS**

**(Co-convenors: Gordon A. McFarlane, Richard J. Beamish, Akihiko Yatsu and Andrei S. Krovnin)**

At the PICES Sixth Annual Meeting, the BASS Task Team sponsored a symposium on the Ecosystem dynamics of the eastern and western subarctic gyres. The purpose was to bring together available information on the two gyres in a comparative framework. Topics included: 1) ocean responses to climate forcing, 2) nutrients and primary production, 3) structure of the lower trophic levels, the mesozooplankton communities, and the epipelagic nekton, 4) the role of midwater fishes, and 5) the importance of these areas to marine birds and mammals. Papers presented at the meeting were published in 1999, in a Progress in Oceanography special issue entitled *Ecosystem Dynamics in the Eastern and Western gyres of the Subarctic Pacific* (Guest Editors: R.J. Beamish, S. Kim, M. Terazaki and W.S. Wooster). The following “key” research problems were pointed out during discussion at the symposium: 1) the need for information on short-term or seasonal changes in the mixed layer, 2) how climate-variation may be changing the stability of the water column, 3) the role of iron: understanding transport mechanisms, 4) community dynamics and the need for small scale diet studies, and 5) biomass estimates of some “key” species.

Members of BASS Task Team felt that the next step should be to develop a conceptual model of the subarctic Pacific basin ecosystems and begin to examine appropriate models. A 2-day BASS Workshop on this topic was convened prior to the Ninth Annual Meeting in Hakodate, Japan (October 20-21, 2000). The objective of this workshop was to identify appropriate approaches, not only modelling approaches but also how to develop studies which will answer some of the questions.

At the workshop, a number of presentations were made on ecosystem models that participants had used. These models were reviewed and discussed with respect to their utility for gyre systems. Trophodynamic linkages that were likely to be common, as well as those that were model-specific, were identified, and shortfalls were highlighted. Discussions included identifying data groups and potential data sources, incorporating climate and oceanographic change in models, and linking gyre models to coastal area models. The following section contains extended abstracts of papers given at the workshop.

### **Investigating ecosystem dynamics with ECOPATH/ECOSIM**

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Two applications of the ECOPATH/ECOSIM modelling approach are presented. The first constructs an ECOPATH model of the central North Pacific pelagic ecosystem, using ECOSIM to investigate the response of the ecosystem to fishing impacts. The ECOPATH model is highly resolved at the top trophic levels including species groups for each of the principal fishery target species as well as fishery impacts of 6 types of fishing gears. The ECOPATH model was used in the dynamic ECOSIM to simulate the response of

the pelagic ecosystem to an elimination of all fishing: a return of the ecosystem to the early 1900s. The ECOSIM model simulation found all the fished species increased in the absence of fishing but a number of prey species including squid, flying fish and lancet fish, decreased as their predators increased. Furthermore, for the top trophic level species, large sharks and blue marlins, their biomass increased more than all other fished species because they benefited from both an absence of fishing as well as an increase in

their prey, small tunas and billfishes, species which increased in biomass when fishing was halted.

A second application of these models was a bottom-up simulation. An eastern tropical Pacific pelagic ecosystem model was constructed and used to simulate the ecosystem response to changes in ENSO periodicity and cadence, and long-term global warming. The ENSO impacts were simulated by changing the phytoplankton availability in the ECOSIM model. An El Niño was simulated by a 30% drop in phytoplankton during one year and a La Niña was simulated with a 30% increase in phytoplankton for one year. The global warming scenario was simulated by using predicted changes in SST from a 100-year global warming modelling exercise. The predicted eastern tropical Pacific SST was converted into phytoplankton biomass with an empirical relationship between these parameters for the eastern tropical Pacific. The ECOSIM results found that bottom-up forcing propagates through the 6 trophic levels of the ecosystem with time lags and amplitude of the forcing which varies by species and can be greater or weaker than the

initial forcing. Changing the ENSO period results in modest changes in trophic transfer and ecosystem structure. For example, less energy reaches the top of the ecosystem when El Niño events occur every 2 years compared to every 6 years. However, the global warming scenario which predicted warming of SST, an increased vertical stratification and hence reduced phytoplankton in the eastern tropical Pacific, was simulated by the ECOSIM model to result in a substantial decrease in the entire ecosystem biomass at all trophic levels.

These and other experiences with ECOPATH and ECOSIM suggest that these models are useful tools to investigate the responses of complex ecosystems to both top-down and bottom-up forcing. However, issues remain regarding how well the models capture the complexity of actual ecosystem dynamics. More evaluations of model results with actual ecosystem dynamics are needed. There is a considerable literature on applications of these approaches and a web site “[www.ecopath.org](http://www.ecopath.org)” which serves as a source for the programs and related literature.

## **ECOPATH as a potential tool for modeling the North Pacific Gyre ecosystems**

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The subarctic North Pacific oceanic gyres contain highly productive pelagic ecosystems. These waters have been subject to past fisheries and are important rearing areas for Pacific salmon (*Oncorhynchus* spp.), marine mammals and commercially harvested squid. Furthermore, the species of the region responds to oceanographic signals on the order of decades, and thus they present a case study for the interactions between climate and marine ecology. However, the ecosystems of these regions are poorly understood, in part due to the difficulty of obtaining consistent data across such large systems.

Extensive biological data exist for these regions and have been gathered by PICES member countries. It would be extremely useful to

assemble these data to provide a meaningful quantification of ecosystem structure and function. To this end, the software package ECOPATH may be a useful tool, as it helps researchers in modeling oceanic food webs, and provides a meaningful context for comparing estimates of biological production across species and regions.

ECOPATH is simply a tool for comparing independent estimates of biomass, production, consumption and diet, migrations, and fisheries catch of the important players in a food web. Such comparisons help determine:

- if available estimates are consistent between species;
- the relative importance of species or guilds within an ecosystem; and

- how targeting increased research effort on critical, keystone species might aid in improving our understanding of the system's structure and function.

In cases where two similar ecosystems are to be compared, such as with the eastern and western subarctic gyres, ECOPATH provides a quantitative basis for comparison.

Creating an ECOPATH model should be a strongly collaborative process among participating scientists. The framework of ECOPATH lends itself to an iterative peer-review process between the primary modelers, the data collectors, and the wider scientific community. There are five main steps in creating a model:

- determining the model framework;
- assembling and documenting the initial data;
- assessing the data in preliminary models;
- peer-review of data and preliminary models;
- use of models to test hypotheses.

Determining the model framework To set up a modeling effort, the boundaries, time period, time step, species of interest, and important hypotheses for the system must be identified. While these identifications may change as the model develops, it is important to have some preliminary framework to aid in collecting data. This stage may also identify key data sources and providers. Generally this task may be completed in a series of discussions over a short time period.

Assembling and documenting the initial data Data assembly and documentation may take from weeks to months depending on the ecosystem in question. This process may involve contacting researchers in many institutions to provide data to a central source. At the same time, the quality of the data

may be assessed and adjustments made to the model framework if necessary.

Assessing the data in preliminary models The initial assembly of data for an ECOPATH model is best conducted in a workshop setting with a limited number of participants who are familiar with aspects of the data. The purpose of such a workshop is to view the pieces of data as a whole for the first time, and make preliminary judgements on the quality of the data and the usefulness of the model. At this stage, plans may be made to revisit hypotheses or attempt to refine data estimates.

Peer-review of data and preliminary models After an initial workshop, participants should be able to show the initial model to a wider community over a period of months. This process allows additional input to be gathered to improve the model. Successive iterations of data exchange during this period will substantially improve the model. In addition, the model may be used to direct further data collection.

Use of models to test hypotheses When the peer-review process has reached the larger research community, the models may be distributed and used to compare the relative roles of anthropogenic effects, predator-prey interactions, climate changes, or dynamic function of the ecosystem through a variety of modeling techniques.

ECOPATH, like all models, is a simplification of nature. However, the quantitative, iterative peer-review process has in many cases contributed to an increased understanding of the ecosystem's structure and function. Overall, ECOPATH is a powerful tool for assembling and synthesizing ecosystem data from disparate sources.

## **Modeling the western Bering Sea ecosystem with help of ECOPATH software**

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The purpose of our presentation is to identify some methodological aspects substantially affecting, or even defining, the quantitative appearance of the

model, and as a result the applied conclusions derived from the model. This modeling work was initiated by our colleagues from the National

Marine Fisheries Service (NOAA, U.S.A.) with the goal of constructing an ecosystem model of one of the major fishing area in the northern Pacific - Bering Sea. The co-operative project stipulated that with the help of the ECOPATH software, we should build a model of the western Bering Sea (WBS) in addition to one of the eastern Bering Sea (EBS) that had already been created by US scientists. Further they intended to combine both models into a general model describing the whole Bering Sea ecosystem.

Following accepted rules, we built a WBS ecosystem model for the 1980s. During that decade TINRO-Centre carried out large-scale investigations of marine biota and collected numerous data on diverse species and groups of pelagic and demersal taxa. Those data allowed tracing seasonal and interannual dynamics of species abundance, distribution, migrations, feeding etc. This information became a base for our model.

The entire Russian EEZ in the western Bering Sea was used as the model area. It covers a total of 702,200 km<sup>2</sup> and encompasses a wide range of marine habitats including shelf, slope and deep basins, but it was treated as a single homogenous region in the model. To describe the WBS

ecosystem, we separated all taxa into 48 functional groups, composed of a single species or an aggregation of ecologically similar species, covering all trophic levels from phytoplankton to marine birds and mammals. The model uses annual averages, i.e. all necessary data on abundance and feeding collected in various habitats were combined proportionally to the areas of those habitats and averaged seasonally and annually to provide year-round annual average characteristics, which were entered into the two main tables (basic input and diet composition). Commercial fishery catch was also included into the model. Furthermore our model was balanced and we have compared the results obtained in the WBS and EBS (Trites *et al.* 1999). Comparison was particularly interesting because both models are composed of a very similar list of functional groups and relate to the same time period. Results are presented in Table 1.

Total biomass in the WBS ecosystem was 1.75 times higher than in the EBS, while other important ecological indices differed in even greater proportions. For example, the sum of all biological production was 4 times higher, the sum of all consumption - 2.7 times, the sum of all flows into detritus - almost by order of magnitude greater and total system throughput - 4.5 times

**Table 1** Descriptive summary statistics for the eastern (EBS), western (WBS) and partially changed (WBS<sup>1</sup>) Bering Sea ecosystem models in the 1980s.

<u>Parameters/model</u>	<u>EBS</u>	<u>WBS</u>	<u>WBS<sup>1</sup></u>
Sum of all consumption	3073.72	8318.623	6445.045
Sum of all exports	2.62 (?)	5194.181	699.061
Sum of all respiratory flows	1620.43	2450.86	2600.98
Sum of all flows into detritus	994.99	9593.33	2984.748
Total system throughput	5691.76	25557	12730
Sum of all production	2612.84	10234	4752
Mean trophic level of the catch	3.3	3.6	3.6
Gross efficiency (catch/net p p.)	0.0021	0.000124	0.000286
Calculated total net primary production	1920	7645	3300
Total primary production/total respiration	0.78	3.119	1.269
Net system production	356.43	5194.14	699.02
Total primary production/total biomass	4.94	17.109	7.385
Total biomass/total throughput	0.045	0.017	0.035
Total biomass (excluding detritus)	255.95	446.846	446.846
Total catches	2.62	0.945	0.945
Connectance Index	0.3	0.168	0.168
System Omnivory Index	0.157	0.203	0.209

higher in the WBS. At the same time, the WBS ecosystem was exploited much less - gross efficiency was almost 20 times lower compared to the EBS. Judging from these statistics in the 1980s, the WBS ecosystem functioned much more intensively but less efficiently compare to the EBS. However, it should be remembered that the EBS is generally warmer and shallower than the WBS, and therefore we might have expected the opposite situation. What is the reason? We assume that the main reason lies in higher average ecological characteristics, and first of all in the values of production/biomass (P/B) and consumption/biomass (Q/B) ratios, we have applied to describe some functional groups of species in the WBS ecosystem.

As follows from Table 2, the annual Q/B values, which were defined for the WBS, are substantially higher in higher trophic level groups (pollock and herring are particularly indicative) and lower – in lower trophic level groups, compare to the EBS. Another important difference is in P/B ratios of phytoplankton (see Table 2). Apparently application of all these values caused the aforementioned differences between the models. To test this assumption we have entered into the WBS ecosystem model P/B and Q/B ratios from the EBS one, keeping biomass and diet composition unchanged. Although the resulting model was found to be slightly unbalanced, the descriptive statistics, as we expected, had intermediate values between both original models (Table 1, last column).

Thus, the values of the such important ecological parameters as P/B and Q/B ratios, entered into the model, are crucial for its

**Table 2** P/B and Q/B values applied in the WBS (above slash) and EBS (below slash) models.

Group name	P/B	Q/B
Phytoplankton	139 / 60	-
Copepods	9.5 / 6.0	26.2 / 22.0
Euphausiids	3.13 / 5,5	17.0 / 22.0
Amphipods	2.5 / 3.5	14.0 / 22.0
Herring	0.7 / 1.0	14.6 / 3.65
Cod	0.52 / 0.40	3.3 / 2.04
Yellowfin sole	0.26 / 0.40	9.8 / 2.96
Rock sole	0.24 / 0.40	6.5 / 3.6
Halibut	0.25 / 0.40	3.5 / 2.49
Juv. pollock	2.5 / 2.5	13.0 / 8.3
Adult pollock	0.5 / 0.5	10.0 / 2.64
Steller sea lion	0.06 / 0.06	18.0 / 12.7
Toothed whales	0.02 / 0.02	17.5 / 13.11

resulted appearance, features, further simulation of commercial exploitation rate and final conclusion. It is difficult to imagine that trophic and productive characteristics of the same taxa differ by several times in the same biogeographical area. Of course, the some differences should take place due to various size-age composition of populations, food conditions, general temperature of environment, etc., however, we presume they are not so drastic.

It is quite possible that the ECOPATH software will be accepted as a standard tool for modeling of ecosystems in diverse Pacific areas. Pacific waters are inhabited by various fauna, but there are no doubt that almost everywhere predominating species and groups of species will coincide in high extent, especially for adjacent areas. Thus, it would be very useful for future modeling efforts to compare and discuss methodical approaches for determining the most important ecological parameters of common species and groups in the northern Pacific.

## **Changes in the Strait of Georgia ECOPATH model needed to balance the abrupt increases in productivity that occurred in 2000**

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ECOPATH is a trophic accounting model that is a practical way of studying the interactions of all species in an ecosystem. We used ECOPATH to study the dynamics of the Strait of Georgia

ecosystem (area: 6,900 km<sup>2</sup>), located between Vancouver Island and the British Columbia mainland. The Strait of Georgia is probably the most important marine ecosystem on Canada's west

**Table 3** Functional groups, biomass, production/biomass and consumption/biomass values used in the Strait of Georgia model and resulting ecotrophic efficiencies.

Functional Group	Biomass (t/km <sup>2</sup> )		Production/Biomass (t/year)	Consumption/Biomass (t/year)	Ecotrophic Efficiency	
	1998	2001			1998	2001
Phytoplankton	36.000	72.000	130.000		0.992	0.912
Kelp/Sea Grass	23.300	23.300	34.000		0.280	0.559
Herbivorous zooplankton	25.000	50.000	20.000	80.000	0.892	0.647
<i>Neocalanus plumchrus</i>	25.000	40.000	20.000	80.000	0.909	0.796
<i>Pseudocalanus minutus</i>	10.000	20.000	20.000	80.000	0.878	0.668
Shellfish	60.000	90.000	3.000	12.000	0.569	0.636
Crab	4.000	8.000	3.500	14.000	0.671	0.461
Grazing invertebrates	40.000	90.000	3.000	12.000	0.729	0.493
Carniverous zooplankton	40.000	50.000	5.000	20.000	0.581	0.912
Euphausiid	80.000	160.000	3.000	12.000	0.755	0.581
Predatory invertebrate	25.000	25.000	5.000	20.000	0.293	0.488
Shorebirds	0.005	0.005	0.100	5.000	0.000	0.000
Herring	9.000	13.000	3.000	12.000	0.787	0.886
Small Pelagics	15.000	40.000	2.000	8.000	0.770	0.704
<i>Lampetra ayresi</i>	0.020	0.020	2.000	8.000	0.782	0.782
Seabirds	0.018	0.018	0.100	5.000	0.009	0.009
Gulls	0.004	0.004	0.100	12.500	0.000	0.000
Misc. demersal fish	20.000	50.000	2.100	8.400	0.431	0.412
Chum	1.000	2.000	2.000	8.000	0.398	0.364
Coho	1.000	2.000	3.000	12.000	0.361	0.357
Chinook	1.000	2.000	2.000	8.000	0.445	0.421
Toothed Whales	0.003	0.003	0.020	0.400	0.000	0.000
Hake	10.000	14.000	0.600	2.400	0.559	0.783
Dogfish	4.500	4.500	0.100	1.000	0.052	0.052
Lingcod	0.350	0.350	0.500	2.000	0.114	0.114
Pollock	2.000	2.000	0.600	2.400	0.124	0.206
<i>Leuroglossus</i>	0.200	0.400	2.000	8.000	0.660	0.342
Yelloweye	0.500	0.500	0.200	2.000	0.070	0.070
English Sole	1.000	1.000	0.180	0.720	0.034	0.034
Sea Lions	0.020	0.020	0.180	21.600	0.013	0.013
Seals	0.050	0.050	0.125	15.510	0.028	0.028
Detritus	38.700	38.700			0.572	0.529

coast, as much of the population of British Columbia lives within 10 km of its shores and it is a key rearing area for Pacific salmon, herring, and other species.

Our ECOPATH model has 32 functional groups. We estimated the biomass, production/ biomass ratios, consumption/biomass rates, and diet compositions for each functional group. We used a number of references and the unpublished results of our own studies over the past 26 years to estimate these data. An important estimate for the lower trophic levels was the hydroacoustic estimate of euphausiids made in 1999 and 2000

(Pearsall *et al.* 2001). The two dominant fish species in the Strait of Georgia are Pacific hake and Pacific herring. Reliable biomass estimates existed for both of these species (McFarlane *et al.* 2000; Schweigert and Fort 2000). Pacific salmon are both abundant as juveniles and important commercially, culturally, and politically. In recent years, juvenile salmon have reared in the Strait of Georgia longer than in the past, but adult coho were virtually absent. Chinook of larger sizes and ocean ages greater than age 0 remained in the Strait but their abundance was much lower in the late 1990s than in the 1970s and 1980s.

**Table 4** Diet matrix in the models.

Prey/Predator	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
Phytoplankton	0.700	0.700	0.700	0.579	0.002	0.176		0.809			0.020	0.005					0.005	0.005	0.005		0.005			0.010	0.020					
Kelp/Sea grass				0.100	0.100	0.300					0.050	0.100		0.010			0.040	0.120	0.200	0.100		0.010		0.010	0.310	0.001	0.011			
Herb. zooplankton				0.030	0.060	0.050	0.359	0.050	0.065		0.050	0.150					0.051	0.050	0.050	0.030		0.020	0.010	0.030	0.300	0.001	0.011			
<i>N. plumbeus</i>				0.050	0.020	0.050	0.404		0.050		0.100	0.070					0.050	0.050	0.050	0.030		0.010	0.010	0.020	0.150					
<i>P. minutus</i>				0.020	0.020	0.050	0.102		0.050		0.100	0.070					0.050	0.050	0.050	0.030		0.010	0.010	0.020	0.150					
Shellfish				0.010	0.150		0.030	0.001	0.055	0.115	0.001	0.030		0.350	0.150	0.172	0.020	0.020	0.040		0.030	0.050	0.038	0.001	0.001	0.001	0.001	0.030		
Crab				0.001	0.010			0.002	0.010		0.001	0.010		0.005	0.005	0.005	0.005	0.005	0.005		0.001	0.010								
Grazing invertebrates					0.200			0.003	0.100	0.500	0.010	0.050		0.090	0.020	0.090	0.095					0.150			0.056		0.130			
Cam. zooplankton							0.050				0.084	0.264		0.080		0.154	0.100	0.145	0.255		0.163	0.110		0.090	0.050					
Euphausiid									0.111		0.580	0.150		0.080		0.100	0.300	0.300	0.220		0.700	0.080	0.030	0.668	0.102					
Predatory invertebrate									0.036	0.200		0.050		0.090	0.030	0.040	0.150	0.150	0.150	0.040	0.005	0.235	0.051	0.050		0.200	0.100	0.020		
Shorebirds																														
Herring									0.022	0.020	0.001	0.020	0.640	0.050	0.069	0.030	0.030	0.030	0.135	0.252		0.020	0.243	0.050		0.100		0.300	0.231	
Small pelagics									0.001	0.050	0.002	0.100	0.199	0.080	0.020	0.050	0.005	0.005	0.005	0.164	0.040	0.042	0.100	0.010	0.010	0.200	0.250	0.113	0.100	
<i>Lampetra ayresi</i>															0.001							0.005	0.010					0.004		
Seabirds																				0.014										
Gulls																														
Misc. demersal fish														0.050													0.446	0.418	0.225	0.175
Chum									0.020		0.001	0.001	0.053	0.001	0.010	0.001	0.010	0.010	0.025	0.001	0.055	0.020					0.010	0.010		
Coho													0.051	0.001	0.004	0.004	0.002	0.002	0.032	0.001	0.070	0.020					0.011	0.008		
Chinook													0.051	0.003	0.003	0.003	0.001	0.002	0.158	0.001	0.070	0.005					0.005	0.005		
Toothed whales																														
Hake											0.001		0.001	0.020		0.010	0.040	0.027	0.001	0.064		0.056	0.050	0.010	0.001	0.050	0.050	0.300	0.464	
Dogfish																						0.005								
Lingcod																													0.001	
Pollock													0.005						0.010	0.001	0.002	0.001	0.001	0.001				0.011	0.006	
<i>Leuroglossus</i>																					0.001			0.050						
Yelloweye																														
English sole																														
Sea Lions																						0.001	0.001	0.001			0.001			
Seals																					0.040									
Deerfish	0.300	0.300	0.300	0.210	0.438	0.374	0.050	0.140	0.500	0.095				0.091	0.700	0.100	0.030			0.146										
Sum	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	

In this report, we model two ecosystem states: one in 1998 and one in 2001. We show that the increase in production that occurred in 2000 had a major impact on the dynamics of the trophic relationships in the Strait of Georgia in 2001. The increase in productivity in 2000 probably resulted from a change in the climate and a corresponding change in the oceanography.

The 1998 model (Table 3) assumed a biomass of phytoplankton of 36 t/km<sup>2</sup> and a production/biomass ratio of 130. The model was balanced with 99.2% of the phytoplankton production being consumed by higher trophic levels. On average, over 90% of the production of the four herbivorous zooplankton groups (euphausiids, *P. minutus*, *N. plumchrus* and other herbivorous zooplankton) was consumed by higher trophic levels. Carnivorous zooplankton (amphipods) contributed 58.1% of its production to higher trophic levels. The biomass of Pacific hake was 10 t/km<sup>2</sup>. The major items in the hake diet were euphausiids (70%) and carnivorous zooplankton (16%). Diet composition for the models are summarized in Table 4. Although adult hake fed on juvenile hake and herring in the past, we have not found fish remains in hake stomachs in the late 1990s. Pacific herring migrate out of the Strait of Georgia after about age 1, and return only to spawn in the winter in their third and subsequent years. We estimated that euphausiids made up 58% of their diet. Euphausiids were also an important prey for juvenile salmon, accounting for 22% to 30% of their diet. Another major fish species in the model was spiny dogfish. Dogfish are omnivorous, but grow only a few mm/year, thus their consumption is small relative to their biomass. The model balanced for 1998 indicated that 75.5% of the euphausiids were consumed by higher trophic levels.

The hydroacoustic study indicated that there was 109.7 t/km<sup>2</sup> and 227.5 t/km<sup>2</sup> of euphausiids in the Strait of Georgia in September/October 1999 and 2000, respectively. The biomass estimates in Pearsall *et al.* (2001) were modified for our ECOPATH model to approximate our interpretation of their life history. The maximum biomass of euphausiids in the Strait of Georgia occurs late in the year and the minimum biomass about June. The life span exceeds one year thus

the P/B will be lower than other groups of zooplankton. Therefore, we estimated the annual biomass to be 80 t/km<sup>2</sup> in 1998 and 160 t/km<sup>2</sup> in 2001. A variety of scenarios would be possible to balance the 2001 model with the increased euphausiid production, but all scenarios would indicate a substantial increase in the biomass of a number of functional groups. The addition of the biomass of euphausiids used in the 2001 model into the 1998 model resulted in 37.8% of the production being consumed by predators and an imbalance of 115.8% of the phytoplankton production. Because euphausiids feed primarily on phytoplankton, the increase in euphausiid abundance most likely was associated with an increase primary productivity. Such an increase would also benefit larval copepod survival. We balanced the 2001 model by increasing the biomass of these and other functional groups that would benefit directly or indirectly from increases

**Table 5** Changes in the abundances of functional groups from the 1998 model to 2001 model, scaled to the impact of the euphausiid biomass increase.

Functional Group	1998 Biomass t/km <sup>2</sup>	2001 Biomass t/km <sup>2</sup>
Euphausiid	80.00	160.00
Phytoplankton	36.00	72.0
<i>N. plumchrus</i>	25.00	40.00
<i>P. minutus</i>	10.00	20.00
Shellfish	60.00	90.00
Crab	4.00	8.00
Grazing invertebrates	40.00	90.00
Carnivorous zooplankton	40.00	50.00
Small Pelagics	15.00	40.00
Miscellaneous Demersal	20.00	50.00
Fish		
Chum	1.0	2.0
Coho	1.0	2.0
Chinook	1.0	2.0
Hake	10.0	14.0
Herring	9.0	13.0
Herbivorous zooplankton	25.0	50.0
<i>Leuroglossus</i>	0.2	0.4

in euphausiid biomass (Table 3). We adjusted the biomass of species that might be directly affected by the increased productivity in the 2001 model (Table 3), but did not change the diets used in the 1998 model.

In our 2001 model, we assigned only 58.1% of the new euphausiid production to consumers, yet there were increases in biomass of 40% for herring and hake, 50% for shellfish, 100% for crab, chum, chinook and coho, 150% for miscellaneous demersal fish, and 267% for small pelagic fishes (Table 5). It is possible that these increases might take longer to develop, however, the model increases would be indicative of the possible changes in biomass. The changes in salmon abundance would be particularly important. In another study we are testing the hypothesis that salmon survival or production is a function of both predation and summer growth. If our hypothesis is correct, the improved summer growth in 2000 will increase marine survival, and the returns of coho and pink salmon in 2001 will be larger than

previous years. We note that if the primary production remains at the 2000 level, there will be continued major changes in the ecosystem as higher trophic levels increase their biomass in response to the increases in prey.

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## Simulating historical changes in the Strait of Georgia ecosystem using ECOPATH and ECOSIM

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The Strait of Georgia (SOG) ecosystem has been heavily exploited for the last 90 years and development in commercial fisheries has shifted the focus from top predators in the ecosystem to more abundant lower trophic level species (Wallace 1998). This phenomenon is known as “fishing down food webs” (Pauly *et al.* 1998; Pauly *et al.* 2000). Salmon fisheries were by far the most important fishery in the early years of fishing development, and by 1897, British Columbia was canning more than 1 million cases of salmon a year (Lichatowich 1999). Both chinook and coho salmon have been heavily exploited in the SOG by the commercial net and troll fisheries, and by sports fisheries (DFO 1999a; DFO 1999b). With almost all SOG coho stocks in jeopardy, a coastwide closure for all coho fisheries was implemented in 1998, with the exception of a

sports fishery for hatchery fish at the mouth of the Capilano River.

As fishing technologies improved, herring fisheries and groundfish fisheries grew rapidly in the 20<sup>th</sup> century, with precipitous results. By the early 1960s, herring stocks were being harvested at unsustainable rates and the fishery collapsed in 1967 (Stocker 1993). Since this time, however, herring stocks have recovered to near historically high levels (Schweigert *et al.* 1998). Prior to 1970, herring were mainly used for fishmeal, but after the collapse, a more valuable roe fishery was developed. Groundfish such as lingcod and several rockfish species were also heavily exploited in the 1900s, and with the introduction of trawl fisheries to the SOG in 1943, exploitation rates rose dramatically (Cass *et al.* 1990; Martell

1999). Invertebrate fisheries have existed in the SOG for the last 100 years, however, until the 1950s the fisheries were mainly focused on dungeness crabs and manilla clams (an exotic species). Since the 1950s, there have been developments in shrimp fisheries, geoduck clams, sea urchin, sea cucumbers and octopus fisheries (Ketchen *et al.* 1983).

Stock assessment reports have attributed the observed declines in abundance to factors other than overfishing. In fact, more attention has been spent on trying to explain environmental processes that may have led to a reduction in marine survival rates in salmon (Beamish and Bouillon 1995), or changes in food availability associated with changes in physical properties (Robinson 1999). At this time, the occurrence of a “regime shift”, or long-term changes in primary productivity in the Pacific Ocean (Beamish *et al.* 1999), is postulated as the major factor leading to abundance declines in the SOG.

An obvious, but often unresolved, issue is the role of trophic interactions in suppressing recruitment or indirectly changing natural mortality rates (generally assumed to be constant). Among fisheries scientists and academia, there is a growing consensus that we can no longer forge ahead and exploit a resource without considering trophic interactions at an ecosystem scale (Walters *et al.* 1997). The majority of data available, however, are usually restricted to species of commercial importance. In the SOG alone for example, there are more than 250 different species of fish, but fisheries statistics are collected for less than 50 species coast-wide (vertebrate and invertebrate combined). Moreover, we have even less knowledge about the specific interactions among members in an ecosystem, a problem we are now forced to face.

The objective of this paper is to carry out a retrospective analysis of the Strait of Georgia ecosystem and use data from single species stock-assessment programs to determine if the observed data suggest that changes in primary productivity have occurred in the last 50 years. We address this issue by comparing reconstructed ecosystems from 1950 to 1998 using two scenarios: 1) assume

that there has been no changes in relative primary productivity, and 2) estimate relative primary productivity regimes that would better explain the observed data. Finally, we compare the estimated primary productivity regimes to environmental correlates, specifically wind speed squared (a measure of shear stress), and the Pacific Decadal Oscillation.

### **Predicting biomass dynamics using ECOPATH with ECOSIM**

The trophic mass-balance model used in ECOPATH uses a set of simultaneous linear equations that assumes the production of group  $i$  is equal to the consumption of group  $i$  by all predators  $j$ , plus export and non-predation losses (including fisheries landings) of group  $i$ , over a specified time period. This function is generally expressed as:

#### **Equation 1**

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

Where  $B_i$  is the biomass of group  $i$ ,  $(P/B)_i$  is the production biomass ratio of group  $i$ ,  $(Q/B)_j$  is the consumption biomass ratio of group  $j$  (predators of group  $i$ ), and  $DC_{ji}$  is the average diet fraction of prey  $i$  for group  $j$ .  $EE_i$  is the ecotrophic efficiency, or the fraction of production that is consumed within the system, including fisheries yields ( $Y$ ).

The following differential equation is used to predict dynamic changes in biomass and is dependent on whether the group is a primary producer or a consumer in the system:

#### **Equation 2**

$$dB_i / dt = f(B) - M_o B_i - F_i B_i - \sum_{j=i}^n c_{ij} (B_i, B_j)$$

Here  $M_o = (1 - EE_i) \cdot (P/B)_i$  represents the fraction of production that is unaccounted for (other mortality),  $F_i$  is the fishing mortality rate, and  $c_{ij}$  is a function used to predict consumption of group  $i$  by predator  $j$ , conditional on the interactions and abundance of the two groups (see Eqn. 4). For primary producers, a simple saturating function is used to predict biomass production:

### Equation 3

$$f(B_i) = r_i B_i / (1 + B_i h_i) \quad (a)$$

Whereas if group  $i$  is a consumer then

$$f(B_i) = g_i \sum_{j=1}^n c_{ji} (B_i, B_j) \quad (b)$$

here  $g_i$  is the growth efficiency and must satisfy the relationship  $B_i (P/B)_i = g_i \sum_j Q_{ji}$ .

Predicting consumption in ECOSIM stems from the "Foraging Arena" concepts proposed by Walters and Juanes (1993). At equilibrium the consumption of  $i$  by  $j$  is:

### Equation 4

$$c_{ij} (B_i, B_j) = \frac{a_{ij} v_{ij} B_i B_j}{(2v_{ij} + a_{ij} B_j)}$$

In Equation 4,  $a_{ij}$  is the mass action consumption rate, and  $v_{ij}$  describes the exchange rate process from "available" to "unavailable" behavioural states. Using ECOPATH estimates ( $Q_{ij}$ ,  $B_i$ , and  $B_j$ ) the mass action consumption rate can be estimated by re-arranging Equation 4. Therefore, the only user specified parameter is the behavioural exchange rate parameter ( $v_{ij}$ ). Equation 4 is structured such that consumption is dependent on both predator and prey biomass. If predator biomass is low then consumption reduces to a mass-action flow, and if predator biomass is high then consumption approaches a "donor control" rate represented by the behavioural exchange rate process  $v_{ij}$  (Walters *et al.* 1997; Walters *et al.* 2000). As  $v_{ij}$  approaches 1, the rate of predation is dependent on the biomass of the predator (top-down control), and as  $v$  approaches 0, prey spend a larger fraction of their time budget hiding from predators and predation is limited by biomass of prey in the system (bottom-up or donor control).

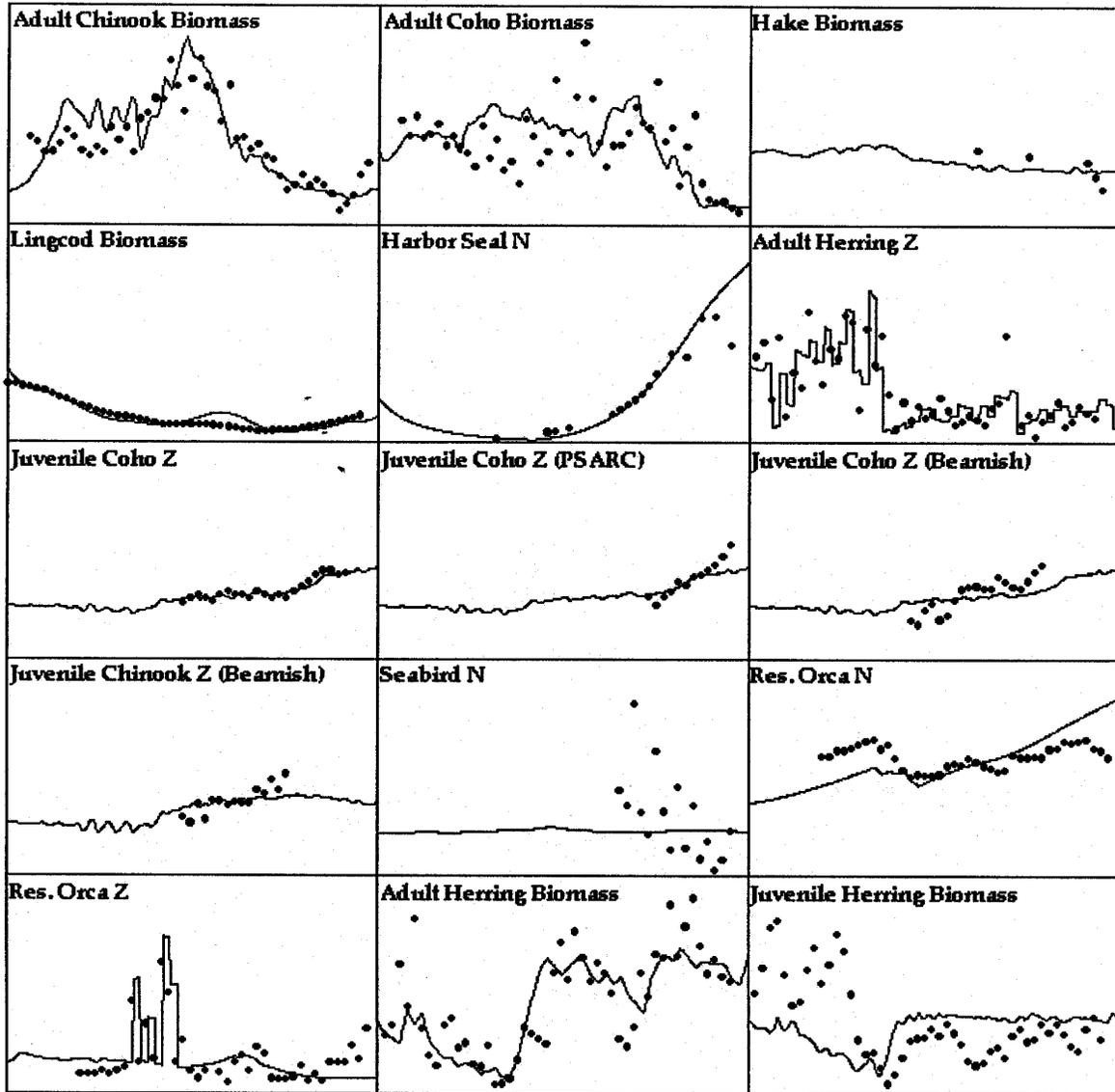
ECOSIM uses a Marquardt non-linear search algorithm with a trust region modification for each of the Marquardt steps to estimate relative forcing inputs and  $v_{ij}$ . To evaluate the differences between predicted and observed data, ECOSIM uses a log-least-squares criterion, which we refer to as SS fit to the data. We allow the search routine to estimate  $v_{ij}$  parameters and, when we assume there have been changes in relative primary production

over time, a relative forcing time series that is applied to the primary production. Estimating  $v_{ij}$  is equivalent to estimating observation errors in a single species stock assessment approach, and the relative changes in primary production is equivalent to estimating process errors.

### Changes in primary productivity

The observed time series data, shown as circles in Figures 1 and 2, are better explained when we assume that there have been substantial changes in primary productivity over the 50-year time series (also see Table 6). Under the constant primary production hypothesis the log sum of squares fit to the data was 115.87, and under a fluctuating primary production hypothesis the fit to the data was 75.24 (roughly a 35% reduction). The probability of this reduction in the SS by chance alone is 0.006, i.e. the observed data do suggest a change in primary productivity must have occurred. Under the constant primary production hypothesis, model biomass predictions generally agree with the observed data. However, it fails to capture recent observations in harbour seal abundance and southern resident killer whales. Marine survival rates for coho and chinook salmon have also declined through the 1990s, and a more parsimonious explanation is that there has been a severe decline in primary production starting around 1990 (Fig. 2).

The estimated changes in relative primary productivity are shown in Figure 3, and we compared this estimated index with other environmental correlates that are linked to primary production. We were unable to find any significant correlations between primary production and Fraser River discharge, wind speed, sea surface temperature, upwelling, or the Pacific Decadal Oscillation. However the overall downward trend in primary production is very similar to the downward trend observed in average wind speed squared (Fig. 4). The square of the wind speed is a measure of sheer stress between air and the water surface, which results in vertical mixing of the water column allowing entrainment of nutrients used in photosynthesis (Blackett, 1993). A similar downward trend is also observed in the Pacific Decadal Oscillation index (PDO).



**Fig. 1** Predicted and observed abundance and total mortality indices assuming the relative primary production has remained constant from 1950 to 1998.  $SS=115.87$ .

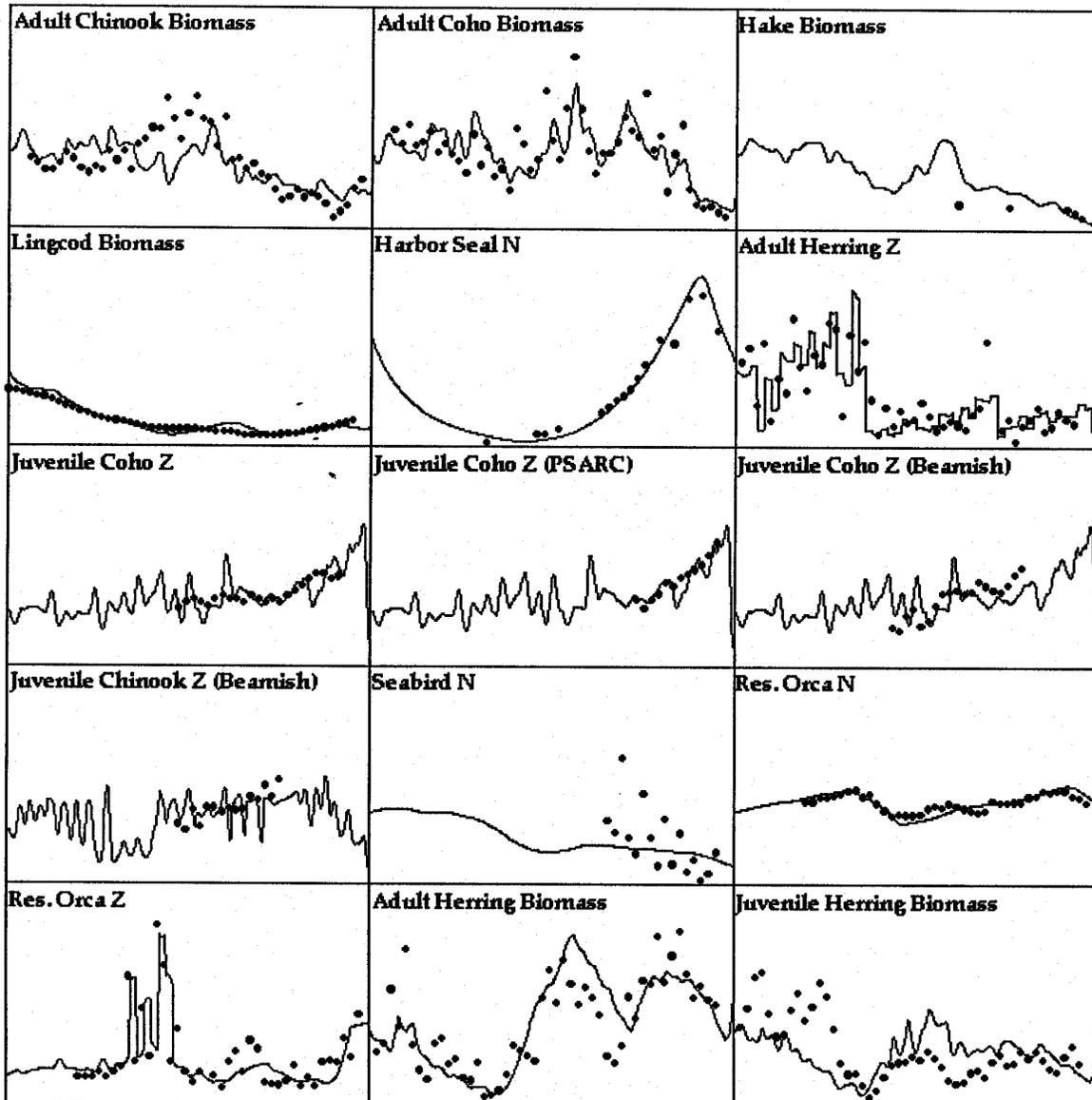


Fig. 2 Predicted and observed abundance and total mortality indices using relative primary productivity sequence shown in Figure 3. SS= 75.24.

**Table 6** Sum of square deviations (SS) between model predictions and observed data for biomass and mortality. *SS no model* is equivalent to fitting a straight line through the data, and *SS no environment* assumes constant primary production.

Data Type	<i>SS No Model</i>	<i>SS No Trophic Interactions</i>	<i>SS No Environment</i>	<i>SS all Effects</i>
Adult Chinook Biomass	13.43	26.61	12.89	6.33
Adult Coho Biomass	14.34	29.68	19.69	3.83
Hake Biomass	0.38	2.97	0.19	1.53
Lingcod Biomass	11.68	72.25	9.95	2.37
Harbour Seal N	15.31	2.09	1.08	1.74
Adult Herring Z	22.79	13.76	17.71	15.91
Juvenile Coho Z	0.47	0.44	0.33	0.62
Juvenile Coho Z (PSARC)	0.56	0.55	0.58	0.13
Juvenile Coho Z (Beamish)	1.57	1.54	1.3	1.12
Juvenile Chinook Z	0.47	0.47	0.59	0.67
Seabird N	10.82	10.75	10.95	9
Res. Orca N	0.37	0.61	1.03	0.18
Res. Orca Z	13.1	6.34	5.53	4.4
Adult Herring Biomass	24.81	103.42	9.14	7.33
Juvenile Herring Biomass	15.78	122.35	24.91	20.08
Total	145.88	393.83	115.87	75.24

## Discussion

The observed time series for 11 of the 15 data types (Table 6) suggest that large fluctuations in primary production must have occurred in the Strait of Georgia over the last 50 years. Declines in average wind speed, and the Pacific Decadal Oscillation index also support the decline in primary productivity hypothesis. Ideally, this study should include direct estimates of primary productivity over the entire Strait of Georgia; unfortunately, we were unable to find these data, if they exist. Nevertheless, it is clear, from our understanding of ecosystem dynamics that observed declines are better explained by assuming primary productivity has declined.

The fisheries stock assessment data used here were not made for the purposes of studying the role of climate effects on ecosystem dynamics. It is important to note that these data are limited in use,

as predictors of relative changes in primary productivity. Untangling the complicated trophic interactions, climate effects, and mortality patterns in ecosystem analysis is difficult; and direct observations on each of these processes will be required to improve our understanding of ecosystem dynamics. Many physical oceanographic studies have been completed, and currently in progress, in the Strait of Georgia. Incorporating these data into the analysis will greatly improve our understanding of ecosystem responses to changing physical environments. Probably one of the more difficult tasks, however, will be to study small-scale processes of changing trophic interactions that are related to spatial and temporal abundance of animals. Predator-prey interactions play a key role in determining optimal exploitation rates in that we need to understand how reducing the abundance of one species effects mortality rates for other species in an ecosystem with variable productivity.

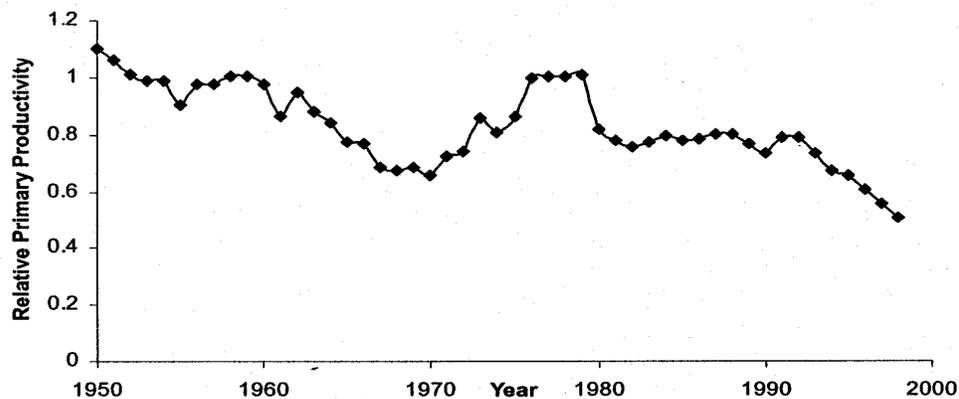


Fig. 3 Relative changes in primary productivity from 1950 to 1998.

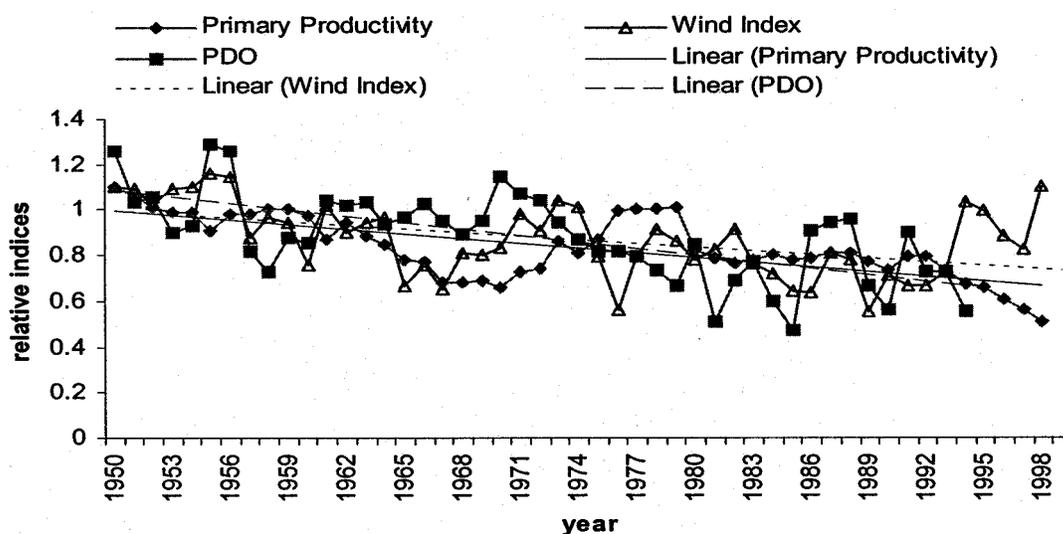


Fig. 4 Relative primary productivity, average annual wind speed squared in the Strait of Georgia (a measure of shear stress) and the Pacific Decadal Oscillation (PDO) from 1950 to 1998. Solid lines represent linear trends line for each index.

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## Preliminary mass-balance ECOPATH Model in the Bohai Sea

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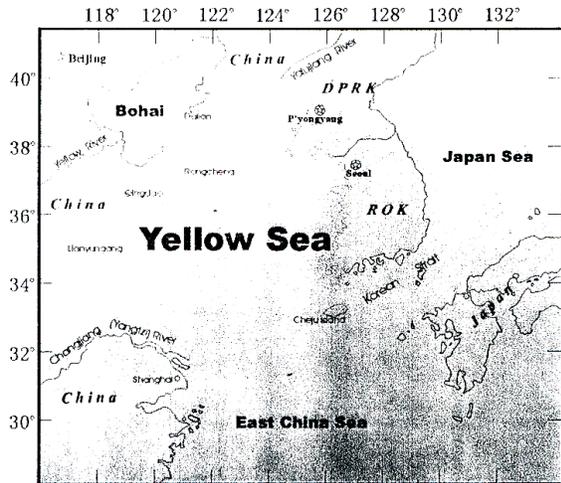
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### Introduction

The Bohai Sea (Fig. 5) is a semi-closed continental water of China, which is nearly encircled by land only with a mouth about 90 km at the eastern apex that connects it to the Yellow Sea. The Bohai Sea is located in the temperate water region between 37°00'~ 41°00'N with 77,000 km<sup>2</sup> in area and the average depth of 18.7 m and the maximum water depth of 70 m. Water temperature changes a lot resulting from the impact of the land climate. The highest SST is

26~30°C in September and the lowest one is 1.2~4°C in February. Much of the fresh waters run into the Bohai Sea from about 20 rivers, for example the Yellow River, Liao River, Raoyang River, Ling River, Luan River, and other rivers. The runoff of fresh water was 31.4 billion m<sup>3</sup> per year in the 1970s and half of it came from the Yellow River. The sea is an ocean space with distinct productivity, strong fishing activity and complicated relationship of food web, and is also polluted by industry and living sewage recently.



**Fig. 5** Bohai Sea region.

The Bohai Sea ecosystem depends on the amount of input of solar energy and the organisms imported from several rivers.  $\text{NO}_3\text{-N}$  and  $\text{PO}_4\text{-P}$  are basic nutrients supporting the primary productivity in the Bohai Sea. The production of organic carbon of the sea is  $112 \text{ gC/m}^2/\text{year}$ . The productivity, like other marine ecosystem, is characterized by seasonal and spatial variability with high levels in spring and fall and in the southern part of the sea, but not much change between years. In the Bohai Sea, the dominant small zooplankton are neritic brackishwater species, such as *Sagitta crassa* Tokioka, *Labidocera euchaeta* Giesbrecht and *Centropages memurricchi* Willey. The Bohai Sea small zooplankton biomass has two seasonal peaks, in June and September, and the biomass of other individual species has only one seasonal peak (Bai *et al.* 1991). The fishing effort in the sea has been increasing more and more since 1962, and has led to a significant variation in the abundance and distribution of the most species in the area. The intensive fishing resulted in the decrease of biomass of demersal species with high economic value (large predatory species), such as *Pseudosciaena polyactis* and *Trichiurus haumela*, while harvesting more of smaller pelagic species, such as *Setipinna taty* and *Engraulis japonicus*.

### Methodology and the ECOPATH model

The first ECOPATH model was developed to describe a coral reef ecosystem (Polovina 1984)

and was further developed by Christensen and Pauly (1992) at ICLARM to make it widely available as a well-documented software running on a microcomputer. Lately the ECOPATH model has been integrated with ECOSIM for dynamic simulation modeling based on a mass-balanced model by Walter, Christensen and Pauly (1997). In an ECOPATH model it is assumed that the ecosystem modeled is in steady state for each of the living groups, which implies that input equals output, i.e.  $Q = P + R + U$ , where  $Q$  is consumption,  $P$  - production,  $R$  - respiration, and  $U$  - unassimilated food. The above equation can be structured around a system of linear equations for expressing mass-balance with the simplest form. It can be expressed for an arbitrary time period and for each element  $i$  of an ecosystem by Equation 1 (see Martell *et al.* this report). It is the simultaneous linear equations used in ECOPATH to state that the production and consumption are balance within an ecosystem.

The ECOPATH model allows rapid construction and verification of mass-balance model of ecosystem. The mass-balance model not only verifies the previously published biomass estimates, but also identifies the biomass required for assessment of marine carrying capacity. Constructing an ECOPATH model includes the following steps:

1. Identification of the area and period for which the ecosystem model will be constructed;
2. Definition of all functional groups (boxes), from primary producers to top predators, in the ecosystem to be included for the thermodynamic balance;
3. Setting parameters of production/biomass ratio ( $P/B$ ), consumption/biomass ratio ( $Q/B$ ), biomass ( $B$ ) and ecotrophic efficiency ( $EE$ ) for each function group, but only three of them are necessary as the basic input parameters in the model, and also entry of the catches to every fishing species;
4. Entry of a diet consumption matrix ( $DC$ ) expressing the diet fraction of predator/prey relationship in the model;
5. Modify the entries of  $P/B$ ,  $Q/B$ ,  $EE$  or the biomass, to balance the ECOPATH model (repeating steps (3) and (4) above) until the mass input equals output for each box.

## Structure of the Bohai Sea ECOPATH model

The resources composition in the Bohai Sea changed a lot along with the fishing effort increase to multi-species fish communities after 1962. The CPUE (catch per horse power) was 7.61 tons in 1962, but it went down to 0.88 ton in 1983. The traditional species fished in the area, such as small yellow croaker, slender shad, cutlassfish, were high valuable in the market, but the biomass of them declined then. The small pelagic fish and small crustacean species appeared more in the landings and fluctuated much more annually. The highest annual landing of *Acetes* (a sergestid shrimp) can be 100 hundred metric tons (1.3 t/km<sup>2</sup>) in the sea. The highest catch of jellyfish reached 280 hundred tons during the 1970s. This reflects a gradual transition in catch from long-lived, high trophic level piscivorous bottom species toward short-lived, low trophic level invertebrates and planktivorous pelagic species. The Bohai Sea is an example of an overfished marine ecosystem leading to smaller, high-turn-over species. It is a peculiarity of the sea that small pelagic fish and jellyfish replace large table fish in an over-exploited ecosystem (Pitcher 1998).

The mass-balance model of the Bohai Sea is aimed at constructing a quantitative description of trophic structure and the relationship among the different groups in the whole Bohai Sea. The model is based on the data of the Bohai Sea ecosystem survey project completed during April 1982 to May 1983. The project collected the data monthly by the bottom trawling and mainly made assessment of the commercial important species and their biological characteristics study. As this is the first ECOPATH model of the Bohai Sea, it only presents a preliminary revelation of the trophic structure and flow in the sea between different functional groups. The functional groups in the model covered the main trophic flows among the living marine species and detritus, but the group definition is very rough because of the limited type of survey data available in the region. The functional group determination is based on the species distribution in the water and their feeding behaviour after inspecting the stomach contents of 54 species from 1863 samples. Considering the

limited data and no existing mass-balance model in the Bohai Sea, the model only has 13 function groups.

One primary producer of phytoplankton was identified. Zooplankton was split into two groups, microzooplankton and macrozooplankton. The former includes small herbivorous and carnivorous zooplankton and the latter mainly consists of jellyfish and *Acetes*. Benthic invertebrates were divided into small mollusca, large mollusca, small crustacean and large crustacean, most species of which were commercial harvest in the sea but the landing data were not readily available. There were no biomass data for some species in the small invertebrate groups so their biomass were estimated by the model using the fixed ecotrophic efficiency (EE=0.95). Biomass for the two large groups were obtained by summing up the biomass data from the survey. Five fish function groups were identified in the model on the basis of 31 fish species which hold about 90% of total biomass for the fish community in the Bohai Sea. The herbivorous feeders group includes mainly *Mugil cephalus* and *Liza haematocheila*. The other four groups were small pelagic fish, demersal fish, benthic feeders and top pelagic feeders, which were important commercial fishing targets. The details of 13 function groups (box) in the Bohai Sea ECOPATH model are summarized in Table 7. Many species are included in one box of the model so it is hard to find P/B and Q/B from one species for the whole group. The P/B and Q/B parameters were based on the parameters from similar function groups in the models of the Strait of Georgia (Dalsgaard 1998), the Brunei Darussalam, South China Sea (Silvestre 1993) and the Georges Bank (Sissenwine 1984).

The basic parameters of biomass (wet weight t/km<sup>2</sup>), P/B, Q/B, EE and harvest for the 1982-83 ECOPATH model of the Bohai Sea ecosystem are presented in Table 8. Detritus is estimated from primary production of carbon by equation A5 of the empirical relationship method (Pauly, D., M.L.Soriano-Bartz *et al.* 1993). Phytoplankton was estimated from Bohai Sea primary productivity of 112 gC/m<sup>2</sup>/year converted to g wet weight phytoplankton m<sup>-2</sup>year<sup>-1</sup> by a wet weight:carbon ratio of 10:1.

**Table 7** Functional groups in the model.

1. Microzooplankton	2. Macrozooplankton
3. Small mollusca	4. Large mollusca
5. Small crustacea	6. Large crustacea
7. Herbivorous feeders	8. Small pelagic fish
9. Demersal fish	10. Benthic feeders
11. Top pelagic feeders	12. Phytoplankton
13. Detritus	

## Results and discussion

To balance import to and export out from every box, the EE values are leading check parameters for equilibration of a model when running the ECOPATH 3.0 software. The EE value should be between 0 and 1. Here, a value of 0 indicates that the group is not consumed by any other groups in the system, nor is it exported. Conversely, a value near or equal to 1 indicates that the group is being heavily preyed or fished, leaving no individuals to die of old age. Some of the original biomass inputs from the Bohai Sea trawling survey in 1982-83 are considered too low, and as a result equilibrium cannot be reached in the model with the high value of EE. This is because the survey data connecting commercial species from bottom trawling and the function groups in the model cover a wide range of living marine species. According to the results obtained by different resource assessment methods (Fig. 7.5; Laevatsu

and Alverson 1996), biomass value estimated by bottom trawling survey is much lower than the ones from other stock assessment methods. It is necessary to modify the biomass data to equilibrate the model. The biomass of small pelagic fish group is estimated from 1.2 to 2.14 ton/km<sup>2</sup>, and the benthic fish group from 0.32 to 0.68 ton/km<sup>2</sup>.

The model estimated the biomass density of commercially utilized species to be at 12.33 ton/km<sup>2</sup> and the density of all fish species at only 4.4 ton/km<sup>2</sup>. A flow chart showing trophic interactions and energy flow in the Bohai Sea is presented in Figure 6. It shows the estimated trophic level of the 13 functional groups and the relative amounts of energy that flow in and out of each box. The trophic flow to detritus, respiration and catch are also represented. Two food paths, a plankton path and a benthic path, are shown, which are the food webs characteristic of the Bohai Sea. The lower trophic level groups have a strong influence on the Bohai Sea ecosystem. High fishing effort leads to decline of high value living marine resources, which can be seen by the negative impacts to the ecosystem from fishery.

No common information is available for the biomass comparison with other ECOPATH models in the Bohai Sea. The values in our model are low compared with densities in other ecosystems, such as the Caribbean coral reef and

**Table 8** Parameter estimation for the group from the mass-balance model of the Bohai Sea. Values in brackets were calculated by the ECOPATH program, and dashes mean no entry.

Group	Catch (t/km <sup>2</sup> )	Biomass (t/km <sup>2</sup> )	P/B (year)	Q/B (year)	EE
Microzooplankton	-	4.40	36.0	186.0	(0.961)
Macrozooplankton	1.40	2.80	3.00	12.0	(0.964)
Small mollusca	0.78	(2.76)	6.85	27.4	0.950
Large mollusca	1.50	0.24	2.00	7.0	(0.890)
Small crustacea	0.20	(2.01)	8.00	30.0	0.950
Large crustacea	0.20	0.37	1.50	11.60	(0.823)
Herbivorous feeders	0.10	0.56	3.00	15.0	(0.903)
Small pelagic fish	0.50	2.14	2.37	7.9	(0.927)
Demersal fish	0.22	0.62	2.10	8.7	(0.808)
Benthic feeders	0.10	0.68	0.80	4.6	(0.902)
Top pelagic feeders	0.15	0.59	0.46	4.1	(0.553)
Phytoplankton	-	15.70	71.20	-	(0.457)
Detritus	-	43.00	-	-	(0.386)

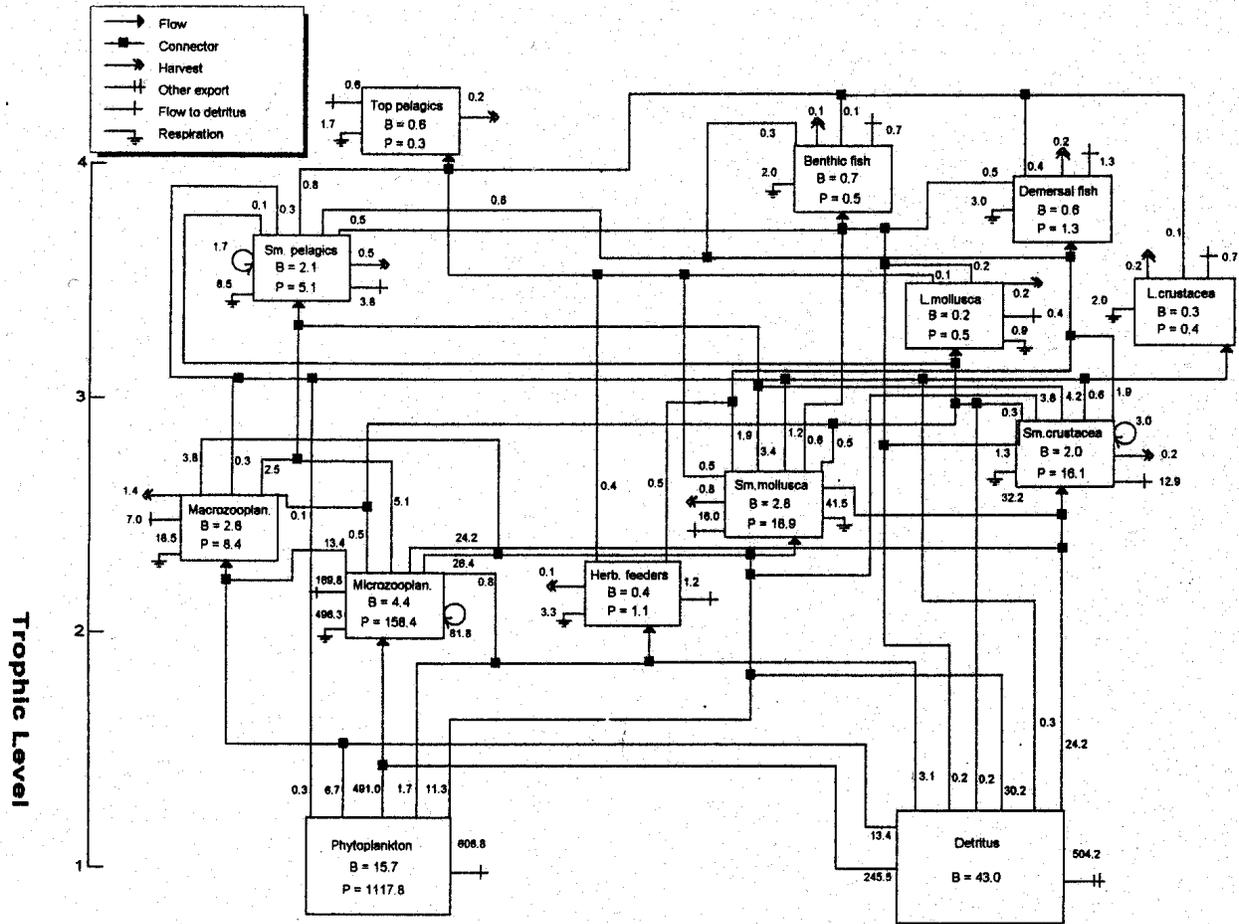


Fig. 6 Flow chart of trophic interactions in the Bohai Sea ECOPATH model.

the southern B.C. shelf, but it is higher than that reported in other models of the Bohai Sea. The output from the ECOPATH model looks more reasonable. We conclude that the total biomass of commercially fished species in the sea is 950,000 t and 338,000 t are fish species of value.

Ecosystem statistic and trophic flow of the Bohai Sea ecosystem model (1982-1983) could be considered as reasonable value, but some problem concerned with the input data have to be taken into account. First the function groups should be split further to estimate more precisely input parameters, like P/B and Q/B, for each box. Then the diet data for some species is also needed to be modified slightly to let all EEs be reasonable. Thirdly, it is better to consider the habitat for different species in the ECOPATH model developed in the future.

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## **Ecosystem modeling, monitoring, and Japanese studies relevant to the Western Subarctic Gyre and Kuroshio-Oyashio transition zone ecosystems**

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Current Japanese programs on ecosystem studies in the oceanic waters of the northern North Pacific have been carried out mainly by Hokkaido University (HU- Faculty of Fisheries) and Fisheries Research Institutes belonging to the Fisheries Agency of Japan (FAJ). The Western Subarctic Gyre (WSAG) and the Kuroshio-Oyashio Transition Zone (TZ) are of major

interests to Japan because of the fisheries resources available there. For example, Wada *et al.* (1998) adapted a trophodynamics model to sardine and walleye pollock populations in the Oyashio Current Region using STELLA-II software. Modeling of the entire ecosystem for WSAG and TZ, however, has not been established.

Aydin (this workshop) raised four discussion points on WSAG ecosystem study: (1) the appropriate boundaries and species groupings of the model; (2) the issues involved with scaling seasonal models of lower trophic levels up to a model with an annual time scale; (3) sources for data and parameterization methods, and (4) the appropriate methods for the inclusion of highly migratory species, specifically Pacific salmon (*Oncorhynchus* spp.) and marine mammals. These are also true for TZ.

In this report I will briefly introduce ecosystem study projects, monitoring activities and major published reports relevant to this workshop. BIOCOSMOS results are summarized in Oozeki (2000).

### **Recent ecosystem projects**

HUBEC (Hokkaido University SuBArctic Ecosystem dynamics and Climate) is a research program organized by oceanographers and fisheries scientists in the Faculty of Fisheries to address the question of how climate change and dynamics may affect the abundance and production of animals in the sea.

ORI-GLOBEC is a project established by the Ocean Research Institute, University of Tokyo, to study response of plankton, micronekton and fish population to climate regime-shift in the Kuroshio-Oyashio region. Progress of ORI-GLOBEC and HUBEC by 1998 was reported in Terasaki *et al.* (1999), where ecosystem-physical modeling of a warm-core ring was presented.

VENFISH (Variation of the oceanic ENvironment and FISH populations in the northwestern Pacific) is a comprehensive study supported by the Tohoku National Fisheries Research Institute (TNFRI-FAJ) and Hokkaido National Fisheries Research Institute (HNFRI-FAJ), etc. in 1997-2002. Study components are:

- Development of a forecasting method for the variation of phytoplankton biomass;
- Development of a forecasting method for the variation of zooplankton biomass;
- Observation and modelling of the variation of resources abundance of saury and Alaska pollock;

- Clarification of response of saury and pollock to the oceanic environmental variation; and
- Development of the forecasting ecosystem model for saury and Alaska pollock abundance (including population dynamics and trophodynamics models).

Only bottom-up processes from physical forcing to saury and pollock populations are considered. Predations on saury and pollock and competition among each trophic level will be treated in the next stage of the project.

High Trophic Ecosystem (1999-200?) is a consecutive project of VENTFISH organized by the National Research Institute of Far Seas Fisheries (NRIFSF-FAJ). Study components:

- Monitoring distribution and abundance of species with driftnet and midwater trawl;
- Stomach content analysis of small cetaceans, sea birds, albacore, skipjack, sharks and squids;
- Trophic level analysis with stable isotope techniques;
- Energetic demand estimation of large predators;
- Input of results on dynamics of lower trophic level ecosystem from VENTFISH project; and
- Ecosystem modeling.

### **Monitoring data**

- HU: Oceanography and driftnet surveys along 155°E, 170°E, 175°E, etc., from 1979-present;
- TNFRI: Oceanography, primary production, zooplankton, driftnet surveys, etc.;
- HNFRI: Oceanography and driftnet surveys along 165°E;
- Other routine observations by FAJ, prefectural governments, etc.

### **Discussion points**

#### ***Boundaries and species groupings of the model***

From oceanographic features, WSAG and TZ have been treated separately. From biological point of view, however, the two ecosystems are interdependent. Small pelagics, squids and predatory animals (sharks, salmon, tunas, birds, marine mammals) migrate across the Subarctic

Front (the boundary between WSAG and TZ) although this front acts as a barrier or a selective filter for some species or species size. Some species such as Pacific salmon migrate in an east-west direction, e.g. between WSAG and the Okhotsk Sea. Minor species components with similar ecological features may be grouped. On the contrary, size (or biologically) segregated migration as in Pacific pomfret may be treated separately.

### ***Scaling seasonal models of lower trophic levels up to a model with an annual time scale***

Because of seasonality in primary production and migrations of zooplankton, nekton, mammals and seabirds, models must be constructed season by season at a first step, then to be combined to include interannual variability. A general problem is the availability of data other than in summer. Seasonal and vertical variations in zooplankton biomass have been monitored in Kuroshio, Oyashio and TZ. Modeling effort of Oyashio region including the effect of the vertical migration of *Calanus/Neocalanus* spp. has been continued by the MODEL Task Team and Hokkaido University's group (see PICES Sci. Report 15: 1-77, 137-139; Kishi *et al.* 2000).

### ***Sources for data and parameterization methods***

Primary and secondary productions have been studied primarily by HUBEC and VENFISH. Biomass estimations are obtained from the routine stock assessment for commercially important species (sardine, mackerel, common squid, etc.). For other species, driftnet and midwater trawl surveys would be useful. Russian surveys are of course important in this aspect (e.g., Shuntov *et al.* 1996). Estimations for production and consumption rates need to be thoroughly examined, since transfer efficiencies from primary production to zooplankton and from zooplankton to fishes in Oyashio were different from those in California Current (Wada *et al.* 1998).

### ***Methods for the inclusion of highly migratory species***

This is the notorious problem that needs monitoring for all seasons. Monitoring activities

have been concentrated in summer season, although some information on seasonal migration of predatory animals is available.

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## BASS Workshop recommendations

As the PICES CCCC Program enters its synthesis phase, modelling will play a more prominent role in CCCC activity. Participants recommended the BASS and MODEL Task Teams to convene a joint workshop to examine the feasibility of using the ECOPATH/ ECOSYSTEM modelling approach as a means to organize our understanding of the marine ecosystems of the subarctic gyres. Specific objectives include to: (a) synthesize all trophic level data in a common format; (b) examine trophic relations in both gyres using ECOPATH/ ECOSIM/ECOSPAC; and (c) examine methods of incorporating the PICES NEMURO lower trophic level model into the analysis.

Participants recommended that collaboration and synthesis of the data into a common format take place prior to the workshop. G. McFarlane will co-ordinate this issue for North America and A. Krovnin and A. Yatsu for Asia. K. Aydin will synthesize the data into the ECOPATH format. If possible, the workshop should be held in conjunction with the PICES Census of Marine Life Workshop to be held March 7-9, 2001, in Honolulu. Locating the venue in Hawaii at this time is seen as a cost-effective way to involve workshop participants from both sides of the Pacific and would lead to a more balanced scientific representation from the nations of the North Pacific.

## BASS Endnote 1

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