National Marine Fisheries Service

Report of the National Ecosystem Modeling Workshop (NEMoW)

H. M. Townsend, J. S. Link, K. E. Osgood, T. Gedamke, G. M. Watters,
J. J. Polovina, P. S. Levin, N. Cyr, and K. Y. Aydin (editors)

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

NOAA Technical Memorandum NMFS-F/SPO-87
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U.S. Department of Commerce
Carlos M. Gutiérrez, Secretary

National Oceanic and Atmospheric Administration
Vice Admiral Conrad C. Lautenbacher, Jr., USN (Ret.)
Under Secretary for Oceans and Atmosphere

National Marine Fisheries Service
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Executive Summary

The NMFS held a National Ecosystem Modeling Workshop (NEMoW) in Santa Cruz, CA on August 29-31, 2007. NEMoW was held as a national workshop analogous to National Stock Assessment Workshops and National Economists Meetings for the purpose of exploring the establishment of EM (shorthand for ecosystem modeling; including a wide range of biophysical, multispecies and ecosystem modeling) standards of use and review for living marine resource management applications. There were 39 participants and 6 observers.

NEMoW was established in response to several observed and perceived needs to more formally review, evaluate, and project the EM efforts of NMFS.

The feedback on the meeting was categorically positive. The benefits of being aware of and transferring best practices among Centers was universal and high.

There was recognition that there is a copious amount of NMFS-wide EM work, an observation not to be overlooked. Often this work is done on an *ad hoc*, individual, or crisis basis, which makes the scope and extent of existing NMFS EM efforts all the more impressive.

Given the expressed interest by a plethora of our stakeholders relayed at the workshop, it was observed that EM efforts should continue or be expanded. A wide range of issues was identified as common and historically important. From these, we identified an extensive set of generic EM objectives and model classes that are widely applicable across NMFS. We also note that addressing these objectives merit or in many cases require an EM approach. It was clear that these more holistic, broader EM issues will persist into the foreseeable future.

This report provides some recommendations for future National EM efforts in NMFS. Three major recommendations are suggestions to: 1) routinely hold NEMoWs, 2) more formally increase EM efforts at each Center, 3) and establish living marine resource EM standards and guidelines. There are altogether 11 proposed recommendations.

Another key conclusion from the workshop was that no one model should be exclusively adopted or avoided. We noted that although feasible, it may not be necessary to establish an EM toolbox. The observation was that doing so might stifle innovation and locally adapted applications of these models. More germane, many of the EM tools, software, etc. are already being exchanged among NMFS ecosystem modelers, but efforts to facilitate these exchanges more efficiently should continue or expand. The workshop recognized the need to identify best practices for EM without becoming too prescriptive.

The broader context of ecosystem considerations in the NMFS was also discussed. Given several forthcoming initiatives and copious calls for ecosystem based management, NEMoW was quite timely. Given the demographic of NEMoW participants and the congruence of a wide range of living marine resource ecosystem considerations, NMFS appears to be in a favorable position as the need to apply EM to key living marine resource issues continues. Certainly the development of expertise and technical capacity is still needed, as is increased engagement of external (to NMFS) partners, but there is a reasonably established foundation for NMFS to build upon for future EM efforts.

Acknowledgements

On behalf of the NEMoW Steering Committee and all NEMoW attendees, we thank the local hosts of the workshop. We acknowledge Churchill Grimes and SWFSC Santa Cruz Laboratory for providing access to their facilities. We graciously thank Jackie Davis and Steve Miller who went above and beyond the call of duty in handling local arrangements, workshop logistics, and meeting support.

We particularly thank George Watters for his myriad dedicated efforts at making this meeting run so smoothly.

We also acknowledge our external observers. There were five foreign EM experts— Eva Plaganyi-Lloyd, Beth Fulton, Alida Bundy, Bjarte Bogstad, and Villy Christensen—who provided their expertise, wisdom and observations to keep us from having a myopic view of our own work. We also acknowledge Mike Uhart of OAR and Marc Mangel of UC Santa Cruz for their observations.

Finally, we thank the NMFS Science Board for their enthusiastic support of this workshop.

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Introduction, Context and Background

The NMFS held a National Ecosystem Modeling Workshop (NEMoW) in Santa Cruz, CA on August 29-31, 2007. There were 39 participants and 6 observers.

NEMoW was designed as a NMFS-wide, national workshop to examine NMFS ecosystem, bio-physical and multispecies modeling approaches. NEMoW was held as a national workshop analogous to National Stock Assessment Workshops and National Economists Meetings for the purpose of exploring the establishment of ecosystem modeling standards of use and review for living marine resource management applications.

Here we define ecosystem modeling (EM) as shorthand for ecosystem modeling; including a wide range of biophysical, multispecies and ecosystem modeling. A more thorough description is given in the keynote address of the many possible model classes that could be considered.

NEMoW was established in response to several observed and forthcoming needs to more formally review, evaluate, and project the EM efforts of NMFS. NEMoW was responsive to a wide range of calls for ecosystem approaches to management (EAM) or ecosystem approaches to fisheries (EAF) and similar endeavors. Topics such as the recent US and Pew Commission reports on oceans, the forthcoming need for Integrated Ecosystem Assessments (IEAs), and several related initiatives (e.g. CAMEO) as well as continued controversies among stakeholders for tradeoffs among living marine resource species (LMRs) all highlight the centrality of ecosystem modeling efforts.

NEMoW was intended to be for NMFS ecosystem modelers by NMFS ecosystem modelers, with a heavy emphasis on state of the art descriptions and what practitioners were encountering- both in terms of success stories and trouble areas to avoid. We invited a limited number of foreign observers and other external observers with expertise or interest in EM. We solicited their input to ensure we did not persist in any agency myopia on the topic.

The emphasis at NEMoW was very much on active participation and discussion, particularly in breakout groups. Presentations were kept to a minimum with the goal of engendering discussion and exchange of ideas across the NMFS Centers and Offices.

One of the questions that came up early on in the workshop planning was why have a NEMoW? Very simply, there have been only limited and *ad hoc* efforts to provide a standardized approach for EM models. There are an increasing number of EM applications and uses. As such, many NMFS EM practitioners wanted to have a more formal examination of our EM efforts. In particular, we wanted to more formally examine:

- software packages
- recommendations for use
- parameterization protocols
- validation protocols
- data requirements
- verification of model results;

so that as further EM approaches are developed and used in LMR management, we as practitioners and more generally NOAA Fisheries will have a higher degree of confidence in EM output and use.

NEMoW was initially conceived as a proposal to NMFS Science Board, which was enthusiastically supported. Given the plethora of initiatives and efforts in this area, *both within the fisheries sector and* *across multiple sectors* (and across multiple Line Offices and NMFS partners), this NEMoW was very timely and highly germane to LMR issues facing the nation's oceans.

A national steering committee was formed (Appendix D) approximately 9 months before the workshop. That steering committee established five Terms of Reference for the NEMoW to address. In our view, a principal outcome were recommendations for further EM use, review, and efforts by the NMFS. At the NEMoW it was emphasized that the main workshop product, this report, must contain suggestions and guidance for future NMFS EM activities. All NEMoW participants wholeheartedly agreed to support the development of this product and its contents.

In this document we provide short descriptions of major ecosystem models, a series of descriptions of EM efforts from each Center, a set of NEMoW recommendations for future NMFS EM efforts, and some supporting information.

These recommendations should be viewed as just that—recommendations. The NMFS ecosystem modeling community recognizes that there are myriad other considerations when deciding when and how to implement recommendations such as these in an agency as large and diverse as NMFS. We trust that by providing these recommendations, we have satisfactorily addressed all of the NEMoW Terms of Reference and have provided useful material for consideration as we continue to collectively develop EM efforts of the agency in years to come.

Terms of Reference for the National Ecosystem Modeling Workshop

Objectives: NMFS will organize and hold a national ecosystem modeling workshop with the following objectives:

1. Identify the main classes of ecosystem, bio-physical and multispecies models used, planned, or needed within NMFS, including:
    - the main objectives of these models
    - basic data requirements
    - when and how to use them relative to their objectives
    - pros and cons of each
2. Compare modeling approaches and methods across the NMFS science centers
3. Evaluate various available modeling software packages and determine the feasibility of establishing a national ecosystem modeling toolbox
4. Recommend further steps (e.g. National EM Standards, EM Model Review Criteria, further engagement of the external modeling community) to advance ecosystem modeling within NMFS.
5. Prepare a report on the above, to be delivered to the NMFS Science Board within six months of the workshop.

National Ecosystem Modeling Workshop (NEMoW)
August 29-31 2007
NMFS Santa Cruz Laboratory
Agenda

29-Aug-07		Topic
830	Welcome & Orientation	
840	Overview, Objectives & Goals	Workshop Purpose & Rationale
900	The role of EM in NOAA-NMFS	NMFS Context and Forthcoming EM Issues
930	Keynote Speaker	Review of Major Model Classes
1030	Coffee Break	
1100		Discussion of Major Objectives & Uses
1200	Lunch	
1300	Break-out Groups	Discuss Model Classification
1400		Report back to plenary Discussion of Model Types as mapped to objectives
1530	Coffee Break	
1600	Break-out Groups	*Overriding Workshop Theme*: Gauge Feasibility of Nat'l EM Standards of use & EM Review Criteria
1700		Report back to plenary & Wrap up
~1730	Adjourn	

30-Aug-07		A ***BRIEF*** summary of the EM efforts and approaches at each Center: maybe multi-authored, but 1 presenter
830	PIFSC	Each SC to provide a short write-up of this before the workshop
845	AFSC	
900	NWFSC	
915	SWFSC	
930	SEFSC	
945	NCBO	
1000	NEFSC	
1030	Coffee Break	
1100		Discussion of Common, Generic Data Needs (diet, surveys, bycatch, etc.)
1200	Lunch	
1300	Break-out Groups	Discuss data requirements, pros & cons of each model type, experiences
1400		Report back to plenary Discussion of pros and cons of each model type & data needs for each (Model & Center)
1530	Coffee Break	
1600	Break-out Groups	Discuss when and how to use each of the models
1700		Report back to plenary & Wrap up
~1730	Adjourn	

31-Aug-07	Model Classes	Examples of specific models- highlights, pros, cons, etc.- given by groups of NMFS users from multiple regions
830	MS	MSVPA
845	MS	MSPROD
900	MS	Gadget
915	Food Web	Ecopath & other Energy Budgets
930	Food Web	Ecosim
945	Biophysical	Water Quality-Habitat
1000	Biophysical	Coupled NPZ-Fish
1015	Biophysical	SEAPODYM+
1030	Coffee Break	
1100	Ecosystem	ATLANTIS
1115	MRMs	Extended SS & MRMs
1130		Discussion of Specific Model Types
1200	Lunch	
1300	Break-out Groups	Discuss Model Software & Development Issues Discuss tips, tricks, etc. & consider feasibility of Nat'l EM toolbox
1400		Report back to plenary
1430		Discussion of Nat'l EM Standards of use, EM Review Criteria
1530		Coffee Break
1600		Discussion of Nat'l EM Standards of use, EM Review Criteria Discussion of Next Steps
~1730	Adjourn	

Editor's note- the final schedule noted above was largely adhered to, with minor adjustments to account for the inevitable logistical changes as the meeting progressed. Since some flexibility was built into the schedule and since the few changes were minor in nature, we do not attempt to recreate the actual, realized schedule of the workshop.

Abstract of Keynote Address

Review of Major Model Classes

Éva Plagányi
Dept. of Maths and Applied Maths, University of Cape Town, South Africa

A brief description will be provided of the various modelling approaches currently available for assessing the impacts of ecological (indirect) interactions between species and fisheries and their implications for marine fisheries management. The different models and their categorization are described in Plagányi (2007). A brief overview is provided of 26 modelling approaches currently in existence, highlighting in particular features of these models which have general relevance to the field of an Ecosystem Approaches to Fisheries (EAF).

Whole ecosystem models attempt to represent all trophic levels in an ecosystem in a balanced way. In contrast, models which represent only a subset of the ecosystem and are thus restricted to represent a limited number of species that are most likely to have important interactions with a target species of interest are termed Minimally Realistic Models. Models that focus on inter-species interactions only are termed Dynamic multi-species models. In contrast, Dynamic system models incorporate the environment and lower trophic levels, although this is often at the expense of not representing the higher trophic levels in sufficient detail (when considered in a fisheries management context). ESAM (Extended Single-species Assessment Models) are those that expand on current single-species assessment models taking only a few additional interactions into account. In classifying models further, it was noted it is important to differentiate between models that take age structure and spatial aspects into account.

In terms of the uses of ecosystem models, it should be noted that there is a continuum of model categories but that these could broadly be categorized as either i) conceptual models aimed at developing understanding of ecosystem processes, or models for ii) strategic and iii) short-term tactical management. It is likely that strategical modelling will mainly be used to inform and evaluate the ecosystem approach to fisheries, with use in tactical decisions rare.

Faced with incomplete knowledge of ecosystem functioning, there has been increasing recognition that definitive conclusions cannot be drawn from a single model structure. There has thus been a parallel increase in efforts to modularize models so that different components can be easily substituted. Spatial considerations are similarly playing an increasingly important role in the development of ecosystem modelling approaches. Other major areas of current research include investigations on the effect of specific formulations (specifically feeding functional responses) on model outputs, the treatment of uncertainty, representation of socio-economic factors and human behavioural drivers, multiple sector dynamics and management and the representation of biodiversity.

A set of commonly asked questions pertaining to EAF is identified, followed by an overview of best practices in developing ecosystem models for informing an EAF, based on the outcomes of a recent FAO workshop (Tivoli, Italy 3-6 July 2007) on Modelling ecosystem interactions for informing an EAF: Best practices in ecosystem modelling. The guidelines are not benchmarks but rather are an achievable set of practices that should guide thinking as to the importance of different model attributes and suggested approaches for handling each of these. The Management Strategy Evaluation [MSE] (or analogously Management Procedure [MP]) approach has been identified as best practice in ecosystem modelling because of its focus on the identification and modelling of uncertainties, as well as through balancing different resource dynamics representations and associated trophic dependencies and interactions. A summary is provided of the current state with regard to both development and application of multi-species or ecosystem MSE approaches.

Plagányi, É.E. 2007. Models for an Ecosystem Approach to Fisheries. FAO Fisheries Technical Paper No. 477. Rome, FAO. 2007. 108p. ISBN 978-92-5-105734-6.

Model Description Abstracts

Each Group of NMFS Ecosystem Modelers was asked to provide a short description of major ecosystem models being used in NMFS. The objective was to provide a background on the models across Centers where possible.
Each group of modeling experts was asked to address the following questions:

What is/has/will the model be used for?
What are the data requirements?
What key data gaps have been identified?
Are these data gaps informing monitoring efforts?
What are the key features/equations/functions/assumptions of the model?
What are the strengths of this model?
What are the weaknesses of this model?
Has the model been published in the peer reviewed literature?
Has the model and software been through a formal peer review?
Have the model outputs been through a formal peer review?
How portable is the model software package?
What remains for model development/improvement/enhancement?
Has/is/will the model outputs be used in LMR management?

Although not all models are used by all Centers, or if it is not every Center perspective was able to be incorporated in these presentations and summaries. Although not every one of the questions noted above was always fully answered, this summary represents some common experiences and considerations when using these types of models. The presentation on the GADGET modeling effort was the only one not fully being used by NMFS personnel.
This collection of EM summaries addresses TOR # 1 and helps to address TOR #s 2-3.

MSVPA Approaches

Lance Garrison, Jim Ianelli, Jason Link

The Multispecies Virtual Population Analysis (MSVPA) approach was developed within ICES as a multispecies extension of cohort analysis. The approach can be viewed essentially as a series of single-species virtual population analysis (SSVPA) models that are linked by a simple feeding model to calculate natural mortality rates. The system of linked single-species models is run iteratively until the predation mortality rates (M2s) converge. The basic model is performed in two primary iteration loops. First, all single-species VPAs are run to calculate population size at all ages for predators and prey, then predation mortality rates are calculated for all age classes of each species based upon the simple feeding model. The single-species VPAs are run again using the calculated M2 rates, and this iteration is repeated until convergence. The MSVPA approach, and the associated forecast model MSFOR, has been applied by the ICES multispecies working group for the North Sea ecosystem. It has since been applied to several other systems including the Georges Bank/Gulf of Maine, the Baltic Sea, and the eastern Bering Sea fish communities. The standard MSVPA approach has recently been modified and expanded with two different approaches and applications to fish communities in the U.S.

The standard MSVPA approach was expanded and applied to the coastal fish community of the mid-Atlantic U.S. with a focus on estimating predation mortality on Atlantic menhaden. This approach, termed MSVPA-X, built upon the framework of the standard MSVPA by incorporating a variety of SSVPA approaches including tuned VPAs, modifying the underlying consumption model, introducing a weak Type III functional feeding response, formalizing the derivation of selectivity parameters from diet data, altering the size-selectivity model, and including predators without age-structured assessment data. The model also includes a forecasting component that allows the exploration of multispecies population trajectories under a range of management scenarios and assumptions about future recruitment. The initial development was supported by the Atlantic States Marine Fisheries Commission, and the application to Atlantic menhaden and its coastal predators (bluefish, weakfish, and striped bass) recently underwent formalized peer-review by the NEFSC's Stock Assessment Review Committee. The MSVPA-X approach is also currently being applied in the Gulf of Maine – Georges Bank fish community to estimated predation mortality rates for both younger age-classes of exploited groundfish stocks and pelagic prey species such as herrings and mackerels.

The Alaska Fisheries Science Center has also worked extensively with the MSVPA approach and developed applications to the eastern Bering Sea fish community. This model and its output have been incorporated into the process of evaluating multispecies management decisions for this community. Recent advances include the integration of statistical catch-at-age models into the basic MSVPA approach. The model is constructed as a state-space, non-linear estimation framework that allows specification of alternative model forms. This approach both allows for incomplete information and the ability to better evaluate available data and represent uncertainty. Research is continuing on this approach to increase the flexibility to model alternative functional responses and change the way diet composition data are treated.

The primary outcomes of MSVPA approaches are quantification of predator-prey interactions and variation in predation mortality rates. These approaches require age-structured catch and assessment data along with information on predator diets, consumption rates, and growth. In addition, biomass estimates for lower trophic level prey are important inputs to adequately model predator diets. Thus, the data demands for implementing these approaches are significant. However, the MSVPA approach uses similar catch and biological data to single-species assessments and results in directly comparable measures of mortality rates, population size, and benchmarks. The MSVPA approach is therefore relatively easily incorporated into fisheries management and provides additional information to evaluate potential trade-offs between ecological processes and commercial fishery yields.

MSPROD

Bill Overholtz, Jason Link

Historic analyses at the NEFSC focused on system level surplus production. Brown et al 1977: analysis of the ICNAF bottom trawl fishery in SA 5+6 during 1961-1972 and Fogarty et al 1992: re-analysis with additional years from 1973-1987, used aggregate catch and effort data to estimate surplus production and Biological Reference Points (BRP) for the commercial components of the entire northeast shelf ecosystem. Conclusions from the Brown et al 1977 study were that "…summing the MSYs from individual assessments may be an overestimate of the total MSY." The 2nd tier quotas (700,000-900,000 mt) estimated from these studies were 30-45% lower than the sum of the individual species quotas (1.3 million mt). Another study estimated predation impacts on Atlantic herring and quantified these results in a stock assessment (Overholtz et al. 2007). This study also proposed several methods for estimating BRP's for herring. Results suggest that predation mortality (M2) should be included in stock assessments of prey fish. Also that single species assessments of prey fish are generally optimistic relative to BRPs. Another general conclusion was that if the fishery and predators utilize the same size spectrum of prey, then explicit consideration of tradeoffs is probably necessary. In the third study examined in the talk, preliminary findings from a multispecies Schaefer model (MSPROD) were discussed. This study examined a suite of ecological and harvest scenarios by using this model to simulate various scenarios. The ecological scenarios were accomplished by modifying competition and predation parameters in the model, while the harvest scenarios were accomplished by changing harvest rates. The goal of the approach was to investigate general properties and responses in a guild based system.

Results showed predation appears to be the dominant biotic term within the model. In general, overall biomass of a guild tends to be stable even though individual species biomasses may change greatly in many of the scenarios. Finally, changes in one biotic factor may cause unexpected results due to predatory and competitive interactions.

Gadget – a flexible modelling tool

Bjarte Bogstad

Institute of Marine Research, Bergen, Norway

Gadget (Globally applicable Area-Disaggregated General Ecosystem Toolbox, www.hafro.is/gadget) is a powerful and flexible modelling framework. It has been developed to model marine ecosystems within a fisheries management and biological context, and can take many features of the ecosystem into account. Gadget allows the user to include a number of features of the ecosystem into the model: One or more species, each of which may be split into multiple components; multiple areas with migration between areas; predation between and within species; single-species or mixed fisheries, growth; maturation; reproduction and recruitment. A Gadget "stock" or "population group" is a group of fish which are all considered to share similar biological characteristics (e.g. growth, mortality). A typical such stock could be an entire species, all mature fish in a species, or even all mature females from one region in a species. Each stock is defined by specifying the length groups, age groups, and length-weight relationship to be used, along with the functions that are to be used to simulate the biological processes that affect the stock.

Gadget works by running an internal forward projection model based on many parameters describing the ecosystem, and then comparing the output from this model to observed measurements to get a likelihood score. The observed measurements may be commercial catch data, abundance estimates from surveys, mark-recapture data and stomach content data. The model parameters can then be adjusted, and the model re-run, until an optimum is found, which corresponds to the model with the lowest likelihood score. This iterative, computationally intensive process is handled within Gadget, using a robust minimisation algorithm.

Gadget has successfully been used to investigate the population dynamics of single- and multispecies stock complexes in Icelandic waters, the Barents Sea, the North Sea, the Irish and Celtic Seas and the Sofala Bank fishery of Mozambique. Fish, shellfish and marine mammal stocks have been modelled.

Gadget is written in C++, and the software is freely available. The program runs on Unix/Linux as well as on PCs using cygwin.

Bioenergetics models and Ecopath

Chris Harvey, John Field, Chris Legault, Sarah Gaichas, Kerim Aydin, Frank Parrish, Clay Porch, Howard Townsend, Joan Browder, and John Carlson

Energy balance models are founded upon the thermodynamic principles of energy and mass conservation in an ecological system. They often involve using sets of empirically and experimentally derived values and relationships to estimate unknown rates or standing stocks.

At the scale of individual species, bioenergetics models characterize an energy budget as a function of temperature, body size and prey quality. Bioenergetics models are rooted in metabolic relationships that have been studied quantitatively for over 100 years and are widely published. Contemporary fish bioenergetics models are often used to estimate growth and feeding of focal species under different conditions, such as variable climate or alternate fishing regimes that affect size distributions. They are frequently linked to other models in order to estimate the role of bioenergetic relationships in population biology or community-scale trophic interactions. Their efficacy is hindered by a lack of data for many species, the inherent difficulty in measuring some parameters, and "parameter borrowing" across species. However, several key components of bioenergetics modeling (size at age, temperature, diets) are central parts of monitoring programs, which bodes continued development and application of this technique.

At the scale of communities or ecosystems, Ecopath is a multi-species, steady-state model that integrates rates of production and consumption of marine populations and functional groups, providing a template for integrating information from stock assessments, survey data, bioenergetics, diet studies, and fishing mortality rates. As such, it allows smaller-scale research or model results to be viewed in the context of the ecosystem. The origins of the approach can be traced to the development of theory on thermodynamics, ecosystem structure and marine ecology, which Polovina (1984) consolidated into a simple, workable mass balance model with fisheries applications. His work was facilitated in part by an observation by Allen (1971), who demonstrated that for populations with von Bertalanfy growth and exponential mortality, the production:biomass ratio (P/B) for a population of fish in an equilibrium condition is equal to the total mortality (Z). Polovina's approach was further developed, and ultimately made into a widely available software application (Christensen and Pauly 1992; www.ecopath.org). The current software packages include a growing array of results, statistics, routines for evaluating the sensitivity to model parameters, and the dynamic (Ecosim) and spatial (Ecospace) applications; however the basic assumptions and equations of the model are unchanged.

The approach is well published, with hundreds of manuscripts in the literature describing a multitude of models for freshwater and marine ecosystems. Thorough evaluations of the model assumptions, applications and shortcomings are also available in the published literature. The most significant criticisms are generally not in the model assumptions so much as the lack of sufficient data, the difficulties associated with adequately reflecting uncertainty, and the often-noted failure to adequately appreciate the model's limitations (Plagányi and Butterworth 2004). Although other shortcomings exist, it is generally accepted that the energetic accounting of the model forces a useful and critical evaluation of the basic interspecific interactions, which can enable an evaluation of relative rates of production, abundance and predation mortality among various components of an ecosystem, as well as among similarly modeled ecosystems.

Allen, K.R. 1971. Relation between production and biomass. Journal of the Fisheries Research Board of Canada 28: 1573-1581.

Christensen, V. and D. Pauly. 1992. Ecopath II - a software for balancing steady-state ecosystem models and calculating network characteristics. Ecological Modeling 61: 169-185.

Plagányi, Á.E. and D.S. Butterworth. 2004. A critical look at the potential of Ecopath with Ecosim to assist in practical fisheries management. In: Shannon, L.J., Cochrane, K.L., Pillar, S.C. (Editors) Ecosystem Approaches to Fisheries in the Southern Benguela. African Journal of Marine Science 26: 261–287.

Polovina, J.J. 1984. Model of a coral reef ecosystem I. The Ecopath model and its application to French Frigate Shoals. Coral Reefs 3: 1-10.

Ecosim and Ecospace

Sarah Gaichas, Chris Harvey, John Field, Kerim Aydin, Frank Parrish, Clay Porch, Howard Townsend, Joan Browder

Ecosim is a whole ecosystem biomass dynamics model based on a mass balance food web model constructed in Ecopath. Ecospace is a spatially explicit model based on Ecosim, which runs in adjacent spatial cells with flow between them (e.g., animals, fishing fleets, etc.). Ecosim was originated by Walters et al (1997) with its key feature being a flexible "foraging arena" model of predator-prey functional response. Recently, improved age-structured dynamics and additions to the functional response such as prey switching have been added to the basic model (Christensen and Walters 2004). The software package Ecopath with Ecosim ("EwE") includes Ecospace and is coded in MS Visual Basic, running under the MS Windows operating system. It is freely available from http://www.ecopath.org/. (A new generation of the software is expected in September 2007, according to the website, so the programming language and operating system information reported here may be outdated soon.)

Ecosim and Ecospace are being used in NMFS Science Centers in a variety of applications. In general, the model is used for describing ecosystems and for improving understanding of how simultaneous physical, ecological, and fisheries interactions affect commercial and bycatch species in those systems. Specific applications have included examining apex predator (and/or protected species) carrying capacity and predicting their responses to changing fishing and primary production; examining effects of changing water quality on key species; examining the ecosystem effects of changing fishing gear; examining the ecosystem effects of different MPA scenarios; and evaluating tradeoffs at the ecosystem level between alternative management strategies. In several Centers, the model has been useful in providing a foundation for developing proposals to integrate ecosystem-based management approaches into the current management regime.

Ecosim and Ecospace can be used in both pure simulation mode and in parameter-estimation/data-fitting mode. Even in pure simulation mode, using this model is a data-intensive exercise because it must be based on an Ecopath model, which requires information on biomass, production, consumption, and diet composition for all modeled groups. Data requirements increase in parameter-estimation mode, which requires time series of biomass, fishing mortality, and/or production for as many modeled groups across as many trophic levels as possible. In both simulation and fitting mode, results can be very sensitive to parameter options selected related to the functional response. At present, the EwE software has limited capabilities for including alternative time series data, and for statistical parameter estimation and the associated estimation of uncertainty. Alternative models have been developed to address these limitations.

Christensen, V., and C. Walters, 2004. Ecopath with Ecosim: methods, capabilities, and limitations. Ecological Modelling 172: 109-139.

Walters, C., Christensen, V., and Pauly, D. 1997. Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. Rev. Fish. Biol. Fish. 7: 139-172.

Habitat and water quality-related ecosystem modeling

Mary Ruckelshaus

Habitat- and water quality-related ecosystem modeling at the NWFSC conceptually can be framed as linking changes in habitat-forming processes to changes in habitat conditions, and in turn, ecosystem responses to those changes. The primary focal species are Pacific salmonids in the modeling we have conducted thus far. The general questions we address with habitat-related models are: (1) Pacific salmon as transfer vectors of nutrients and energy into terrestrial ecosystems, (2) integrated climate-watershed process-habitat-salmon population analyses, (3) scenario-based watershed restoration decision support system, (4) pesticide effects on chinook salmon individual and population growth, and (5) coho salmon pre-spawn mortality (PSM) models examining the impacts of continued urban growth on established wild coho. We use these models to identify which habitats or habitat-forming processes have been degraded and would benefit from restoration; and which of those habitat changes in turn would most benefit listed species. Outputs of these models provide estimates of the ecological response (changes in habitat quality and quantity and species population dynamics) to protection and restoration actions. The models allow us to forecast species dynamics in the face of future climate, changes in land use and land cover, hatchery, hydropower, and harvest management practices. The resulting outcome of these analyses is to help prioritize restoration strategies and actions through evaluation of alternative management strategies. Advantages for most of these modeling approaches are that they are flexible and can be tailored to varied questions, data availability, and spatial resolutions or extents. The habitat-multi-species models allow translation of potential ecological response (e.g., compared to species or habitat objectives) to changes in management strategies. Nevertheless, most of the true 'models' are not of sufficient detail to help identify impacts of specific restoration actions. All of the habitat-based ecosystem models are data-intensive, requiring at least information on survival and capacity of each species at each life stage, functional relationships between physical or biological drivers and changes in demographic vital rates, species dispersal information, and habitat data. In addition, many of the more complex models are virtually impossible to validate, thus interpreting and explaining results for managers is not easy. Also, scales of effects of many habitat attributes are local and ephemeral, and they often are difficult to capture in long-term dynamic modeling of species or food webs. Finally, models designed to capture the effects of contaminants on salmon are not yet capable of including environmental and cumulative ecosystem impacts. Habitat and water quality ecosystem models under development include: (1) a Puget Sound hydrodynamic model as a tool to prioritize sites for habitat restoration, (2) Desktop watershed--an emerging, process-based model structure that predicts river habitat conditions from landscape and land use attributes, and ultimately links habitat attributes to population performance; and (3) a food web/ecosystem model for upland, terrestrial, and marine portions of Puget Sound.

Coupled Nutrient-Plankton-Zooplankton-Fish Models: Major efforts within NOAA

Howard Townsend, Tom Wainwright, Buck Stockhausen, Andrew Leising, Hongguang Ma

To quantitatively describe a marine/coastal/ or estuarine ecosystem for the purposes of ecosystem-based fisheries management, can be accomplished through an integration of physics, biology and chemistry. Physics (primarily hydrodynamics) is necessary to describe the transport of nutrients and organisms. Chemistry is necessary for description of nutrient cycling. The level to which incorporation of these disciplines is necessary depends on the questions to be answered about an ecosystem. Given the focus on multi-sector uses of aquatic ecosystems inherent with ecosystem-based management, ecosystem modeling requires more than quantitative population biology descriptions common to single-species stock assessment approaches.

Because fisheries science has traditionally focused on biology of fishes, and ecosystem-based modeling requires a multi-disciplinary focus, many fisheries modelers who have moved to ecosystem modeling, have drawn heavily on marine ecosystem models developed from classical ecology – Nutrient-Phytoplankton-Zooplankton (NPZ) related models. NPZ models can linked to fish population dynamics, larval transport, and mass-balance multi-species models. Several NMFS Science Centers have developed major modeling efforts derived from linking NPZ to classical singles-species and multi-species models in order to answer questions about effects of climate and water quality on fish stocks. In this presentation we outline 3 such efforts currently underway: 1) NEMURO (North Pacific Ecosystem Model for Understanding Regional Oceanography) Modeling Suite, DisMELS (Dispersal Model for Early Life Stages), CBWQM and FEM (Chesapeake Bay coupled Water Quality Model and Fisheries Ecosystem Model).

The NEMURO suite is an NPZ model that is dynamically linked to fish bioenergetics and population dynamics model. Originally developed and extended for climate impacts and species-to-species interactions for small pelagics in the North Pacific basin. This approach has been thoroughly reviewed and will soon be implemented in fisheries management planning for the North Pacific.

DisMELS is a coupled biophysical individual-based model that incorporates ontogenetic changes in early life stage parameters and simulates egg and larval dispersal under 3-dimensional (3D) oceanographic currents. This model was developed to create recruitment forecasts based on patterns of advective transport and climate patterns for early spring-spawning flat fish in the eastern Bering Sea. This model has not been formally peer-reviewed for management.

CBWQM and FEM has been developed by tow agencies. The Chesapeake Bay Water Quality modeling suite includes the linked Airshed Model, Watershed Model, Estuarine Hydrodynamic Model, Estuarine Water Quality Model, and Living Resources Model developed by the Chesapeake Bay Program (led by EPA). Chesapeake Bay Fisheries Ecosystem Model (using EwE) was developed by NOAA Chesapeake Bay Office. The modeling suites are linked using physical forcing functions. These linked models are being used to understand the impact of water quality management on fisheries productivity in the Chesapeake. This approach has not been formally peer-reviewed and has been used for qualitative description and discussion with resources managers.

SEAPODYM and APECOSM: "end-to-end" models for considering pelagic species in an ecosystem context.

George Watters

SEAPODYM (Spatial Ecosystem and Populations Dynamics Model, P. Lehodey et al.) and APECOSM (Apex Predators Ecosystem Model, O. Maury et al.) are being developed to address questions such as

1) what is the relative importance of fishing and the environment in structuring pelagic ecosystems;
2) what mechanisms explain observed variation across species, trophic pathways, regions, etc. and which have the greatest predictive power;
3) what alternative states might occur in pelagic ecosystems, what are their consequences, how might they be caused, and are they reversible; and
4) given knowledge about environmental forcing and both the direct and indirect effects of fishing, what might be the consequences of alternative allocations of fishing mortality among different fishing methods?

These questions paraphrase some research foci of the GLOBEC CLIOTOP (Climate Impacts on Oceanic Top Predators) Program, and both SEAPODYM and APECOSM are largely being developed within this context. As such, both models are currently focused on tunas and tuna fisheries (although an example of "sardine habitat" has been developed in SEAPODYM), and, given the international agreements under which these fisheries are managed, it is unclear how their outputs will ultimately contribute to the management process.

As "end-to-end" (i.e., physics-to-fisheries) models, the data requirements for both SEAPODYM and APECOSM are substantial. Both models use the same environmental data (e.g., temperature and primary production) and fisheries data (e.g., effort expended by longline and purse-seine fleets) as, respectively, bottom-up and top-down forcing variables. Both data sets are horizontally resolved to a minimum of 1-degree square and, where appropriate, vertically resolved to a minimum of three layers. The environmental data are themselves outputs from coupled physical-biogeochemical models, while most of the fisheries data are compiled from information provided by relevant Regional Fishery Management Organizations (RFMOs). Between these physics and fisheries "end points," the models are very different structurally, and, therefore, each is parameterized using different assumptions and types of information. For example, independent estimates of growth (by tunas) are used as fixed inputs to SEAPODYM, while growth is an emergent property of bioenergetics and fitness dynamics in APECOSM. Data are also used to "validate" both models. The spatio-temporal distributions of catches by tuna fisheries have usefully been compared to those predicted from both models. SEAPODYM and APECOSM also predict the abundance and distribution of "tuna forage," and this is generally a key data gap – there are limited data to which these predictions can be compared.

While each model is an important contribution in its own right, it is my opinion that the pair is synergistic, with the comparative approach offered by two structurally different models using the same basic inputs and predicting the same basic outputs providing a greater benefit than either model provides independently. Unfortunately, while SEAPODYM can be downloaded from the Internet (www.seapodym.org), run on a single PC (in both Linux and Windows environments), and has to some degree been vetted in the peer-reviewed literature, APECOSM can only be obtained from the author (although I imagine he would be happy to make it available), appears to require a cluster of PCs or highly parallelized code to run in a workable amount of time, and is currently undergoing its first instance of peer review in the literature.

Atlantis

Elizabeth A. Fulton, Isaac C. Kaplan, Chris H. Harvey, Phil S. Levin, Jason Link, and Howard Townsend

Atlantis, a simulation modeling approach developed by CSIRO scientists in Australia, achieves the crucial goal of integrating physical, chemical, ecological, and fisheries dynamics in a three-dimensional, spatially explicit domain (Fulton et al. 2003a,b, 2004a,b,c). The generic Atlantis code is well developed at this time, and Fulton and others (2003a,b, 2004a,b,c) have parameterized it for several systems in Australia, as well as the U.S. West Coast (Brand et al. in press) and the Northeast U.S.

Atlantis models typically include:

- ~60 biological groups, such as habitat-forming species like kelp, corals and sponges, as well as vertebrate consumers, benthic invertebrates, zooplankton, phytoplankton and detritus.
- Age structured vertebrate dynamics and biomass pool dynamics for invertebrates
- Multiple spatial zones and depth layers
- Daily hydrodynamic flows, salinity, and temperature inputs from a high-resolution Regional Ocean Modeling System (ROMS) or similar oceanographic models
- Dynamics of multiple fishing fleets or gear types
- Assimilation of data from fisheries landings, surveys and monitoring, life history studies, diet studies, and stock assessments

Atlantis utilizes a simulation framework known as Management Strategy Evaluation, or MSE (Butterworth et al 1997, Cochrane et al 1998, Butterworth and Punt 1999, Sainsbury et al. 2000). In MSE, a model of the biology is linked to simulated monitoring, assessments, and decisions. By repeating this cycle on an annual basis, we can test the utility of modifying the monitoring or assessment methodology, policy options (e.g. harvest rates or marine protected areas), or overall management strategies (e.g. individual quotas vs. fleetwide quotas). Atlantis has been used to successfully identify ecological indicators for the SE Australian coast and a large bay near Melbourne, Australia (Fulton 2005), and to test options for restructuring southeastern Australia’s trawl fishery.

Atlantis is a C++ code base that requires considerable expertise to use and understand properly. Run times range from one hour to four days, depending upon the complexity and time scale of the model. Recently we have been developing new plotting software for Atlantis output, as well as enhanced ability to incorporate observations of fish diets. These efforts combined with planned development of a user interface should make Atlantis more accessible to new users.

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Fulton, E. A., and A. D. M. Smith. 2004. Lessons learnt from a comparison of three ecosystem models for Port Phillip Bay, Australia. South African Journal of Marine Science 26:219-243.

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Fulton, E. A., A. D. M. Smith, and C. R. Johnson. 2004. Effects of spatial resolution on the performance and interpretation of marine ecosystem models. Ecological Modelling 176:27-42.

Fulton, E. A., Smith, A. D. M., and Punt, A. E. 2005. Which ecological indicators can robustly detect effects of fishing? ICES Journal of Marine Science, 62: 540-551.

Sainsbury, KJ, Punt, A.E., and Smith, A.D.M. 2000. Design of operational management strategies for achieving fishery ecosystem objectives. ICES Journal of Marine Science, 57: 731-741.

Multispecies Statistical Model (Minimum Realistic Model example)

Jim Ianelli

The purpose of this model is to use a statistical approach to modeling trophic interactions with fewer assumptions than is required with MSVPA methods. This should provide a basis for evaluating food-web dynamics relative to data generated for standard assessment methods used for fisheries management. The data requirements include diet composition, ration, survey and fishery age composition estimates, fishery catches, demographic characteristics (e.g., maturity, weight-at-age), and abundance indices. Data gaps include full spatial and seasonal diet composition information, annual bioenergetic ration estimates (requiring observed growth and temperature), information that best describes functional responses, and age composition information for all species. These gaps are providing impetus to improve stomach sampling methods and coverage.

The model is constructed following a state-space non-linear estimation framework that allows easy specifications of alternative model forms (unobservable states) that map into the “observables” that link to available data. This approach allows for incomplete information and provides the ability to more fully evaluate available information with fewer assumptions and a better representation of uncertainty. Fundamentally, the model allows for an arbitrary number of species with an arbitrary number age classes, each combination of which can have an arbitrary number of trophic interactions. If no trophic interactions are specified, then the model reduces to simultaneous independent age-structured stock assessments for each species included. Since some aspects of the model specification still requires making assumptions (e.g., the ration), adopting a Bayesian approach allows these assumptions to be cast as prior information (with uncertainty) as opposed to fix assumed “known” values. They structure the model separately from the data and allow better evaluations of hypotheses and the importance of different data types. For projection purposes, some degree of stationarity is required (relative to the historical pattern observed). For pragmatic reasons, the number of interactions among species is limited. Presently, alternative functional responses are not included (though work on adding alternatives has progressed). Simplified versions have been published (see below) but model software has only been checked against results from standard assessment models. The model software is extremely portable and can run on nearly any platform. Software documentation and implementation aspects (e.g., a GUI) are nonexistent. Enhancements include generalizing the code, adding the ability to change the functional response, changing how the data are read, and changing the way the diet composition data are treated. Conceptually, this type of model can be switched into simulation mode for testing. Currently, the model plays a role in evaluating the multispecies management methods used by the AK Regional Office and this is likely to continue.

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Ecosystem Modeling Efforts at NMFS Science Centers and Offices

Each Center was asked to provide a synopsis of its EM efforts. These were to be as inclusive as possible and collectively illustrative, the EM efforts that have been executed by NMFS.

Each Center was asked to addressing the following questions:

- what models are used
- what these models are used for
- what are the major data needs
- what are the pros and cons of the EM approaches.

This collection of Center EM efforts partly addresses TOR #1 and fully addresses TOR #2.

PIFSC

Jeffrey J. Polovina[1]*, Albert Harting*[2]*, Evan Howell*[1]*, Donald R. Kobayashi*[1]*, Frank Parrish*[1]

[1]Pacific Islands Fisheries Science Center, NOAA Fisheries , 2570 Dole St., Honolulu, HI 96822-2396
[2]Harting Biological Consulting, Bozeman, MT

Coral reef Ecopath/Ecosim model

The original French Frigate Shoals Ecopath model, which was developed in the mid-1980's, continues to be updated as improved parameter estimates are obtained from fieldwork. The most recent update of the model is improved diet composition of the endangered Hawaiian Monk Seal from a large fatty acid study. The model is currently being used to evaluate the carrying capacity of the Monk Seal populations at selected banks in the Northwestern Hawaiian Islands. The modeling approach is well-suited to address carrying capacity and trophic dynamics issues since it estimates the ecosystem energy budget. We also use the dynamic version (Ecosim) to simulate ecosystem dynamics at higher trophic levels resulting from changes in primary productivity. We find the temporal lags at higher trophic levels due to bottom-up forcing insightful for monitoring and prediction. An advantage of the Ecopath/Ecosim approach is that it enables us to explore trophic dynamics for the entire ecosystem. A drawback is it doesn't couple well with a high resolution ocean circulation model.

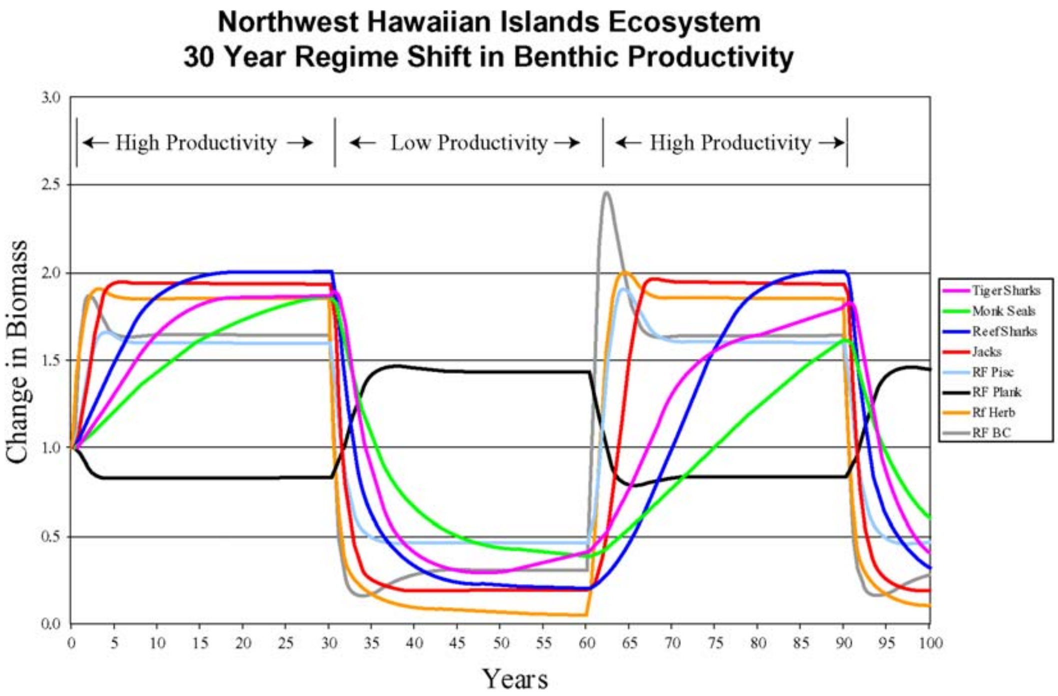


Figure 1. An ECOSIM simulation of the French Frigate Shoals ecosystem under periods of high and low primary productivity.

Ocean circulation and coupled Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) model

The physical model is based on the Regional Ocean Modeling System (ROMS). The model covers the Pacific with a horizontal resolution of 50 km in both zonal and meridional direction and 30 levels in vertical direction. The physical model is first integrated for 60 years with climatological air-sea fluxes (wind stress, heat and fresh water flux) from the COADS (Comprehensive Ocean-Atmosphere Data Set). This ROMS circulation model has been coupled to a biogeochemical ecosystem model based on the CoSINE (Carbon, $Si(OH)_4$, Nitrogen Ecosystem) ecosystem model (Chai et al., 2002). The CoSINE model includes silicate, nitrate and ammonium, two phytoplankton groups, two zooplankton grazers, two detrital pools, TCO_2 and recently oxygen has been added to constrain the remineralization processes in the model. Nutrients (nitrate and silicate) are initialized with the World Ocean Atlas 98 climatological annual mean values. The governing equations in the biological model are solved simultaneously with those of the physical model. The physical-biogeochemical model is integrated with the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP-NCAR) reanalysis starting in January of 1960, and monthly averaged model fields are used for this study.

The model was used to investigate physical-biological linkages at the northern end of the Hawaiian Archipelago. The model provided a time series of estimates for the northern atolls of monthly nutrients, phytoplankton, zooplankton, and detritus over the period 1964-2006. Further, the model results showed that the changes in productivity at these atolls can be viewed from a geographic perspective. The atolls lie at the northern edge of a subtropical gyre which is characterized by a strong physical, chemical, and biological gradient. This gradient moves north and south seasonally and inter-annually resulting in changes in lower trophic level productivity around the atolls fixed position. The obvious drawback with the NPZD model is that it is only a lower trophic model.

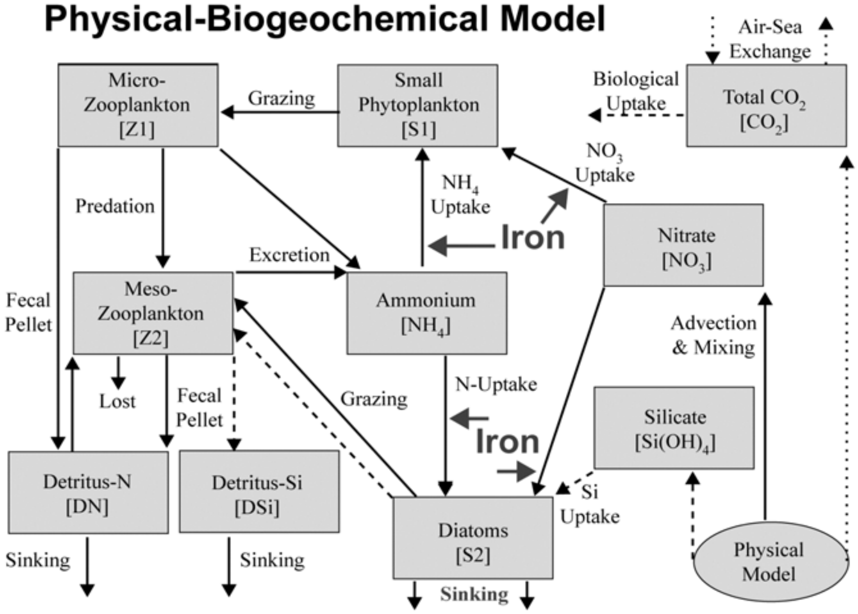


Figure 2. The coupled ROMS-CoSINE model. Solid arrows show the path of N; dashed arrows show the path of Si; and dotted arrows show the path of CO_2.

Coral reef larval transport model

Larval transport modeling has been applied to the coral reef ecosystem in the Hawaiian Archipelago to address many research topics in recruitment dynamics, metapopulation connectivity, and biogeographic linkages. This approach relies heavily upon ocean circulation data, either from sophisticated general circulation models or currents data from satellite altimetry, wind measurements, ocean drifters, and/or moored/shipboard instrumentation. Since many insular populations are thought to be recruitment and/or settlement limited, it is vital to incorporate the ecology of the pelagic phase propagules into successful ecosystem management. However transport modeling is just the first step in this process as it does not incorporate important aspects of the pelagic ecology of propagules. Swimming and orientation abilities which develop during the latter phases of the pelagic stage and the possibility of protracted or early larval settlement are neither understood or incorporated in the model for our reef species.

Monk Seal Population Dynamics Model

In collaboration with researchers at Montana State University, PIFSC developed a comprehensive stochastic simulation model for the Hawaiian monk seal. Although this is a species-specific model, rather than an ecosystem model in the usual sense, it includes an elaborate representation of environmental stochasticity. It also models certain other ecosystem variables (shark predation and other) known to influence monk seal demography. The model is a mechanistic, metapopulation model with provisions for handling uncertainties in input parameters and modeled processes. It is heavily data driven, capitalizing on the demographic and life history data collected over more than two decades in the Northwestern Hawaiian Islands. Required data are based primarily on annual monk seal resightings, which are then used (in a suite of ancillary programs) to calculate demographic rates, migration rates, and other input parameters. The model provides multiple options for simulating natural perturbations (for example, generic survival or birth catastrophes) and management interventions (captive rearing/release, translocations, shark removals, etc.). It includes an extensive implementation for density dependent adjustment of demographic rates with multiple options for: the type of density dependence model, the model parameters, the demographic rates subject to density dependent regulation, and the strength of the density dependence response.

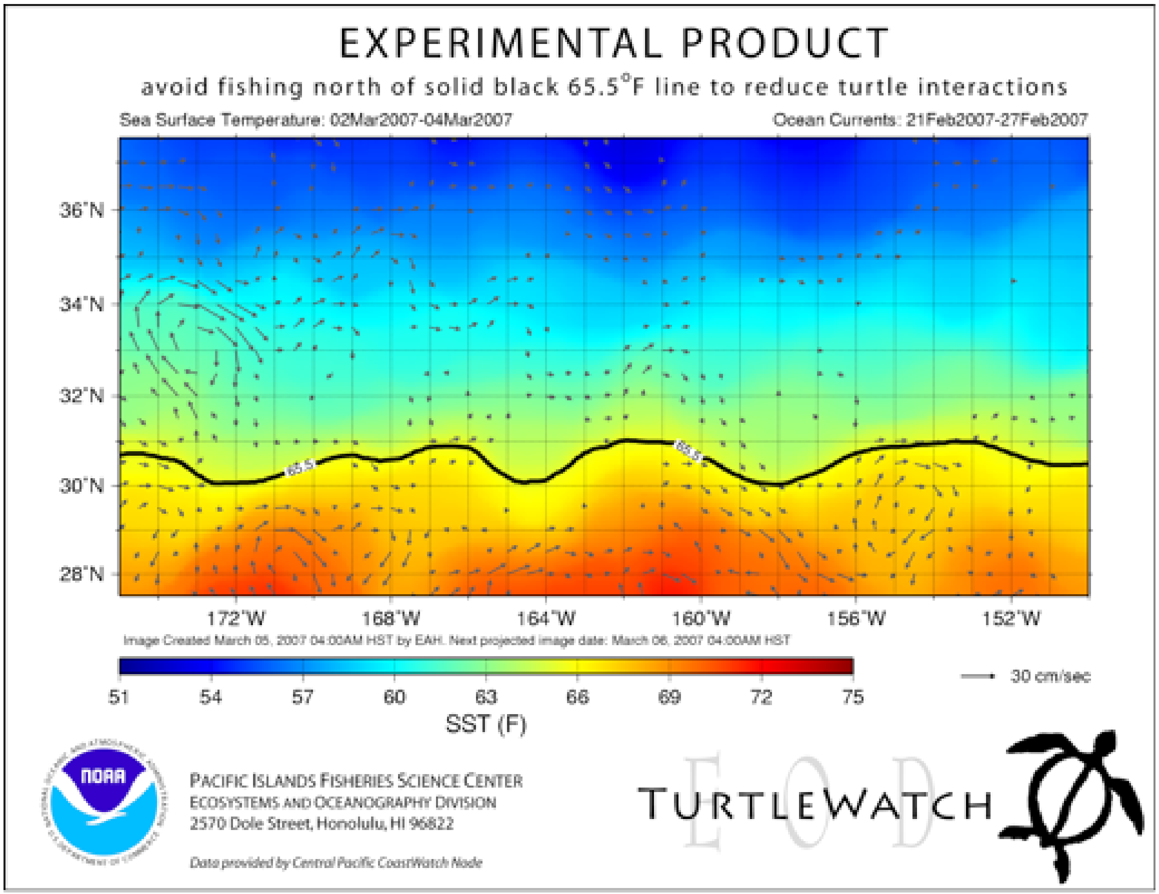
The monk seal model has been regularly used in core research and management, for such purposes as analyzing the impacts of shark predation on monk seal recovery, conducting NEPA evaluations, analyzing potential impacts from an epizootic outbreak in the NWHI, evaluating likely outcomes from captive care intervention, and other applications. New features and refinements are added to the model as required by an emerging issue or an analytical need in monk seal management.

The principal shortcoming of the current model is uncertainty about the key environmental variables that drive the observed annual fluctuations in monk seal demographic rates. While some inferences are possible (based on observations from seal instrumentation and tentative links with oceanographic phenomenon), our ability to predict the timing and intensity of major demographic perturbations remains weak. This uncertainty limits the model’s power for short term prediction which may be a key aspect for the development and application of future intervention efforts.

Loggerhead sea turtle pelagic habitat model

Understanding pelagic habitat needs is important for the effective management of both the high-seas ecosystem and for organisms which only utilize the pelagic environment at some point in their life-history. As a step towards this goal, we analyzed 10-years of satellite track data for 186 loggerhead sea turtles in the North Pacific Ocean and used remotely-sensed environmental data to characterize the basin-wide pelagic habitat for this endangered species. A large number of candidate habitat variables were merged to the satellite track data and statistically compared to background values over a large spatio-temporal grid of overall occupancy. Five statistically significant variables were identified out of the sixteen environmental variables examined. Habitat selectivity for these variables was quantified using preference curve methodology established in the foraging literature. The output from the selectivity curves was utilized to predict a multivariate loggerhead sea turtle habitat index across the pelagic North Pacific. This predicted habitat was ground-truthed with newly available satellite track data not used in the initial analysis. This information will be very useful towards single-species and ecosystem management, protected-species mitigation, and contribute towards a greater understanding of pelagic animal ecology. In order for this approach to be most useful for ecosystem management, a clearer understanding of individual animal behavior is needed (e.g. knowing exactly what cues and responses are operating at the individual level as it navigates through the habitat).

At the PIFSC we are examining how this type of habitat model may support management. In order to reduce loggerhead sea turtle takes in the Hawaii-based longline fishery we use results from a loggerhead sea turtle habitat model to identify a region, based on sea surface temperature (SST), with a high probability of fishery and turtle interactions. PIFSC distributes weekly maps covering the fishing grounds advising fishers to avoid regions with a high probably of loggerhead turtle takes. The position of the 65.5° F SST contour, indicated on the figure below, changes weekly so the map needs to be updated and distributed weekly.



AFSC

Kerim Aydin, Sarah Gaichas, John Heifetz, Sarah Hinckley, James Ianelli, Bern Megrey, Ivonne Ortiz, and Buck Stockhausen

The following provides a summary of multi-species modeling work that is actively being developed at the AFSC. For each model we outline a) a basic description of the model, b) the objectives of the modeling effort, c) the data needs of the model, and d) its pros and cons.

Single species stock assessment ecosystem considerations

Stock Assessment and Fishery Evaluation (SAFE) prepared annually by many authors (Hollowed, program leader)

a) All AFSC single species stock assessments contain an Ecosystem Considerations section where ecological interactions are noted for the assessed species. Information included in this section ranges from simple literature reviews of diet composition and habitat requirements to statistical analysis of stomach contents data over time and results from ecosystem model simulations, depending on the species. Habitat requirements and/or other physical changes to the environment can also be included in this section.

b) The objective of including ecosystem considerations sections in single species stock assessments is to provide auxiliary information for stock assessment, with the goal of incorporating key ecosystem interactions directly into single species stock assessment models and management advice wherever possible.

c) Data include diet compositions, habitat requirements, and information on population trends for known predators for the assessed species, as well as habitat or climate indicators from the Ecosystem Considerations SAFE (a separate chapter compiled annually by J. Boldt). Some assessments include ecosystem model outputs; see descriptions below.

d) Pros: ecological context for the assessment is provided, and key interactions other than fishing may be identified which have management implications for the stock. *Cons:* information may be difficult to compile, unclear which information is most relevant to many stock assessments at this time, so while the information is presented, few assessments integrate this information into models or harvest advice at present.

Extended single species models

Gulf of Alaska pollock Management Strategy Evaluation (A'mar, Punt, and Dorn)

a) The Management Strategy Evaluation (MSE) approach is used to assess the impact of ecosystem changes and multi-species interactions on management strategy performance. Hypotheses regarding the effects of ecosystem shifts and multi-species interactions on the dynamics of walleye pollock, *Theragra chalcogramma*, in the Gulf of Alaska (GOA) are developed based on the results from Ecosim models. These hypotheses, which include natural mortality-at-age varying systematically over time, are parameterized to form the basis for an operating model for use in MSE evaluations. A management strategy based on the actual approach used to provide management advice for the GOA walleye pollock fishery is then evaluated in relation to its ability to satisfy goals related to avoiding undesirable levels of depletion and fishing mortality, and permitting high, stable catches.

b) The model was developed because ecosystem changes are known to have occurred in the North Pacific Ocean. However, the timing and impact of these are uncertain, but may influence the ability of management strategies to achieve fishery and ecosystem management goals.

c) Data requirements include the entire single species assessment for pollock in the Gulf of Alaska, plus all data necessary to build the GOA dynamic food web model (see below), plus climate indices.

d) *Pros:* substantial complexity is included in this operating model, allowing for management strategy evaluation over a broad range of conditions observed in this ecosystem. *Cons:* development of this approach is on hold as modifications to the GOA dynamic food web model are being completed.

Key references:

Livingston, P. A., and R. D. Methot. 1998. Incorporation of predation into a population assessment model of eastern Bering Sea walleye pollock, p. 663-678. In F. Funk, T. J. Quinn II, J. Heifetz, J .N. Ianelli, J. E. Powers, J. F. Schweigert, P. J. Sullivan, and C.-I. Zhang (editors), Fishery stock assessment models. Alaska Sea Grant College Program, University of Alaska Fairbanks, AK-SG-98-01.

Hollowed, A B., J. N. Ianelli, and P. A. Livingston. 2000. Including predation mortality in stock assessments: a case study for Gulf of Alaska walleye pollock. ICES J. Mar. Sci. 57:279-293.

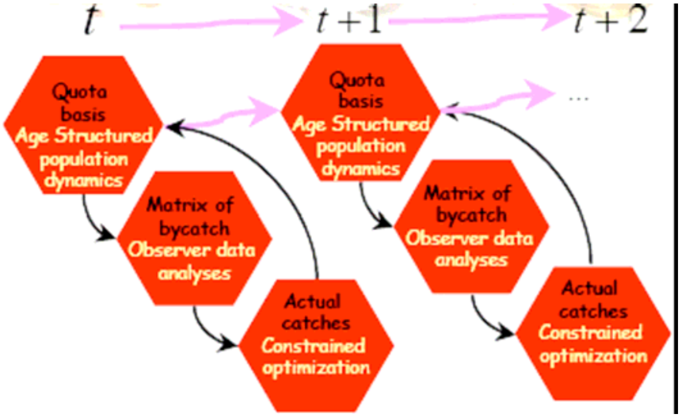
Fishery interaction models (gear interactions)

North Pacific multi-species management model (Ianelli)

a) The multispecies management model links stock assessment information on single species population dynamics within a multispecies, multigear representation of fishing fleets working within the constraints of Alaska’s inseason fishery management system.

b) The model was developed to provide a more “realistic” analyses of fishing alternatives for a programmatic environmental impact statement (published 2004, http://www.fakr.noaa.gov/sustainablefisheries/seis/intro.htm). The goal was to provide a tool that accounted for uncertainties in future stock conditions (via recruitment variability) relative to the array of area specific fisheries subject to alternative TAC constraints (such as prohibited species limits, quota allocations among fleets and overall maximum quotas such as the 2 million t limit).

c) Detailed catch composition data, including both landed catch and at-sea discards, for each fishery and gear type is linked to the management and population dynamics for key species in this model. This resulted in tracking 110 species or species groups (about 25 of which had age structured assessments) over 67 fisheries (defined as being a particular gear-type targeting a main species within a sub-area). A linear programming (LP) approach was used to approximate the behavior of the TAC setting process at the Council and subsequent catches were submitted to the individual species population projections. The LP invokes a constrained optimization procedure which uses species-specific landed values as part of the objective function and a large number of constraints.



d) *Pros:* This approach improves single-species projections since the interaction of realized bycatch patterns and multispecies quota limits are taken into consideration. Rudimentary economic factors are taken into account and the model provided a way to interactively view alternative management scenarios. *Cons:* The current version of the model can handle stochastic changes in bycatch estimates from each fishery but a full evaluation is pending (the bycatch matrix is presently treated as static). A direct linkage between single-species stock assessment “gear” and bycatch matrix “gear” is absent. Since actual management and that estimated as “optimal” using the LP could be quite different, results were screened for patterns that were unreasonable and additional limits (e.g. a particular fishery expansion) were required.

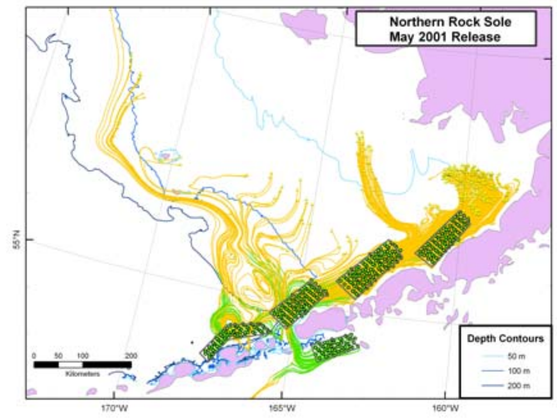
Single species bio-physical individual based models (IBMs)

Dispersal Model for Early Life Stages (DisMELS) (Stockhausen, Hermann, Duffy-Anderson, Wilderbuer)

a) *DisMELS* is a coupled biophysical individual-based model that incorporates ontogenetic changes in early life stage parameters and simulates egg and larval dispersal under 3-dimensional (3D) oceanographic currents. Individuals can actively “swim” up or down in the water column to occupy user-defined “preferred” depth ranges on a diel basis (diel migration is turned off by specifying the same preferred depth range for both day and night), and may undergo random walk behavior, as well. Growth, mortality, and life stage are also tracked. Ontogenetic shifts in vertical behavior, growth and/or mortality rates are incorporated as individuals grow through a series of life history sub-stages. Size- and age-at-metamorphosis are used to define competency to settle. Recruitment indices to predefined nursery areas are computed as a weighted sum of the number of super individuals with tracks that intersect a nursery area.

b) The objective of this model is to develop recruitment forecasts based on patterns of advective transport for two early spring-spawning flatfish, northern rock sole and Alaska plaice, in the eastern Bering Sea.

c) The model uses stored output of 3D oceanographic currents, temperature and salinity fields from an oceanographic model of the northeast Pacific (NEP ROMS) to simulate advective transport of pelagic eggs and larvae (see figure). DisMELS uses a 4th order Lagrangian predictor/corrector scheme to integrate the 3D trajectories of a set of “super individuals” through time.



d) *Pros:* Modeling studies demonstrate that particle depth can substantially influence transport paths. Early life stage studies have shown that typical depth ranges for early stage flatfish change ontogenetically (e.g., as eggs change buoyancy with development), and for larvae diurnally. Coupled biophysical models are needed to incorporate this behavior to more accurately predict dispersal trajectories. *Cons:* Tides are not currently included in the physical model, whereas tidal currents are substantially larger than mean currents on the EBS shelf. If larvae are capable of selective tidal stream transport, then the model will substantially underestimate dispersion rates. Larval behavior may be more complex than that incorporated in the model, leading to divergence between actual and predicted dispersal patterns. In the model, vertical position is determined by stage-specific depth ranges based on results from limited field studies. However, depth itself may not be the causative factor responsible for the observed positions in the water column—thus position in the water column may differ under environmental conditions different from those coinciding with the observations.

For flatfish stocks, abundance at recruitment (defined here as the first age included in an appropriate stock assessment model) reflects both abundance at settlement in suitable nursery habitats and subsequent juvenile survival to the age at recruitment. In turn, abundance at settlement reflects the number of individuals that both survive and are transported to nursery habitats. Pre-settlement survival reflects potentially complex interactions among mortality due to abiotic environmental conditions, mortality due to predation, and individual growth rates that may not be adequately captured in the model. Juvenile survival is not included in the model, but may be density-dependent, reflecting conditions in micro-environments utilized as nursery areas.

Bio-physical IBMs with food web interactions

Species centric IBMs (Hinckley et al)

Individual-based Model of snow crab (Chionocetes opilio) larval transport and survival in the Bering Seal (Hinckley, S., Parada, C., Armstrong, D., Orensanz, J., Ernst, B.)

a) The snow crab IBM uses output (current and temperature fields) from the ROMS model to simulate the transport of snow crab from hatching, through the larval and to the early juvenile (settling) stage. Data from studies on female reproductive output and historical distributions of female snow crab are used to initialize the model. Changes in depth with development, and effects of temperature on growth and stage duration are included. Trajectories (in 3D) of larvae are followed, as well as location of potential settlement, temperature at settlement, area of origin, and histories of growth and mortality. This model will be coupled with a lower trophic level ecosystem model to investigate the effect of ice edge blooms on larval survival, and data on cod distributions to investigate the effect of cod predation on survival of early settled juveniles.

b) The objectives of this modeling effort are (1) to investigate whether snow crab will be able to repopulate the southeast Bering Sea from the northwesterly distribution recently seen (“The Environmental Ratchet Hypothesis”, Orensanz et al. 2004), (2) to investigate causes for recruitment variability in snow crab, and (3) to investigate possible effects of loss of sea ice and global warming on snow crab.

c) The model uses 3D output (currents and temperature) from the ROMS model to simulate movement of early stages of crab through the Bering Sea. Data on historical distributions and abundances of snow crab adults, and their reproductive capacity, for use as initial conditions, are derived from NMFS databases. Parameters of growth, mortality, depth distributions, etc. are derived from the literature.

d) *Pros*: This model provides an integrative tool for use in examining effects of transport and environmental conditions on snow crab distribution, transport and survival. So far, the model has given indications that the availability of juvenile settlement habitat may be significantly reduced under warmer environmental conditions, which has important implications for recruitment and population viability under scenarios of Bering Sea warming and loss of sea ice. The model builds on earlier work on female snow crabs, and extends this to investigate hypotheses that have important ramifications for managing this stock under conditions of climate change and loss of sea ice. *Cons*: The model presently uses ROMS output from a 10-km grid. The development of a ROMS model with a 3-km grid would aid in better resolution of currents, however computer and personnel time are extensive in producing output from the ROMS model.

Key Reference:

Orensanz, J. L., B. Ernst, D. Armstrong, P. Stabeno, and P. Livingston. 2004. Contraction of the geographic range of distribution of snow crab (*Chionoecetes opilio*) in the eastern Bering Sea: An environmental ratchet? CalCOFI Rep. 45: 65-79

Individual-based Models of Walleye Pollock Recruitment Processes in the Gulf of Alaska (Hinckley, S., Parada, C., Hermann, A., Megrey, B.)

a). The IBM for walleye pollock in the Gulf of Alaska is part of a coupled model set that includes the ROMS hydrodynamic model, the IBM, which follows young pollock from spawning through the larval and 0-age juvenile stages, and an NPZ model designed specifically to provide a spatially and temporally varying food source. The IBM includes stage (egg, yolk-sac larvae, feeding larvae and 0-age juveniles) specific mechanistic processes (such as temperature-dependent egg and yolk-sac larval development), an encounter model of feeding that includes turbulence effects for larvae, bioenergetics for larvae and juveniles, ontogenetic changes in vertical and horizontal swimming behavior, and size-based or stage based mortality, including predation. The model uses ROMS current fields to drive larval and juvenile movement, and temperature and salinity fields to drive biological processes. The model also uses output from an NPZ model which focuses on simulating the temporally and spatially explicit distributions of the different stages of *Pseudocalanus* spp., and euphausiids, which are major prey items for young pollock. Output from the model includes time histories for each individual on location, stage, weight, age, and condition.

b) The objectives of this modeling include: (1) investigation of mechanistic processes underlying recruitment variability of pollock, (2) investigation of whether this model can be useful as a recruitment forecasting tool, either for long-term forecasts (ie. prediction of recruitment scenarios under differing climate scenarios), or short-term forecasts, and (3) investigations of pollock stock structure as it can be inferred from information on successful spawning locations and spawning area-nursery area connections (which will give indications on whether the current practice of managing pollock in the GOA as a single stock is useful).

c) The model uses 3D output (currents and temperature) from the ROMS model and prey distributions from an NPZ model to simulate movement and success of early stage pollock individuals in the GOA. Parameters and algorithms to model mechanistic processes in each life stage are derived from process and lab studies, especially those done by the Fisheries Oceanography Coordinated Investigations (FOCI) program. Data used to initialize the model are derived from historical distributions of spawning pollock from NMFS databases. Data to validate the models are derived from surveys and studies done by FOCI program.

d) *Pros*: This IBM provides a tool to integrate our knowledge on recruitment processes and mechanisms for pollock, and potentially may provide a tool for predicting recruitment. It can be used to investigate individual processes, such as the effects of turbulence on larval feeding, that may be critical to recruitment success; and to perform model experiments to explore, for example, the effect of spawning time or location on recruitment success. *Cons:* It is very data intensive. Simulations are personnel and computer-intensive, and depend on time series of output from the ROMS model, which take much time to produce. Data used in the model, such as time series of pollock spawning times and locations, or estimates of predation on juvenile pollock, are incomplete.

Key References:

Parada, C. S. Hinckley, J. Horne, M. Dorn, A. Hermann and B. Megrey. In press. Comparing simulated walleye pollock recruitment indices to data and stock assessment models from the Gulf of Alaska. Mar. Ecol. Prog. Ser.

Hermann, A.J., S. Hinckley, B.A. Megrey and J.M Napp. 2001. Applied and theoretical considerations for constructing spatially explicit, individual-based models of marine larval fish that include multiple trophic levels. ICES J. Marine Sci. 58(5): 1030-1041

Hinckley, S., A.J. Hermann and B.A. Megrey. 1996. Development of a spatially-explicit, individual-based model of marine fish early life history. Mar. Ecol. Prog. Ser. 139:47-68.

Multispecies models (MSM; age structured population dynamics with food web interactions)

MSM model of the Eastern Bering Sea (J. Ianelli et al.)

a) *Multi-species Statistical Model* extends the statistical age-structured approaches used for stock assessments to include diet composition data and estimates of consumption and relative contribution to total mortality (of prey species). Currently, the model constructed includes three important species for the Eastern Bering Sea and results compare with past approaches (e.g., multispecies VPA).

b) The objective of this work is twofold. First, we wish to develop statistical approaches that use state-of-the art estimation methods and provide realistic bases for evaluating ecosystem hypotheses relative to observed data. Secondly, the extension of this model lends itself to projections with alternative fishery scenarios. Both of these are considered critical for developing statistically sound operating models to use in testing simpler, empirical approaches to fisheries management (e.g., single species quota management).

c) The model uses data at the same level as present assessments (e.g., length-frequencies for species that lack age-composition data). Additionally, information on ration and diet composition over time is included. Previous results indicated that (with some assumptions) the added complexity of trophic interactions combined with the diet composition data could lead to improved abundance estimates.

d) *Pros:* This approach provides the means to evaluate the information content of data in a statistically defensible manner. Key players in the ecosystem are included and the relative impact of alternative fishing mortalities can be extended. The structure of these types of models lends themselves to simulation testing. *Cons:* The model includes only a segment of the ecosystem and may miss processes that are important controlling factors. While some work has progressed on implementing alternative functional responses to prey, the robustness of evaluating alternative forms is limited.

Key Reference:

Jurado-Molina J., P. A. Livingston and J. N. Ianelli. 2005. Incorporating predation interactions to a statistical catch-at-age model for a predator-prey system in the eastern Bering Sea. Canadian Journal of Fisheries and Aquatic Sciences. 62(8): 1865-1873.

MLMAK (Kinzey and Punt)

a) *MLMAK* extends the single species stock assessment catch-at-age model framework AMAK to include the effects of predation so that natural mortality can vary by age- or length-class and year. The modeling framework accounts for the age-structured dynamics of each population as the result of a Beverton-Holt spawner-recruit relationship (expressed as steepness), fishing mortality, and non-fishing mortality. Non-fishing mortality can be separated into mortality due to predation by the other species in the model, and residual mortality due to species outside the model and other factors. The model can be run in either of two modes: 1) "predation on", in which case the model incorporates the diet data and predator-prey interactions in estimating the parameters of the population dynamics; or 2) "predation off", in which case the parameter estimates for the population dynamics are single-species, based only on the fisheries and survey data and model components without the diet data and predation components. We apply this framework to the populations of Atka mackerel, walleye pollock, and Pacific cod in the Aleutian Islands region of Alaska, and compare the estimates of some population attributes of interest from multispecies and single-species analyses. Seven alternative models for the predator functional response are compared using AIC.

b) Fish populations are conventionally assessed using single-species models of population dynamics that assume that non-fisheries natural mortality is independent of year and age (or length). The objective of this work is to provide a framework for direct comparisons of single species and multispecies modeling methods and results.

c) The parameters of the model, including those that determine predation, are estimated using data on diets from stomach samples as well as more conventional data sources such as catch biomass, catch-at-age for fisheries and surveys, and survey biomass.

d) *Pros:* the ability to run with predation off and on allows direct comparisons between standard assessment results and those incorporating predation. Estimating functional response parameters using annual diet data improves on the traditional assumption that diets are known without error. Incorporating and comparing multiple models of predator functional response permits further evaluation of the effect of model structure on results. *Cons:* there are no clear statistical methods for comparing the results of models incorporating entirely different datasets (e.g. diet data vs. no diet data). Predators without detailed diet and demographic data (e.g., sea lions) cannot be included in this framework, even if they inflict substantial mortality on modeled species.

Multispecies Virtual Population Analysis (MSVPA) model of the Eastern Bering Sea (Jurado-Molina et al.)

a) *MSVPA* extends the Virtual Population Analysis approaches used for some stock assessments to include diet composition data and estimates of consumption and relative contribution to total mortality (of prey species). The model includes eight important species for the Eastern Bering Sea.

b) The objective of this work is to develop alternative natural mortality and trend analyses to single species models.

c) The model uses survey, fishery, and age composition data from surveys, and additionally uses diet data from the key species in the analysis.

d) *Pros:* Provides natural mortality trends in an assessment framework. *Cons:* The reliance of MSVPA on age-based (rather than length-based) foraging creates a dependence on age/length keys which may especially vary for juveniles. MSVPA code base is less flexible in terms of input files and procedures; this has led to MSVPA being used for the basis of the MSM model, described above.

Key reference:

Livingston, P.A. and Jurado-Molina J. 2000. A multispecies virtual population analysis of the eastern Bering Sea. ICES Journal of Marine Science 57: 294-299.

Lower trophic level food web models

NEMURO (Kishi et al, 2007)

a) NEMURO is a 11 state variable mechanistic numerical simulation model of a subarctic lower trophic level (LTL) marine ecosystem. Biogeochemical process equations describe the dynamics of nitrogen and silicon (the model currency) flow through the system in units of mole N or Si l^{-1} day^{-1}. There are two phytoplankton functional groups (small (PS)-dinoflagallates and large (PL)-diatoms) and three zooplankton functional groups (small (ZS)-microzooplankton, large (ZL)-copepods, and predatory (ZP)-euphausiids). All biological rates are mediated by temperature using a Q10 formulation. The model is coded in FORTRAN and MATLAB. Model source code is publicly available at http://www.pices.int/members/task_teams/MODEL.aspx.

b) The objectives of this model were twofold: (1) to represent the minimum trophic structure and biological relationships between and among all the marine ecosystem components thought to be essential in describing ecosystem dynamics in the North Pacific (i.e. the best balance between realism and complexity) and (2) to use the model as a tool to test the hypothesis that physical forcing factors regulate primary production and that the effect is apparent in zooplankton standing stock and then transferred to variation in higher trophic levels. Objective 2 was implemented by using a strategy of applying the same model structure and climate scenarios to three different ecosystems under the assumption that by removing the model as a confounding variable, any observed differences in dynamic response will be due to local characteristics and forcing

c) Data Needs: Initial starting values for all state variables and empirical equations to describe annual variations in solar radiation (PAR) and water temperature.

d) *Pros:* Using detailed process equations and mechanistic descriptions of the marine ecosystem allow close examination of the time-dependent fluxes through the ecosystem and the ecosystem response to perturbations. Data needs identify information gaps and sensitivity analyses isolate parameters that control model dynamics. *Cons:* Data demands are high. NEMURO needs 75 individual parameters. Using FORTRAN is not the most user-friendly modeling environment, making model post-analysis and the production of graphics awkward.

Key Reference:

Kishi, M. J., M. Kashiwai, D.M. Ware, B.A. Megrey, D. L. Eslinger, F.E. Werner, M.N. Aita, T. Azumaya, M. Fujii, S. Hashimoto, D. Huang, H. Iizumi, Y. Ishida, S. Kang, G. A. Kantakov, H-C. Kim, K. Komatsu, V.V. Navrotsky, S. L. Smith, K. Tadokoro, A. Tsuda, O. Yamamura, Y. Yamanaka, K. Yokouchi, N. Yoshie, J. Zhang, Y.I. Zuenko and V.I. Zvalinsky. 2007. NEMURO - A lower trophic level model for the North Pacific marine ecosystem. Ecological Modeling 202(1-2): 12-25.

Multi-trophic level food web models

NEMURO.FISH (Megrey et al, 2007)

a) NEMURO-FISH is an extension of NEMURO in which the LTL NEMURO is dynamically linked to a higher trophic level model of adult fish growth and population dynamics (i.e. the LTL and HTL are solved simultaneously). The HTL fish model is also a mechanistic numerical simulation model based on detailed process equations. A bioenergetics formulation is used to model fish growth and standard population dynamics equations, including an environment-dependent spawner-recruit model, are used to model population numbers. NEMURO.FISH has been configured for Pacific saury and Pacific herring. The fish life cycle for the herring version is closed, allowing multi-year simulations. All mass in NEMURO are expressed in units of mol N $l^{-1}day^{-1}$ and then converted to g wet weight m^{-2} day^{-1}. Biological processes do not simply scale with size/age. NEMURO.FISH uses different processes equations for unique ontogenetic life stages. Fish prey on three different zooplankton prey items represented with a multi-species Holling Type II functional response formulation. All fish biological rates are mediated by temperature.

b) The objective of NEMURO.FISH overlaps NEMURO objective (2): to use the model as a tool to test the hypothesis that physical forcing factors regulate primary production and that the effect is apparent in zooplankton standing stock and then transferred to variation in higher trophic levels (i.e. small pelagic fishes).

c) Data Needs: Principle forcing variables include water temperature, light, atmospheric climate index, and air temperature. The later two variables are needed for the environment-dependent spawner-recruit model. Other required parameters include weight and temperature parameters for the consumption and respiration process equations, temperature effect, prey vulnerability, and half saturation constant parameters.

d) *Pros:* See above. Using a well know mass balance approach based on the Law of Thermodynamics allows one to focus attention on important external regulators such as temperature and diet composition. Fish size-at-age data is typically available permitting an out-of-sample data source to validate and calibrate the fish model. *Cons:* The fish model adds an additional 78 parameters to NEMURO.

Key Reference: Megrey, B.A., K.A. Rose, R. Klumb, D. Hay, F.E. Werner, D.L. Eslinger and S L. Smith. 2007. A bioenergetics-based population dynamics model of Pacific herring (*Clupea harengus pallasii*) coupled to a lower trophic level nutrient-phytoplankton- zooplankton model: Description, calibration and sensitivity analysis. Ecological Modeling 202(1-2): 144-164.

Spatial lower trophic level food web models

ROMS-NEMURO (Arango)

a) Hernan Arango, at the Institute of Marine and Coastal Sciences, Rutgers University, has merged NEMURO with ROMS. A beta version is now available at http://www.pices.int/members/task_teams/MODEL.aspx

b) The objective of this work was to replace a simple NPZ (N-P-Z) with a more realistic NPZ LTL model (NEMURO – N-P-P-Z-Z-Z) into the ROMS model.

c) Data Needs: See the above web site for ROMS data needs.

d) *Pros:* Allows simultaneous solution of the ocean model primitive equation as well as NEMURO differential equations. Allows a more realistic simulation of the physical influences on biological production in the marine environment. *Cons:* Model complexity increases substantially. Use of ROMS requires a steep learning curve. ROMS has to be customized to the unique characteristics of each physical system (i.e. topography, bathymetry, boundary conditions, etc.) and requires independent data for model validation/assimilation.

Full ecosystem mass balance food web models

1990s Eastern Bering Sea, Gulf of Alaska, and Aleutian Islands food web models (Aydin, Gaichas, Ortiz et al)

a) Food web models account for energy flow between biomass pools throughout a given ecosystem as a “snapshot” in time. These models can be extended into spatial models and dynamic models (see below). The initial 1950s and 1980s Bering Sea models were constructed in Ecopath, and modeled 25 functional groups. The initial 1980s EBS Ecopath model was dis-aggregated to include 38 functional groups for comparison with a 36 group WBS model. The 1990s models of the EBS, GOA, and AI were constructed outside the EwE software but using Ecopath algorithms implemented in Visual Basic. This was done to include extensions facilitating spatial strata for field collected groundfish diets, standardized diet estimation from literature sources, improved expression of uncertainty and visualization of results, and much greater taxonomic detail (including juveniles and adults of all major groundfish and for dozens of forage species, birds, marine mammals, and for many detailed taxonomic categories within benthos and zooplankton), with the number of model groups ranging from 124 (AI) to 132 (EBS). Despite the contrast in the numbers of model groups, all of these models are most detailed and data-rich at the mid to high trophic levels occupied by the well-studied commercial groundfish species.

b) Each food web model had the basic objective of describing key energy flows within the ecosystem for the time period of interest; however, each set of models had differing additional objectives. The initial 1950s and 1980s EBS models were developed to test hypotheses regarding the effects of commercial whaling on the structure of that ecosystem. The 1980s EBS and WBS models were developed and compared to evaluate the differences and similarities between these linked but distinct regions, and to provide a unified framework for examining large scale climate and human induced changes in these LMEs. The 1990s EBS, GOA, and AI models were designed to fully exploit the large amount and high quality of data available for Alaskan fisheries and ecosystems. This level of detail was considered necessary to provide ecosystem based management advice, including estimates of predation mortality and diet composition to be used in single species stock assessments. Detailed Alaskan fisheries catch data was used to define 14-16 fisheries in each model with a full suite of target and incidental bycatch (both retained and discarded) species. This provides the capability to evaluate ecosystem effects of bycatch mortality on nontarget as well as target species. Low trophic levels and detritus groups were modeled in more detail to separate these important processes. In addition, both phytoplankton and zooplankton groups were separated to clarify and test hypotheses regarding energy flow pathways between large and small phytoplankton and copepods, euphausiids, mysids and other pelagic groups.

c) The models are all built to correspond to the spatial and temporal scale of present stock assessments (e.g., annual timestep for an entire region). Data on biomass, production, consumption, and diet composition are required for each modeled group. The models for more recent time periods contain the highest fractions of species and area appropriate parameters (due to continuous improvements in data collection across taxa), although all models resort to generalized literature-derived values for data-poor groups to some extent.

d) *Pros:* these models use the same biomass and productivity data as current stock assessments. Assembling the required data in the same units for all modeled groups clearly show data gaps; the resulting models represent comprehensive collections of databases and literature sources for future analyses. Building the models at a high level of detail allows for the broadest range of food web analyses, because large models can be aggregated to form simpler models. Comparisons of fishing and predation mortality for commercial species provide additional information for fishery management. Food web models have identified key interactions currently being investigated with more detailed multispecies modeling. Comparisons of similarly constructed models provide insight into ecosystem structure despite data gaps if assumptions are similar across systems. *Cons:* these models require food habits and consumption data for all groups which, for some key species, are not routinely collected. Taxonomically aggregated models may fail to represent important interactions between groups within the aggregate; however, taxonomically detailed models suffer from missing data for many groups. Both factors increase the uncertainty in model results. The larger models are complex to analyze (but can be aggregated, see above). Although these models serve as educational tools at present in the Alaskan fishery management process (and they have informed one FEP so far), the data they provide is difficult to integrate within the current management system.

Spatial full ecosystem food web models

Aleutian Islands (Ortiz)

a) This is a series of 14 longitudinally contiguous food web models (not based on ECOSPACE) along the Aleutian Islands extending from 164°W to 170°E (*i.e.* it covers the entire American portion of the Aleutian Archipelago as opposed to only the NPFMC management region of the Aleutian Islands as in the full mass balance ecosystem food web model). Each model covers 2-longitudinal degrees, portrays a simplified food web of 25 functional groups plus total fisheries removals, and was built *with data specific to the corresponding 2- longitudinal degrees area*. The models are independent, standardized (same functional groups and methodology across models) and follow the same equations and methodology as the mass balanced models but are left unbalanced to reflect the estimated biomass required to satisfy consumption by predators in each 2-degree area. Estimates of area-specific production for each of the 4 groundfish predators are later compared to cumulative removals by predation and fisheries. Like the models described above, this model accounts for energy flow between biomass pools throughout a given ecosystem and shows how the food web structure changes across space as a “snapshot” in time.

b) The objective of this work is to 1) evaluate changes in food web structure across space, 2) identify food web structure within ecosystems defined irrespective of management areas, 3) evaluate estimated local production vs. local removals by predation and fisheries, and 4) compare spatial results to those of the spatially aggregated food web model.

c) The models use data from all three Alaska management regions: the Aleutian Islands (central and western Aleutian Islands), the Eastern Bering Sea (northern portion of the eastern Aleutians) and the Gulf of Alaska (southern portion of the eastern Aleutians). Data on biomass, production, consumption, and diet composition are required for each modeled functional group. Values for production and consumption are the same across areas and were taken from the full ecosystem mass balance model for the Aleutian Islands. The food webs are based on biomass estimates for 7 predators which include: Steller sea lions (SSL), planktivorous and piscivorous nesting seabirds (6 and 10 species respectively), Atka mackerel, Pacific Ocean perch (POP), walleye pollock, and Pacific cod. Their feeding habits added an additional 17 groups: flatfish, rockfish, sculpins, other groundfish, salmon, myctophids, forage fish, crabs, shrimp, polychaetes, gelatinous zooplankton, euphasiids, copepods, benthic invertebrates, benthic amphipods, other zooplankton and offal. The selection of the functional groups was based on strong links for fish and SSL with feeding habits calculated from over 20,000 stomachs analyzed and scat (for SSL) analysis, reflecting the longitudinal changes in feeding habits along the Aleutian chain. Seabird biomass and diet were based on the species composition of the planktivorous and piscivorous groups at each 2-degree area. Fish and SSL biomass in each area is based on area-specific estimates. Fisheries removals include the total removals of Atka mackerel, POP, pollock and Pacific cod and the area-specific removals were proportioned based on an analysis of observer data. Scats from SSL were collected 1990-1998, fish stomachs used were collected 1981-2001 with most between 1986 and 1997.

d) *Pros:* it is based on local area-specific data with minimum assumptions. Model conveys clear changes in food web structure across a longitudinal gradient. Functional groups were chosen on strong links for any predator in any given area, so it captures prey groups that are important at local scales. Identifies areas where local production might be compromised due to excessive removals by predation and fisheries. Links global (ecosystem-wide) results to local condition (area-specific). Highlights different roles of the same predator depending on its location in the ecosystem. Highlights differences of effects of fisheries removals depending on location with ecosystem *Cons:* data intensive, requires all data to be spatially explicit (mostly with latitude and longitudinal information for each record). Data management can be challenging as it involves multiple management areas and requires GIS. Is not dynamic, the amount of data available allows either for spatial aggregation with annual temporal resolution or spatial resolution at 2 degrees but temporally aggregated. Updating is only worthwhile if sufficient new data across the entire archipelago is collected (that requires surveys from EBS, GOA and AI). Includes non-predation biomass estimates only for the predator groups, does not includes habitat, sediment type, etc.

Dynamic full ecosystem food web models

Gulf of Alaska (Aydin, Gaichas) with EBS and AI under development

a) Dynamic simulation models for Alaskan ecosystems have been developed in C/C++ using modified Ecosim equations (reference: Aydin et al. 2006) and the food web models developed for the

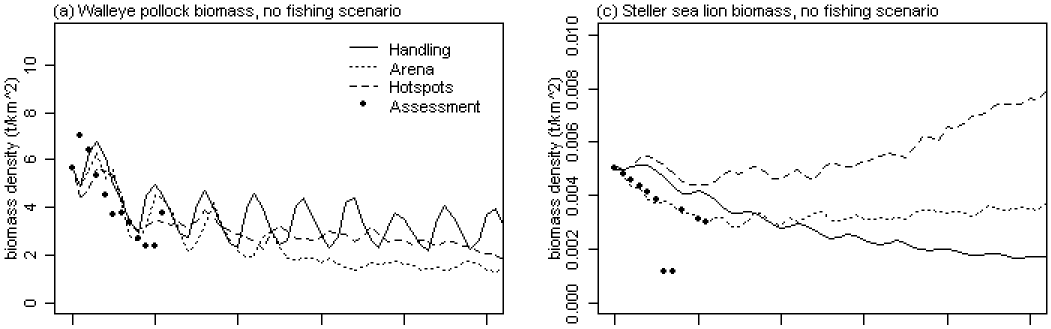
1990s described above. The Gulf of Alaska model accounts for age structured dynamics of 10 species of groundfish, 2 pinnipeds, and for the biomass dynamics of the remaining 107 model groups. The model can be forced with input time series of gear specific catch, biomass, production, mortality, and/or recruitment for any given functional group, and estimates a full suite of energetic and functional response parameters to fit to time series of total catch and biomass. Incorporating time series of diet data in parameter estimation is currently in progress.

b) The objectives of this modeling effort are to extend and improve the capabilities of Ecosim in order to evaluate hypotheses regarding the interaction of climate, fishing, and predation the Gulf of Alaska and other Alaskan ecosystems. A secondary objective was to free the model from its Windows operating system constraint to use a Linux parallel computing cluster in computationally intensive analyses. The model is currently being used in a variety of applications, including a Management Strategy Evaluation for GOA pollock (see above), scenario testing for a draft Steller Sea Lion Biological Opinion, and investigations of aggregate fishing thresholds in the GOA, as well as ecosystem indicator testing for the annual Ecosystem Assessment for the North Pacific Fishery Management Council.

c) The model implicitly requires all of the data used to construct the 1990s GOA food web model described above, as well as growth data for age structured species and time series to force the model. Time series of catch data as far back as 1800 have been used to force the model, but most biomass time series used in fitting do not begin until 1960, and are stock assessment model-generated time series. Time series of groundfish diet data from fishery independent surveys begin in 1980 and continue triennially or biennially through the present.

d) Pros: Increased flexibility over Ecosim software in terms of simulation length, allowable data types, and estimable parameters. Improved statistical parameter estimation and incorporation of uncertainty for examining different functional responses and performing full dynamic parameter fitting (see Figure). *Cons:* Time series data for mid and low trophic level forage species and primary production are lacking in this ecosystem. Time series of biomass are lacking for heavily exploited whales and king crabs, resulting in difficulties with hindcasts.

Key



Reference:

Aydin, K., Boldt, J., Gaichas, S., Ianelli, J., Jurado-Molina, J., Ortiz, I., Overland, J., Rodionov, S., 2006. Ecosystem Assessment. In: Boldt, J. (Ed.), Ecosystem Considerations for 2007, Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions. North Pacific Fishery Management Council, 605 W. 4th Ave., Suite 306, Anchorage, AK 99501. pp. 24-89.

Habitat models (spatial fishing impacts)

Model for evaluating fishery impacts on habitat, (Fujioka and Rose)

a) The model for evaluating fishery impacts provides estimates of the reduction habitat features for different fisheries conditional on assumed values of impact per unit of effort, recovery rates, and habitat distribution. Because we are primarily concerned with the net result of a habitat’s recovery rate and the rate at which it is impacted, differential equations were used to model recovery rate and impact rates on habitat, and to compute the level of impacted and unimpacted habitat over time. Impact rate decreases the amount of unimpacted habitat over time in the same way instantaneous fishing rate decreases the amount of fish over time. The model is similarly parameterized.

b) The model was developed for the evaluation and development of alternatives for mitigating impacts of North Pacific Fishery Management Council (NPFMC) fisheries. The final regulations for essential fish habitat (EFH) require Fishery Management Councils to act if a fishing activity adversely affects EFH in a manner that is “more than minimal and not temporary in nature .....”. Lacking further guidance from the NMFS Habitat Office, the NPFMC’s EFH Committee asked scientists of the Alaska Fisheries Science Center to provide guidance on criteria for determining “minimal” and “temporary”. After considerable deliberation, it became clear a basic logical mathematically consistent framework was needed to evaluate fishery impact. The term “temporary” was considered as a qualitative description associated with a high rate at which a habitat recovers from an impact and the term “minimal” as a low rate at which a habitat is impacted.

c) The parameterization of fishing impact allows effort data from the Observer Program to be utilized. However, data on habitat impact per unit effort for each habitat had to be assumed, as data are lacking.

d) *Pros:* the model provides a mathematically consistent framework to unify the elements of fishing impacts on habitat. *Cons:* the lack of information on the habitat impact per unit of effort, recovery rates of different habitat or habitat features, and the distribution of bottom habitat will likely prevent definitive conclusions.

NWFSC

Ecosystem simulations and bioenergetic models

Atlantis

Atlantis is a simulation modeling approach developed by CSIRO scientists in that it integrates physical, chemical, ecological, and fisheries dynamics in a three-dimensional, spatially explicit domain (Figure 1). In Atlantis, ecosystem dynamics are represented by spatially-explicit sub-models that simulate hydrographic processes (light- and temperature-driven fluxes of water and nutrients), biogeochemical factors driving primary production, and food web relations among functional groups. The model represents key exploited species at the level of detail necessary to evaluate direct effects of fishing, and it also represents other anthropogenic and climate impacts on the ecosystem as a whole. We built an Atlantis model of the Northern California Current, and efforts are now underway to build a smaller scale version of this model focusing on central California. Additionally, models are being constructed for the Gulf of California and Puget Sound.

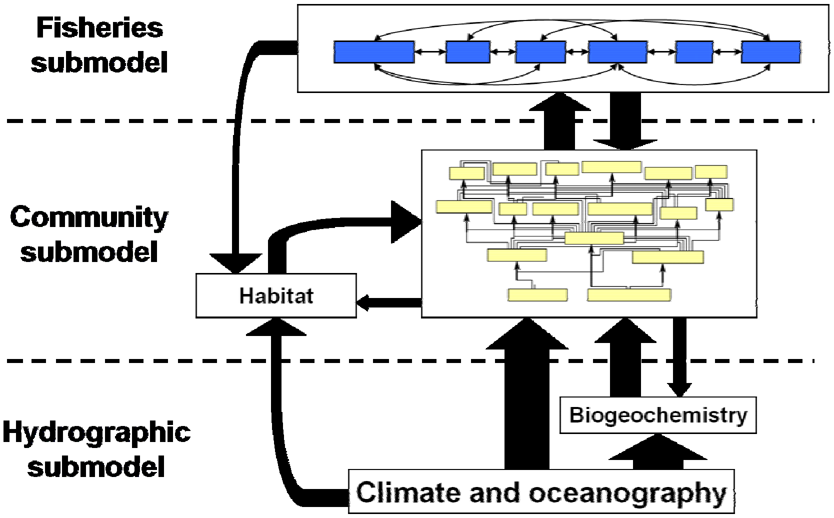


Figure 1. Schematic of the Atlantis ecosystem model which achieves the critical goal of integrating oceanography, climate, habitat, trophic interactions and fisheries dynamics in a single whole-ecosystem framework.

Marine Ecosystem Climate Change Analysis Framework

We are currently adapting the NEMURO suite of plankton and coupled fish bioenergetics models (described in a special issue of Ecological Modelling, vol. 202, no. 1-2) into the Earth Systems Modeling Framework (ESMF; www.esmf.ucar.edu). This project will provide a software framework for international collaboration on analysis of marine ecosystem response to climate change. The NEMURO models have been developed by the PICES MODEL Task Team specifically for this purpose, but their use is limited by the need to re-implement the code within different ocean circulation modeling frameworks. Implementing the models as components of the ESMF will ease the process of adapting them to alternative circulation models, thus opening their use to a broader community of climate researchers. Initial code release is anticipated in fall 2007. Data needs vary with the particular application, but ideally would include high frequency observations of nutrients, phytoplankton, and zooplankton concentrations and fish abundances and weights at a number of locations within the model domain. *Pros:* The NEMURO suite of models provides a standard set of coupled plankton/bioenergetic models that has been applied across the North Pacific, and could be adapted for other areas. *Cons:* The models have high data requirements, and have not yet been well-tested against data.

California Current Plankton Production

We have developed a coupled biophysical model of the Northern California Current coastal upwelling zone to produce a “biological productivity-upwelling index.” A time series of nutrient and plankton observations from the Newport Hydrographic (NH) Line is being used to calibrate both physics and biological components of the coupled model. We have compared two plankton models (a simple NPZ model and the more complex PICES NEMURO model) for one year of observation data using a simplified one-dimensional cross-shelf physics model driven by the Bakun coastal upwelling index at 45° N (Wainwright et al. 2006). Following this preliminary work, we determined that a model of intermediate complexity would be most appropriate for our purposes, so we implemented a 6-compartment “NNPPZD” model (2 nutrient, 2 phytoplankton, one zooplankton, and 1 detritus compartments). A more rigorous calibration of this model to 1997-2003 data has been completed. We are continuing development of this model of the NCC coastal upwelling zone, incorporating more realistic physics and validating the model against longer-term nutrient and plankton data series. *Pros:* the model provides a rapid calculation of plankton production that allows non-linear estimation and Monte Carlo studies. *Cons:* the model is quite site-specific, and probably could not be adapted outside of a coastal boundary current upwelling zone.

Northern California Current Pelagic Foodweb

We developed two quantitative, mass-balance food-web models for the upwelling season of the northern California Current ecosystem over the Oregon inner-shelf within the EcoPath framework (Ruzicka et al. 2007). The models are parameterized for spring and summer seasons and are based upon the annual scale model developed by Field et al. (2006). In an initial application, we investigated the importance of large jellyfish and their role as potential competitors for zooplankton prey with coastal pelagic fish including juvenile salmon. Information about fish and jellyfish biomass, distribution, and diet was derived by pelagic trawl surveys, and information about lower trophic-level production was provided by time-series zooplankton surveys. Further applications will examine top-down, bottom-up, and sideways influences of the ecosystem on juvenile salmon survival. Data needs are similar to any EwE model. *Pros:* the model provides an integrated view of the local ecosystem mass balance. *Cons:* There is little data available to validate the model, so results have a high degree of uncertainty.

Columbia River Plume Integrated Modeling

We are using simulation models to develop a better understanding of the mechanisms that link river management and climate variability with salmon survival. Four types of models will be used: physical circulation, plankton production, salmon bioenergetics and migration, and foodweb models. The models are being used in an integrated framework to link field and laboratory data to a number of hypotheses regarding early marine survival of salmon in and near the Columbia River plume. The models are in various stages of development and application, resulting in different time lines for model development and validation. The physical circulation model (SELFE) is already implemented and tested for this system. We are currently adapting existing plankton models into the physics modeling framework, and anticipate an operational model within a year. The salmon bioenergetics model is currently being developed. This is a site-specific suite of models with intensive data needs, and so is not portable to other situations. It could, however, serve as an example of integrating a variety of models and data for a regional ecosystem assessment.

Northern California Current Ecospace model

This model was built using the Ecospace module of the Ecopath with Ecosim (EwE) software. Ecospace is a spatial mass balance model that arrays a food web, habitat types, fishing fleets, and both physical and biological oceanographic properties into a grid-based domain. Within each grid, Ecosim-style dynamic food web models operate at monthly time steps, with food web components and fleets able to move to adjacent cells based on user-defined movement rates. The Northern California Current model is an adaptation of the Northern California Current EwE model for the 1990s that was developed by Field (2005). It is being used to run qualitative scenarios that examine the effects of different marine protected area (MPA) configurations, as measured by fishery and ecological indicators. Data requirements include the core data needed for each component of an EwE food web (biomass, production and consumption rates, ecotrophic efficiency, fishing mortality by fleet, diet), along with information required to contextualize the food web spatially (e.g., locations of coastlines, locations of bathymetric contours, locations of demersal habitat types, species affinities to different habitats, dispersal rates, seasonal migration patterns, locations of ports, ranges of fishing fleets). Ideally, available data would include time series of biomass measurements for several key species against which to compare model outputs and/or to use as a basis for adjusting the strength of species interactions. *Pros* of the approach include: (1) the ability to account for patchiness, migrations, and other spatial forms of food web complexity; (2) web-based interfaces to data on bathymetry and mean sea surface chlorophyll of numerous marine ecosystems, which greatly eases development of the grid-based model domain; (3) the ability to add in management zones, such as marine protected areas, to examine policy alternatives; and (4) the ability to easily extract ecosystem and fishery indicators from the model output. *Cons* include: (1) some oversimplifications of migratory patterns; (2) physical forcing through circulation patterns is difficult to incorporate; and (3) time series of model outputs at subregional scales are difficult to extract when using some versions of the software.

Groundfish bioenergetics models

Bioenergetics models are dynamic fish energy budgets. They can be fit to existing data or used to make predictions under assumed environmental conditions. The models use observed or experimentally determined relationships between fish physiology, fish size, prey quality, temperature, and possibly other variables (e.g., salinity, dissolved oxygen, flow velocity) to estimate variables such as prey consumption or growth. Bioenergetics models are often used to explore how environmental variability (namely changes in temperature or diet composition) will affect fish growth; how much predatory impact a fish population has on its community; and how certain materials such as contaminants or tracers are accumulated. Bioenergetics models are currently being applied to several species of Northeast Pacific groundfish to estimate their responses to climate anomalies and to draw hypotheses about the potential for prey competition among key assemblages. Data requirements include parameters that describe size- and temperature-dependent functions of consumption, respiration and waste production; size-dependent diet information; energy or mass investment in reproduction; and seasonal temperature data. *Pros* of this approach include: (1) the flexibility to explore a wide range of hypotheses on how environmental conditions affect fish growth and consumption; and (2) a substantial experimental, theoretical and empirical literature. *Cons* include: (1) a lack of laboratory-derived metabolic parameters for many species, leading to parameter "borrowing" from similar species; and (2) a lack of ontogenetic diet information for many groundfish species of interest.

Puget Sound food web/ecosystem modeling

We are developing ecosystem modeling frameworks to address 2 main questions: (1) how do changes in nearshore habitat distribution and spatial extent affect the flow and quantity of ecosystem services throughout the Puget Sound region? and (2) what is the likely impact of alternative strategies (e.g., land use changes, protection of habitats, harvest management, setting instream flows, managing water quality, or locations of marine protected areas) on the status of ecosystem components? The ecosystem services modeling is using a combination of GIS-based spatial and statistical models relating the distribution and extent of different nearshore marine habitats to changes in the dynamics of species and the ecosystem services they provide. We also will model how changes in nearshore habitats due to human activities affect the magnitude and flow of ecosystem services.

Multi-species models

Multi-salmon species modeling

Several projects are using life-cycle models of salmon to ask how climate, freshwater, estuarine, and marine habitat conditions, and harvest, hatchery, and hydropower management affect population status and species interactions. In Puget Sound, we are modeling chinook metapopulation dynamics as a function of changes in the upland/freshwater habitat capacity and quality and the estuarine/marine environmental capacity and quality using the SHIRAZ model. Competition from hatchery salmon (all species), harvest, and climate-mediated changes in ocean and freshwater conditions also are included in the model. Twenty-two populations are included in the model, each with distinct distributions of survival and capacity in freshwater, estuarine, and marine habitats. Changes in survival and capacity at each life stage are a function of climate and local environmental conditions, potential for intra- and interspecific competition, and harvest rates. Similar modeling efforts in the Columbia River Basin are exploring the impacts of climate variability, harvest, hatchery interactions, and hydropower impacts on population dynamics of several salmon species using matrix population models.

Groundfish multispecies model

This model simulates rockfish population dynamics, predation by Pacific hake on juvenile rockfish, and bycatch of adult rockfish in hake fisheries. The purpose was to discern which hake-related mortality source (predation or bycatch) was most important for overfished rockfish stocks, and whether Pacific hake predation on juvenile rockfish was sufficient to affect rockfish rebuilding times. Each species has an age-structured, dynamic population whose biology is based on recent stock assessments, with direct and indirect interactions affected by stochastic climate forcing variables. The overall goal of using this approach is to determine if dynamic species interactions such as predation are important enough to be explicitly incorporated into stock assessments and/or rebuilding plans of key fish species. Data requirements include core life history parameters of each species, consumption rates by the predator upon the prey, harvest and bycatch rates of both species, and rebuilding targets for the overfished species. *Pros* of this model are: (1) the flexibility to easily change life history parameters so that different predators or prey can be examined; and (2) the incorporation of three major ecosystem-scale factors (predator-prey interactions, fishing, and climate) into a relatively simple modeling framework, which allows for rapid, heuristic examination of hypotheses. *Cons* of the model are: (1) a lack of spatial resolution; (2) insufficient information on the form of the predator-prey functional response; and (3) simplistic and arbitrary assumptions about factors such as the effect of climate anomalies on spatiotemporal overlap of the two species.

Multivariate auto-regressive first-order models

A major challenge facing those who study community dynamics is characterizing how the constituent populations interact. A recently developed technique to solve this problem takes the approach of statistically fitting a stochastic community model – specified as a multivariate auto-regressive first-order (MAR-1) process – to time series data to infer community interaction strengths. When applied to a time series of a sufficiently long duration, MAR-1 models can provide insight into community dynamics (Figure 2). Using simulation models, we have demonstrated that such models can provide robust descriptions of interaction strengths of west coast groundfish assemblages. We are now in the process of analyzing different subsets of data to determine the strength of interactions among members of guilds and among different guilds.

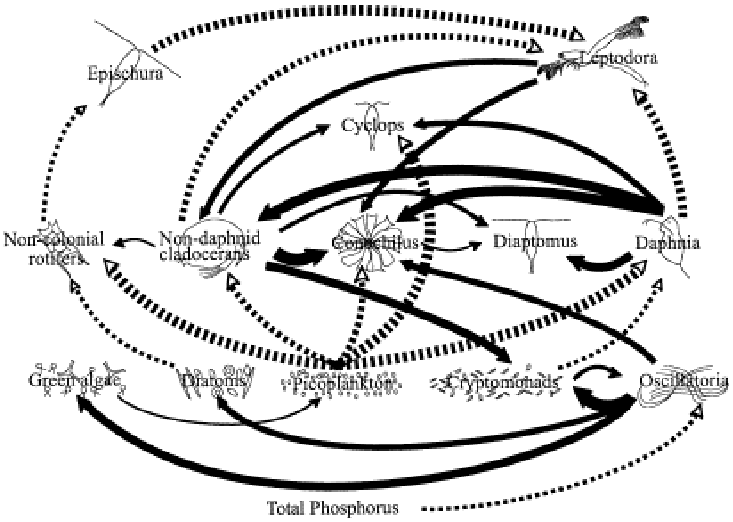


Figure 2. Food web interactions suggested by a community-wide MAR model. Line thickness reflects coefficient size. Arrows point toward the response species. Solid lines are negative effects, and dashed lines are positive effects. (From Hampton et al. 2006)

Climate related models (not covered in simulation section)

Global climate and land-use impacts on freshwater and estuarine habitats and salmon

Two modeling projects use a series of linked models to project future scenarios of climate and land use conditions, and ask how those alternative futures affect freshwater habitat conditions and salmon population dynamics. In the Puget Sound region, two global climate models (GCMs) were downscaled and generated alternative forecasts of precipitation and air temperature data that then were input into a mechanistic hydrology and land cover model (DHSVM). The alternative futures also included different land use/land cover scenarios based on projections of watershed restoration or degradation due to human activities. The outputs of the hydrology /land use models were then input into a fish-habitat life cycle model (SHIRAZ) for estimating population status and the likelihood of recovery for salmon. The impacts of climate and habitat restoration on stream temperatures, flows, and freshwater and estuarine habitat capacity were thus translated into consequences for salmon population dynamics. A similar modeling project is near completion for two watersheds within the Columbia River Basin.

Modeling the effects of ocean acidification

Ocean acidification caused by anthropogenic increases in atmospheric $C0_2$ is likely to cause significant changes in marine food web dynamics as susceptible species are reduced in abundance or entirely eliminated. To understand how the ocean may change with acidification, we are developing ecosystem models that consider predator-prey dynamics coupled with links to environmental drivers. With these models, we can see how changes in one part of the ecosystem from ocean acidification propagate throughout the entire system. Our research is focusing on two spatial scales, 1) Puget Sound, and 2) NE Pacific shelf. The Puget Sound project has a higher spatial resolution and looks at effects in a complex estuary. The NE Pacific shelf project is looking at a courser spatial scale and comparing upwelling, downwelling and transition zone responses to ocean acidification. These projects are in the early stage of development, but are likely to become a high priority.

Quantitative toolset to forecast the effects of climate variability on the population dynamics of Pacific salmon.

The centerpiece of this effort is a stage-based, stochastic life cycle model for Pacific salmon (Zabel et al. 2006). Within the model, survival from one life stage to the next is related to the physical environment based on statistical model fits to empirical data (e.g., Scheuerell and Williams 2005, Crozier and Zabel 2006). Using various greenhouse gas emission scenarios and climate model outputs from the University of Washington Climate Impacts Group, we are developing indices of future ocean conditions (e.g., Mantua et al. 1997) and freshwater temperatures and flows (e.g, Battin et al. 2007) to use as input drivers to the life-cycle model. We can then use various climate scenarios to project future population trajectories and estimate viability measures such as population growth, mean abundance, and probability of extinction. Data requirements are extensive and include demographic information for parameterizing the salmon life-cycle model, spatially explicit habitat information (e.g., temperature, flow, pool area), and gridded climatological data.

Habitat and water quality related models

Pacific salmon as transfer vectors of nutrients and energy across ecosystem boundaries

This modeling effort examines the important role of Pacific salmon in transferring nutrients and energy among ocean, estuarine, freshwater, and terrestrial ecosystems via two major avenues of research. The first involves relatively simple mass-balance models of nutrient import-export to compare historical and contemporary biogeochemical cycles as driven by density-dependent salmon population dynamics (e.g., Figure 3). This straightforward approach requires basin-specific counts, and size distributions, of juvenile and adult salmon. The second model relies on the use of stable isotopes as natural tracers to identify the movement of nutrients and energy from salmon to freshwater and riparian food webs (e.g., Kline et al. 1990, Scheuerell et al. 2007). This information is then being used to develop a multivariate "map" of ecosystem status with respect to food-web structure and modified/restored habitat conditions. Collection and processing of extensive stable isotope data can be time consuming and expensive, but the resulting information is very useful for examining energetic pathways in ecosystems.

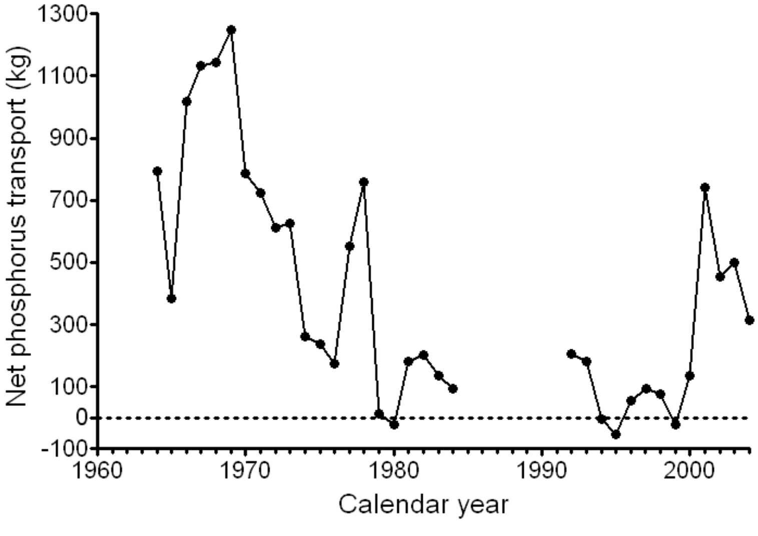


Figure 3. The net transport of phosphorous as a function of upstream migration by adult salmon and downstream migration by salmon smolts. (From Scheurell et al. 2005)

Puget Sound hydrodynamic model as a tool to prioritize sites for habitat restoration

Success of a restoration projects depends not only upon opportunities for restoration, but on the hydrodynamic processes that impact those sites and how individuals in the populations use them. We are developing methods to explicitly incorporate movements of individuals into an existing hydrodynamic model of the Whidbey Basin, which will allow us to make specific predictions about how processes influence site suitability and how populations make use of them. Our goal will be to create an add-on module to existing visualization software of passive particles (i.e. NOAA's GNOME model for oil spill mediation), which by linking to real-time output of a hydrodynamic model, allows planners to visualize where to refocus restoration efforts in the estuary and along shorelines.

Integrated watershed process-habitat-salmon population analyses

Not a model per-se, but links many disparate simple models that describe (1) land use effects on habitat and (2) habitat effects on fish. Historical analysis of habitat change is used to identify losses and degradation of multiple habitat types within watersheds and deltas while life-cycle models or limiting factors models identify importance of each habitat loss to salmon species. Historical analyses of land use change identify causes of habitat change, and simple landscape models help estimate land use effects on sediment supply, hydrology, and riparian functions. These landscape/habitat analyses identify necessary restoration actions.

Desktop watershed

An emerging, process-based model structure that predicts river habitat conditions from landscape and land use attributes, and ultimately links habitat attributes to population performance. The formal model is in it's conceptual stages, but simple case studies have been completed recently, including modeling of 'intrinsic potential' of river reaches to function as salmon habitat, predicting floodplain extent and dynamics, predicting spawning gravel locations and characteristics, and predicting stream temperature. These models can be combined with salmon life-cycle models to estimate natural potential production from river basins and to assess impacts of land uses.

Watershed-scale restoration decision support system

The model is a scenario-based decision support system to guide the development of a watershed scale management plan for Pacific salmon. The decision support system enables a series of predictions about future landscapes given alternative watershed scale management strategies. It organizes empirical data and predictions from multiple models including hydrological, sediment, riparian, egg-to-fry survival, life cycle, and spawning capacity models. The decision support system provides predictions of the quantity, quality, and distribution of aquatic habitat as well as capacity and survival predictions for multiple species that might result from particular watershed scale restoration actions.

A model of pesticide effects on chinook salmon growth

A model of pesticide effects on chinook salmon growth investigates the extent to which pesticide-induced reductions in invertebrate (prey) availability combined with sublethal exposures to pesticides might affect the physiology and behavior of salmon with an emphasis on somatic growth, survival, and long-term population productivity. The model relies on a series of relationships to link the acetylcholinesterase inhibition in individual salmon to the feeding, growth and size and juvenile survival of individual chinook salmon. The survival is then fed into a life-history population model adapted to incorporate a size-dependent survival rate for a three-month interval during migration to the ocean to see how these pesticide exposures could influence population productivity.

Coho salmon pre-spawn mortality (PSM) models

Coho salmon PSM models examine the impacts of continued urban growth on established wild coho populations and metapopulations by using scenarios which simulate changes in land use, runoff management or rain events. PSM has been observed at rates from ~20% to 90% in the urban streams of Puget Sound, and a weight of evidence suggests causative factors involve stormwater runoff from urban and residential areas.

Contaminant exposure effects on chinook salmon

The objective is to investigate contaminant exposure effects on chinook salmon populations utilizing the Lower Columbia River (LCR). This model examines the potential effects of sublethal contaminant exposure during freshwater and estuarine residence on the growth rates and productivity of 22 populations of fall chinook within the LCR Chinook ESU. Population changes were modeled by changing demographic rates through: 1) reduced first year survival; 2) delayed mortality; and 3) reproductive inhibition to simulate toxicant effects which were documented in field and laboratory studies. We assessed the impacts of heterogeneous contaminant distribution by applying differential exposure scenarios to the LCR fall chinook populations connected by straying and treating them as a metapopulation

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SWFSC

George Watters, Jay Barlow, John Field, and Andrew Leising

Here we outline a set of population- and system-dynamics models that meet two criteria: 1) models that are in use or under active development by researchers at the Southwest Fisheries Science Center (SWFSC); and 2) models that, to various degrees, go beyond single-species approaches by including information on a species' prey, predators, or competitors. Note that our second criterion excludes those approaches in which population-dynamics models for single species are extended to consider how the distribution and production of that species are related only to the physical environment. Our focus on population- and system-dynamics models further excludes research on so-called "ecosystem indicators" and on using statistical models to describe the physical and biological habitats of species. Note, however, that all three types of work excluded from this outline are important components of research being conducted at the SWFSC. Our outline is presented in an order of increasing model complexity (where complexity is indicated by the number and type of interactions among species), starting with "extended single-species" models and ending with food-web and "whole ecosystem" models. For each model we identify a) what model is being used, b) what it is being used for, c) its data needs, and d) its pros and cons. Plagányi (2007) provides substantial, general information on data needs and the pros and cons of various modeling approaches; thus, with respect to these topics, our presentation mainly focuses on issues that are specific to our efforts.

Extended single-species models (least complex)

Extended age- and size-structured model (J. Field et al.)

a) An age- and size-structured model describing the dynamics of an important forage fish has been extended to include the use of food-habits data collected from predators of that fish. The model is implemented in Stock Synthesis 2 and fitted to food-habits data that provide information about variations in cohort strength of the forage fish.

b) The objective of the modeling effort is to characterize and describe changes in the biomass of shortbelly rockfish (*Sebastes jordani*) in the California Current. This species is not currently targeted by a commercial fishery, contemporary bycatches are small, and historical catches were modest to inconsequential. This rockfish is, however, a key forage species for many fishes, birds, and marine mammals. There are plans to continue developing this model, in particular to use information on the abundance of sea lions and their demand for prey to develop an index of changes in the natural mortality rate of the prey fish.

c) The model is fitted to indices of abundance developed from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) larval surveys, West Coast triennial trawl surveys, central California trawl surveys for juvenile rockfishes, and frequency of occurrence in the food-habits data for both common murres and sea lions. Generalized linear models are used to standardize these series. The model is also fitted to length-frequency information from the sea lion food-habits data (where length compositions are based on fish length-otolith length regressions) and to a point estimate of spawning biomass based on the larval production method.

d) *Pros:* The food-habits data are informative about variations in the abundance of an important forage fish despite the absence of substantial fishery impacts. *Cons:* The model essentially maintains a single-species focus, and there is no consideration of how variations in forage biomass in turn affect predators. Similarly, although the importance of shortbelly rockfish as a forage species is explicitly acknowledged, the model does not include temporal variations in natural mortality that are driven by temporal variations in predator demand. There are plans to address both of these issues in the future.

Extended Pella-Tomlinson model (G. Watters et al.)

a) The Pella-Tomlinson model has been extended to include temporal variation in the carrying capacity (*K*) of a top predator. Annual estimates of carrying capacity are fitted to indices of prey abundance (“observations of *K*”) that are developed from field sampling (e.g., with nets or acoustics). The model is Bayesian and implemented in OpenBUGS.

b) This model is currently used to provide status assessments for three stocks of short-beaked common dolphins (*Delphinus delphis*) and advise on sustainable mortality levels (i.e., potential biological removals, PBRs, and dolphin mortality limits, DMLs) for these stocks. There are plans to apply the model to other dolphin stocks (e.g., northeastern offshore spotted, *Stenella attenuata,* and eastern spinner, *Stenella longirostris*, dolphins) in the eastern tropical Pacific.

c) The model requires estimates of annual, incidental mortality; estimates of abundance from research surveys; observations of *K* (e.g., indices of prey abundance developed from net or acoustic samples); and prior information about various other parameters.

d) *Pros:* The model can be used to provide concrete, tactical advice on sustainable mortality levels while explicitly acknowledging both that *K* may have changed over time and that there is uncertainty in the nature of such changes (the model also integrates over other sources of uncertainty). The model is likely sufficiently simple to be implemented as the "assessment model" in a multispecies-MSE (and there are plans to do so). *Cons:* The model essentially maintains a single-species focus (e.g., there is no consideration of how dolphin predation affects prey biomass). Simulation testing is needed to identify an appropriate sampling scheme (e.g., how often to observe *K*) and evaluate the general efficacy of fitting to observations of *K* (e.g., whether such fitting leads to bias when there actually is no relationship between the observations and *K*).

Minimally realistic models (models of intermediate complexity)

Prey consumption by cetaceans (J. Barlow et al.)

a) A mass-specific consumption model has been used to estimate prey consumption by cetaceans in the California Current, and these calculations have been extended by using a simple trophic transfer model to estimate the fraction of the annual net primary production in the California Current that supports these cetaceans. The trophic transfer model is extended from previous work to include a carbon:wet-weight conversion factor and a term describing the efficiency of energy transfer between trophic levels. Calculations are made for 26 groups of cetaceans (most of which are resolved to the species level) and eight prey categories from different trophic levels. The model is implemented in Microsoft Excel.

b) This work takes a trophodynamic perspective and uses contemporary estimates of cetacean abundance with an aim to examine the role of cetaceans in the California Current ecosystem.

c) The model requires data on cetacean biomass (which itself is estimated from group-specific estimates of mean body mass, abundance, and information on sex ratios), the diet composition of cetaceans relative to predefined prey categories, the trophic level and carbon:wet-weight conversion factor for each prey category, and the efficiency of energy transfer between trophic levels. The model also uses area-specific estimates of primary production. These latter estimates are derived from remotely sensed surface chlorophyll *a* concentrations, photosynthetically active radiation, and sea-surface temperatures.

d) *Pros:* The model demonstrates that although the total biomass of baleen whales is about four times that of toothed whales, the estimated prey consumption by these two taxa is about equal and, together, may require about 9% of the primary production in the California Current (assuming that the trophic transfer efficiency is 10%). Furthermore, the level of primary production required to support baleen whales is less than one fifth that required to support toothed whales. *Cons:* The model estimates how much prey is required to support cetaceans; it does not address how this demand relates to demand by competing predators or how it might affect forage groups. Current data only provide a snapshot of the consumption requirements for cetaceans. Model predictions depend on the values of multiple parameters, but the effect of uncertainty in these values has not been fully explored (although alternative assumptions about the efficiency of energy transfer between trophic levels have been considered).

Zooplankton IBM (A. Leising et al.)

a) An individual-based model has been developed to describe how varying environmental conditions (both physical and biological conditions) cause copepods (*Calanus pacificus*) to go into and come out of dormancy. This is an important process because it mediates the availability of copepods as prey to pelagic predators such as anchovies and sardines. When copepods are dormant, they are not vulnerable to predation. Furthermore, the reproductive potential of an individual copepod is partly determined by aspects of the dormancy process. The model is implemented in MatLab.

b) The proximate objectives of this effort are to understand how past environmental conditions may have influenced the dynamics of copepod populations in the California Current. The ultimate objective of this work is to develop a tool that can be used to forecast how copepod populations will respond to climate change and thus become more or less vulnerable to predation by pelagic fishes.

c) Data requirements for this IBM include temperature (at a variety of depths) and phytoplankton biomass (the magnitude, timing, and length of the spring bloom). One or both types of these data can be obtained from observations or predicted from another model. In the latter case, temperatures can be predicted from ocean circulation models, and phytoplankton biomass can be predicted from NPZ models. Thus, there are plans to link the copepod IBM to these other approaches (which themselves require various types of data) and develop a broader modeling framework. Note also that other types of information (e.g., from laboratory experiments) are required to parameterize the behavior and growth dynamics of copepods within the model.

d) *Pros*: This modeling effort provides a method of simulating a mechanistic, rather than a statistical, link between the physical environment and the abundance of an important prey species within the California Current. *Cons:* Currently, copepod predators are not an explicit component of the model and, therefore, there are no behavioral responses to top-down pressures within the IBM.

FOOSA (formerly krill-predator-fishery model) (G. Watters et al.)

a) FOOSA is a minimally realistic and spatially explicit predator-prey model designed to address the problem of how fishing on a forage species might impact its predators. The model describes the dynamics of one prey group, up to four predator groups, and a fishery in each spatial cell. A simple, but flexible, power function is used describe how predator breeding success is determined by prey availability. FOOSA includes functions to conduct Monte Carlo simulations and simplified management strategy evaluations (MSEs), summarize model output using a suite of performance measures (for the prey, predators, and fishery), and visualize results using a variety of plots. FOOSA is implemented in R.

b) FOOSA was initially developed with the intent to advise the Commission for the Conservation of Antarctic Marine Living Resources on tradeoffs involved with krill fishery management in the south Atlantic – particularly with regard to subdividing a basin-wide catch limit for krill among 15 “small scale management units” in which various predators (e.g., seals, whales, penguins, and fishes) breed. The current framework could easily be adapted for use in the California Current, and there are plans to further generalize FOOSA for application to other systems where there is less interest about the effects of fishing for forage species and more interest about the effects of fishing for top predators that compete with protected resources for a common prey resource (e.g., effects of tuna fishing on dolphins in the eastern tropical Pacific).

c) Currently, FOOSA cannot be fitted to data, and, therefore, data must, as far as possible, be processed externally to develop "informed" parameter estimates. A wide variety of spatially and seasonally explicit parameter estimates are required to run the model, including those describing stock-recruitment relationships and movement rates for prey, functional responses and stock-recruitment relationships for predators, and the amount of bias and observation error in future monitoring schemes. When data are not available to estimate a parameter, FOOSA is structured to facilitate sensitivity analyses that bracket uncertainty. FOOSA also requires spatially explicit estimates of predator and prey abundance; these are used to initialize the model. There are plans to enable parameter estimation within FOOSA, and it is likely that time-series data (e.g., of prey and predator abundances) will be used for fitting.

d) *Pros:* A flexible parameterization and Monte Carlo capability facilitate exploration of uncertainty. FOOSA facilitates simple MSEs, and is focused on describing how management strategies affect the performance of prey, predators, and the fishery itself. *Cons:* Despite an attempt to be minimally realistic, results are sensitive to parameters for which there are limited or no data to support their estimation. Consumption of prey by juvenile predators is not in the accounting. FOOSA may require customized coding to alter fishing patterns beyond the six available options.

SEAPODYM and APECOSM (G. Watters et al.)

a) SEAPODYM (Spatial Ecosystem and Populations Dynamics Model, developed by P. Lehodey et al.) and APECOSM (Apex Predators Ecosystem Model, developed by O. Maury et al.) are being used to model the dynamics of skipjack, yellowfin, and bigeye tunas in a comparative study that is being conducted under the umbrella of the GLOBEC Climate Impacts on Oceanic Top Predators Program (CLIOTOP). Both of these models use the same forcing fields (e.g., temperature and dissolved oxygen), but they have different representations of tuna prey at middle trophic levels (e.g., SEAPODYM has six forage components while APECOSM has two size-structured forage components). Both models also use advection-diffusion equations to model spatial dynamics, but have different representations of tuna behavior and physiology (e.g., SEAPODYM describes habitat preferences phenomenologically while APECOSM describes them from an individual's physiological status). Both models predict catches and catch rates for multiple tuna fisheries, and these predictions are compared to observations.

b) This work aims to identify the relative importance of fisheries and the environment in structuring "tropical tuna ecosystems" and determine whether there are mechanisms that explain variations observed across species, trophic pathways, and ocean basins. These objectives are being addressed by first parameterizing SEAPODYM for the Pacific Ocean and APECOSM for the Indian Ocean and then "switching" ocean basins for both models without reparameterizing them (e.g., simply use the Indian Ocean physical forcing fields to drive SEAPODYM without changing the description of tuna habitat preferences). Comparisons to observed data will be made in both phases: to aid in parameterizing both models in the first phase, and to assess the predictive capability of both models (and thus their underlying assumptions) in the second phase.

c) Both models require a substantial amount of data. They are driven from the bottom-up using fields (e.g., temperature, dissolved oxygen, and primary production) that are both hindcasted and forecasted from coupled physical-biogeochemical models (currently the coupling is offline). The models are driven from the top-down using historical data on fishing effort (e.g., from longline and purse-seine fleets). It is intended that, ultimately, the spatio-temporal resolution of all these forcing fields be 0.5° x 0.5° x month. Various other data are also used to parameterize both models (e.g., data recorded by archival tags are used to develop habitat preference models and observed catches by various tuna fleets are used in comparison with model predictions).

d) *Pros:* Both models make reasonable predictions about temporal and spatial trends in tuna catch rates. Both models provide methods of simulating mechanistic, rather than a statistical, links between the physical environment, the abundance and distribution of forage groups, and tunas. The comparative approach offered by utilizing two different models that are forced with the same fields is appealing. *Cons:* Neither model currently describes competition among tunas for common prey resources (different runs are conducted for different tuna species). Neither model includes top-down forcing from known tuna predators (e.g., billfishes). There are few time-series data to condition or validate predictions for the forage components in either model. Both models are very compute-intensive and run times are long.

Food-web and ecosystem models (most complex)

Food-web model of the northern California Current (J. Field et al.)

a) Ecopath with Ecosim (EwE) has been used to describe the food web in the northern California Current (NCC). This is a complex implementation of EwE with 63 groups (21 of which are commercially important) that includes physical forcing from both the bottom-up (*via* changes in primary and secondary production) and the top-down (*via* changes in the vulnerability of various prey species to migratory predators such as hake). The model is most highly resolved at middle trophic-level predators, particularly groundfish.

b) The initial objectives of this work were to improve our understanding of how physical, ecological, and fisheries processes interact to affect the abundances of commercially important fish and shellfish populations, and, ultimately, to provide a foundation for developing proposals to integrate ecosystem-based management approaches into the management regime for the NCC. More recently, there has been an effort to use this model for better understanding the specific role of squid (particularly *Dosidicus gigas*) in the NCC and how the role of squid in the NCC compares to that in other ecosystems.

c) As with most EwE models, the basic Ecopath parameters (e.g., initial biomasses, productivities, consumption rates, and diets) were developed from a large pool of source material that includes traditional peer-reviewed literature, grey literature, stock-assessment reports, meta-analytic methods, and various databases that were available to the authors. The Ecosim is conditioned on time-series data taken from a large number of single-species stock assessments (e.g., for hake, sablefish, and various rockfishes), the West Coast triennial trawl surveys (e.g., for a variety of flatfishes), and catch data (for shrimps, crab, and salmon). Default values are used for many Ecosim parameters, but unique “mediation functions” are used to mimic the effects of environmental variability on the spatial distributions of some groups.

d) *Pros:* As with many applications of EwE, this approach is useful for considering many, possibly disparate, sets of data within a unified framework. This particular application demonstrates the important role that migratory species (whose distributions are largely determined by environmental conditions) have in the NCC; it has also provided an important basis for generating discussion about ecosystem approaches to management by the Pacific Fisheries Management Council. *Cons:* The aggregation of species (and species assemblages) and lack of size, age, or ontogenetic structure for many groups may mask many significant interactions. It is not possible to predict permanent state shifts.

NPZ modeling of the California Current (A.Leising et al.)

a) An NPZ-style model describing the lower trophic levels specific to the California Current ecosystem has been developed. This model includes two types of bacteria (cyano- and heterotrophic), three classes of phytoplankton (small and large diatoms, and autotrophic dinoflagellates), and three classes of microzooplankton (obligate bactivores, small omnivores, and larger omnivores, e.g., heterotrophic dinoflagellates and ciliates). The model also tracks nitrogen, ammonia, iron, silica, and detrital pools. Thus the model has 13 major components, and spans up to three trophic levels. This model is implemented in MatLab.

b) The end objective of this work is to build the simplest model which can adequately describe primary production and chlorophyll standing stocks throughout the California Current (both the high productivity near-shore upwelling regions, and the more oligotrophic offshore areas). Short term objectives include using the model for diagnosing effects of changing mixed layer dynamics on a regional basis, sensitivity of coastal regions to the formation of harmful algal blooms, and as an input field for other, higher-trophic level models (such as the IBM zooplankton modeling described above). Eventually, such a model can be coupled to physical models such as ROMS for use in hindcasting and limited forecasting of the effects of climate change on the base of the food web.

c) Forcing for the model includes modeled and observed subsurface temperature data and light levels. The model is also constrained by nutrient and primary production measurements (primarily those provided through CALCOFI surveys). If coupled to a 3D circulation model, then the data requirements would also then reflect those requirements for the 3D physical model. Biomasses and parameters for the organisms in the model are derived from the literature and further constrained by both shipboard and laboratory experimentation. Initial biomasses of the organisms are not as critical in such a model, as they are mostly driven by bottom-up control, along with the interaction terms, such that biomasses rapidly equilibrate given a particular nutrient input level. Thus the relative biomasses and production of the different plankton classes are the major terms which can be compared with observational data to assess model validity.

d) *Pros:* The biomasses and production of different organism classes are driven in a purely mechanistic fashion (i.e., from biological principles). The model can be used for both predictive and diagnostic studies and provides a direct method for examining the effects of physical variability on primary production. *Cons:* Because the model does not extend beyond microzooplankton, there is no top-down feedback from higher trophic levels (mortality of the top predator in the model is set *a priori*). Results are only as good as the parameters and coefficients used to constrain the model, many of which are not well known (i.e., the affinity of heterotrophic bacteria for free Iron).

Food-web model of the eastern tropical Pacific (G. Watters et al.)

a) A description of the food web in the eastern tropical Pacific (ETP) has also been constructed in EwE. This model has 38 groups and is most highly resolved at upper trophic levels (e.g., tunas, billfishes, sharks, mammals, and birds). Physical forcing of fishes at upper trophic levels can be both “indirect” (*via* the cascading effects of changes in the biomass of Large Phytoplankton) and “direct” (*via* changes in egg production and juvenile survival).

b) Initially, the objective of this work was to develop a hypothetical description of the ecosystem in the pelagic waters of the ETP, with special emphasis on defining the relationships among the target and bycatch species of high-seas tuna fisheries. Following this, additional objectives included explorations of how climate forcing (both during the El Niño cycle and in response to greenhouse warming) and the distribution of fishing mortality between longline and purse-seine fleets might affect the ecosystem.

c) As with most EwE models, the basic Ecopath parameters (e.g., initial biomasses, productivities, consumption rates, and diets) are developed from a large pool of source material that includes traditional peer-reviewed literature, grey literature, stock-assessment reports, meta-analytic methods, and various databases that were available to the authors. Some ecotrophic efficiencies were set on the basis of the ratio F/M (with higher ecotrophic efficiencies being assigned to groups with higher ratios), and the unassimilated fraction of each group’s diet was estimated from data on the proximate compositions of each group’s prey and the digestibility of dietary fat, protein, and carbohydrate. The Ecosim was conditioned on biomass and total mortality (Z) time series from single-species stock assessments (e.g., for some tunas and billfishes) and catch per unit effort time series for some bycatch species (e.g., for sailfish and wahoo). Time series of fishing effort for five fleets were also used to condition the Ecosim. Default values were assumed for many Ecosim parameters, but the “fraction of other mortality sensitive to changes in feeding time” was determined by the size and trophic level of each group.

d) *Pros:* Here again, the EwE framework has been useful for bringing together many different data sets. This application effectively demonstrates the different effects that various tuna fisheries may have on structuring the pelagic ecosystem. The model further demonstrates that top-down cascades are mediated by the nature of physical forcing. *Cons:* The Ecopath is most sensitive to parameters for the two groups at the center of the food web (*Auxis* and squids) and for which very little is known. Furthermore, there is substantive uncertainty in large sections of the diet matrix. The model smoothes over a substantial amount of spatial variability that is known to exist in the ETP. Predicted responses to greenhouse warming do not consider the possibility that the spatial distributions of many animals may change.

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SEFSC

Summarized by Josh Sladek Nowlis

The Southeast Fisheries Science Center (SEFSC) conducts multi-disciplinary research programs to provide management information to support national and regional programs of NOAA's National Marine Fisheries Service; and to respond to the needs of Regional Fishery Management Councils, Interstate and International Fishery Commission, Fishery Development Foundations, government agencies, and the general public. The SEFSC develops the scientific information base required for fishery resource conservation, fishery development and utilization, habitat conservation, and protection of marine mammals and endangered species, the impact analyses and environmental assessments for management plans and/or international negotiations; and pursues research to answer specific needs in the subject areas of population dynamics, fishery economics, fishery engineering, food science, and fishery biology.

Increasingly, the SEFSC focuses on ecological issues within fisheries. This work falls into five basic categories: multispecies virtual population analyses (MSVPA), primary and secondary production models that focus on production at lower trophic levels, habitat-based modeling efforts that rely on empirical information about spatiotemporal ecological structure to increase the power of data analyses, mass-balance (i.e., Ecopath with Ecosim, or EwE) models of whole ecosystems, and empirical studies of ecological assemblages that, though not modeling efforts per se, provide invaluable benchmarks to guide modeling efforts.

MSVPA

The Atlantic States Marine Fisheries Commission (ASMFC) has been pursuing the application of multispecies trophic models for the last several years focusing on improving assessments of Atlantic menhaden. In particular, these studies have applied MSVPA to estimate natural mortality rates of menhaden resulting from predation by bluefish, striped bass, and weakfish. As the stock sizes of these piscivores have rebounded, there has been a decline in menhaden productivity prompting questions about whether trophic interactions are responsible for the decline in the stocks of this both economically and ecologically important forage species. Doug Vaughan has participated in ASMFC's multispecies technical committee and helped to develop model inputs for Atlantic menhaden and other clupeids, and assisting in model evaluation by conducting sensitivity analyses. This model application was reviewed by the NEFSC's stock assessment review committee (NEFSC, 2006).

Primary and secondary production models

Kyle Shertzer and colleagues have worked extensively on modeling an experimental ecosystem. It was a chemostat system housing rotifers and algae, and the models were systems of differential equations. One pertinent result from this work was that, even in the best case scenario (few trophic levels, few species, experimentally derived estimates of model parameters, and known and constant environmental conditions), modeling ecosystem dynamics is extremely difficult to get right (Fussmann et al., 2005).

Nekton population parameters in coastal wetlands have been difficult to estimate because of sampling problems, landscape complexity, tidal dynamics, and limited information on growth and mortality. Tom Minello, Lawrence Rozas, and colleagues are combining landscape analyses of land-water patterns in regularly flooded wetlands of Texas and Louisiana with models of small-scale (1-50 m) distribution patterns of nekton over the marsh surface to estimate population abundances of juvenile brown shrimp *Farfantepenaeus aztecus*, white shrimp *Litopenaeus setiferus*, and blue crab *Callinectes sapidus*. These models are deterministic and represent average population levels over an annual period. In addition to the above data, this modeling approach requires information on size-frequencies, size-weight relationships, and growth rates to estimate population biomass and production of these species from salt marshes and open water habitats in estuaries of the northern Gulf of Mexico.

Tom and Lawrence also have an individual based model (IBM) project on brown shrimp production. This work is being conducted with Kenny Rose and Brian Roth at Louisiana State University. They are using a spatially explicit IBM to investigate the relative influences of inundation and habitat fragmentation on brown shrimp production in northern Gulf of Mexico salt marshes. The model simulates the mortality, growth, and movement of a population of four million post-larval brown shrimp from their arrival into a 25-ha estuarine salt marsh in spring to their emigration as sub-adults in summer and fall. They quantify production over a single calendar year in terms of total biomass production and sub-adult export from the marsh. Maps depicting different marsh landscapes in various stages of degradation are used in conjunction with measured marsh elevations and tidal records to examine the effects of landscape configuration and tidal flooding patterns. These models also require information on shrimp densities, growth rates, and mortality rates in different estuarine habitats. In addition, information on patterns of shrimp movement within shallow estuarine habitats is critical to model success.

A simulation model of pink shrimp growth and survival was developed by Browder et al. (1999, 2002) and applied to Florida Bay. Growth and survival are functions of salinity and temperature. Two aspects of natural mortality are included: physiological mortality and mortality from predation. Physiological mortality is modeled as a direct function of salinity and temperature and their interaction. Predation mortality is modeled as an exponentially decreasing function of size, which depends upon growth rate, and thus on salinity and temperature indirectly. Potential harvests are simulated to integrate the influence of juvenile survival and growth rates on the harvests in the offshore fishery. Physiological mortality as a function of salinity and temperature was defined by a series of 28-day experiments involving, in total, 2000 young pink shrimp in Florida Bay. Recent analyses of size-frequency distributions of juvenile pink shrimp are being used to evaluate and further refine the model. The model runs on daily salinity and temperature data from locations in Florida Bay, acquired from observations at fixed stations or modeled as a function of freshwater inflow. Several models, from simple statistical models to hydrodynamic models, link salinity to freshwater inflow. Empirical relationships obtained from analysis of data collected by Robblee and others were used in Browder et al. (2002) to scale model results to expected densities based on local seagrass cover. The pink shrimp simulation model is being used to evaluate alternative water management scenarios in the Comprehensive Everglades Restoration Project. Other projects based on a more comprehensive model of pink shrimp dynamics in south Florida include an investigation of pathways and processes of pink shrimp larvae migration from the Tortugas to the edge of Florida Bay (Criales et al., 2005, 2006) and determination of physical limits to migration of pink shrimp postlarvae into the interior of Florida Bay (Criales et al., in prep.).

Habitat-based models

Habitat can serve as an organizing framework when acknowledging spatial heterogeneity. Habitat types are defined by examining spatial patterns in data such that areas categorized as the same habitat show common characteristics while those categorized as different habitats show distinct characteristics. These ecologically-relevant habitat types are then used as a core element of the analysis as a factor, either in habitat-based stratified random sampling (a priori use), or habitat-based standardizing of non-random data (a posteriori use). This technique has been used extensively in modest ways for standardizing fishery-dependent catch rate data, which serve as abundance indices. Recently SEFSC scientists have put greater emphasis on the use of habitat through species associations (Stephens and MacCall 2004) and tied to oceanographic features for pelagic fish species (e.g., Kleisner et al., in press) and turtles and mammals (Garrison 2007). Center staff have also used these techniques as the basis of scientific advice for the design of marine protected areas and networks (e.g., Friedlander et al. 2003).

As part of their intensive involvement in South Florida Ecosystem Restoration, SEFSC scientists conducted a meta-analysis of existing databases using General Additive Modeling techniques and developed predictive models of fish and shrimp distributions in Florida Bay (Johnson et al. 2002a, 2002b, 2005). Most available datasets had density data on many species and associated data on seagrass, relative topography (bank, basin, near-key), salinity, and temperature. Data on freshwater inflows, distance to shore, tidal amplitude zone, and sea level were obtained and also tested for their predictive value. About a dozen dominant species were modeled, and model results were combined to show community changes in response to change in freshwater inflow. The models are being used in water management planning as part of the Comprehensive Everglades Restoration Project and State activities designed to safeguard the water supplies of Florida Bay. GAM models have many advantages when dealing with non-normal data and relationships of unknown structure (Harrell 2002).

This technique requires consistent sampling of data broader than simply the species of interest. Data will vary depending on the ecology of the system of interest, but can include benthic habitat characteristics, physical oceanographic characteristics, and species assemblages. The technique lends an element of comparability across complex datasets, which can greatly increase statistical power and lead naturally to advice on spatial management options. When applied to non-random data, the technique has the disadvantage that identifying comparable samples for comparison may eliminate a large proportion of the original data, and thus give the perception of lost statistical power. However, this perception is based on the concept that the original data were amenable to statistical assumptions and so the “loss” may often only be an explicit acknowledgment of the true power of the data.

Mass-balance models (EwE)

Fisheries in the Gulf of Mexico and southeast United States traditionally target shrimp and menhaden but efforts are also directed towards predatory species such as sharks, tunas, mackerels, and swordfish. In the 1980’s, increasing fishing effort and subsequent landings caused declines in stocks of swordfish, sharks, and bluefin tuna. Many of these stocks are currently overfished or still suffering from overfishing. There are conflicting views surrounding the ecological interactions between sharks and fisheries. One view suggests that removals of keystone species are thought to cause a cascading trophic effect within the remaining community (Carpenter and Kitchell 1993). These effects may involve changes in species composition among the prey or changes in the preferred prey of the predator. An alternate view has been suggested that the high diversity of oceanic systems may oppose strong “top-down” effects (Strong 1992; Jennings and Kaiser 1998). In light of the recent publications on the reductions of higher trophic levels species and fishing down food webs by Pauly et al. (1998), Myers and Worm (2003), and Baum and Myers (2004), an improved understanding of the role of keystone predators in the Gulf of Mexico and southeast United States would be useful in evaluating the impacts of fishing on the marine ecosystem.

Using Ecopath with Ecosim, hypotheses regarding the depletion of apex predators, and their impact on predation mortality of major prey groups are being examined by John Carlson. Ecopath with Ecosim is a valuable tool for exploring management alternatives, and for testing hypotheses relating to ecosystem function that may not be possible through classic removal experiments. Further, hypotheses regarding the role of complementary niches among top level predators are being explored.

South Atlantic Fishery Management Council effort

The South Atlantic Council has been working with partners since 2003 to develop a fishery ecosystem plan (FEP) and comprehensive ecosystem amendment. The FEP is a source document to use to plan for, and help guide, an ecosystem-based management approach to fisheries. The FEP is based on the Council's Habitat Plan for the South Atlantic Region (HPSA), which supported the Comprehensive Essential Fish Habitat Amendment approved by the Secretary of Commerce in 1998. The FEP updates much of the material in the HPSA. The FEP represents a compilation of all pertinent information about the South Atlantic large marine ecosystem (LME) (North Carolina south through the Florida Keys). It is envisioned as a living document that is updated periodically to incorporate new knowledge about the ecosystem and its components, with a complete update every five years. The FEP serves as the source document to the Comprehensive Ecosystem Amendment, which will comprise the various regulatory actions to be incorporated into existing Fishery Management Plans.

Ecosystem modeling is an integral part of the SAFMC long-term approach to implementing Ecosystem-Based Management in the region. Anticipating the need to evaluate ecosystem models as new tools supporting future management needs, the Council collaborated with the University of British Columbia in the PEW funded Sea Around Us Project to develop a straw man 42-component model, followed by a 98-component preliminary EcoPath with EcoSim (EwE) model, of the LME area. These models were designed and parameterized to help organize trophic data (including fish, macroinvertebrates, mammals, turtles, and birds) and identify and prioritize information needs. Shortfalls in resources prevented full parameterization, workshop review, and a fully operational model with all available fleet characteristics. However, these previous modeling efforts have led to a new phase of modeling collaboration with an expanded regional team that will come together at a kick-off workshop in the Fall of 2007. The new effort is enhanced by the availability of new model-integrated visualization tools.

Gulf of Mexico Fishery Management Council effort

The Gulf of Mexico Fishery Management Council was one of four regional fishery management councils along the Gulf and Atlantic coasts selected in 2004 to participate in a pilot project to begin developing an ecosystem approach to fisheries management. As part of that effort, the Gulf Council, through its Ecosystem Scientific and Statistical Committee (SSC), convened a 3-day workshop in May 2007 to demonstrate the feasibility of using ecosystem modeling to address fishery management issues and to expose capabilities and gaps in ecosystem model applications. Dr. Carl Walters and Dr. Villy Christensen of the University of British Columbia led the workshop and focused on a specific type of model, Ecopath with Ecosim (EwE). An ecosystem model of the Gulf of Mexico developed by expanding a previous EwE model of the west Florida shelf (developed by the Florida Fish and Wildlife Research Institute in collaboration with UBC) was used as the strawman model. This model simulates species-specific age-structured population dynamics of a collection of important fish species and the biomass dynamics of an additional 32 ecosystem functional groups ranging from phytoplankton to other fish species and commercial shrimp. Members of the Council's Ecosystem SSC and invited experts participated in the workshop, which was held at the Florida Fish and Wildlife Research Institute in St. Petersburg, Florida. A number of issues related to fishery management were applied to the Gulf of Mexico ecosystem model to demonstrate how the model might be used and what types of results it would produce. These issues included evaluating impacts of shrimp trawl bycatch, harmful algae blooms (red tide), the hypoxic zone off Louisiana and Texas, and the effectiveness of marine protected areas for single-species management. Presentations at the Workshop included "Modeling a Clupeid-dominated Ecosystem on the West Florida

Shelf" subjected to both Red Tide and Other Piscivore Stresses" by John Walsh", "A Spatial Ecosystem Model for Atlantic Coast Multi-species Fisheries Assessments" by Jerald Ault, "Quantitative Methods for Functional Group Assignment by Ernest Peebles, "Fishmod, a population dynamics and fishing-effort distribution model, as applied to the evaluate the management of gag grouper on the West Florida Shelf" by Carl Walters and Behzad Mahmoudi, and "A Bibliography of Estuarine and Marine Trophic Information for the Gulf of Mexico" by James Simons. A Workshop Report is being prepared for presentation to the Council.

Caribbean effort

A literature review and synthesis entitled "The Ecological Basis of Fishery Yield of the Puerto Rico-Virgin Island Insular Shelf", initiated by SEFSC scientists more than a decade ago, was recently finalized and published as a NOAA Technical Report in the SEDAR series (Jacobsen and Browder 2006). The document had a limited distribution at the time it was prepared and was used in the development of several ecosystem models.

Fishery managers in a number of southeast jurisdictions are considering or have begun using no-take marine reserves to supplement conventional management tools. Marine reserves have shown to be particularly important in coral reef ecosystems where multigear, multispecies fisheries are generally found to be data-poor. In the US Caribbean, some managers have been reluctant to try marine reserves because of uncertainty in the timing of changes and the inability to estimate the magnitude of expected benefits. One reserve being considered is in La Parguera, Puerto Rico under managemet of the Puerto Rico Dept. of Natural and Environmental Resources, with interest by the Caribbean Fishery Management Council. A modeling project was instituted, funded by the NOAA Coral Reef Conservation Program, to characterize the La Parguera reef ecosystem with Ecopath, evaluate fishing policies on a broad scale with Ecosim, and model marine reserve dynamics with Ecospace. This project is building dynamic trophic models to predict changes in target species, assess reserve performance based on inclusion or exclusion of different habitat types, and to predict time frames within which changes in species abundance and size distributions can be expected. Hypotheses generated through modeling can be tested by continued monitoring after closure. To achieve project goals several iterations of a trophic model of a generalized Caribbean coral reef ecosystem have been built using the Ecopath with Ecosim (and Ecospace) package.

These models began with a published model available from University of British Columbia (Opitz 1996). The Opitz model was evaluated and updated. Fishery information was added and simulations from that work were presented at the 2002 Gulf and Caribbean Fisheries Institute meeting and at the 10th International Coral Reef Symposium, Okinawa, Japan (June-July 2004). Presentations shared information about our coral reef modeling, highlighted our progress, and discussed the limitations imposed by small-island fishery data collection. Subsequent evaluations revealed enough shortcomings (e.g., within group cannibalism) that the modeling was reinitiated. The general model will be followed by a detailed model specific to the Turromote Reef Platform (La Parguera, PR), an intensively studied coral reef platform, with data sets extending back more than 20 years. Working in conjunction with the University of Puerto Rico-Mayagüez (UPRM), Dept. of Marine Sciences and their NOAA-funded Coral Reef Ecosystem Studies (CRES 2002: Integrating Science & Management in The Caribbean) partners we have completed an inventory of data, including previously published and unpublished data as well as data collected under CRES over the last 6 years. Data from collaborative work between UPRM and NOAA's National Centers for Coastal Ocean Science projects in the area have provided additional local diet composition information. Certain findings, characterized as lessons-learned, were presented in a special symposium, *Re-inventing reef fisheries management: emphasis on the US Caribbean* as part of the Gulf and Caribbean Fisheries Institute annual regional fisheries conference in San Andrés Island, Colombia (November 2005). The presentation and a companion manuscript highlighted the importance of matching available data sources, research data collection, and model groupings to specific questions addressed through the modeling. We have recently contracted with a research associate at UBC to complete our coral reef ecosystem/marine reserve project under the supervision of SEFSC-Galveston scientists. A secondary objective is to extending/adapting the marine reserve model to produce modeling tools to support CFMC ecosystem-based fishery management needs.

Supporting empirical efforts

Kyle Shertzer and Erik Williams have been working on assemblage analyses of snapper-groupers species in the Atlantic. One possible approach for data-poor stocks is to manage them as part of an assemblage, with status of the entire unit determined by a data-rich indicator species. This study addresses the feasibility of that approach, focusing on reef fishes off the southeastern United States. Statistical analyses were applied to identify (1) geographic areas with similar composition of landings and (2) assemblages of finfish species. Time series of relative abundances were then computed and examined for synchrony in population dynamics. Results indicated that composition of landings differs between the South Atlantic Bight and southeast Florida, suggesting that these two areas could be managed as separate regions. Fish assemblages are weakly coherent, but consistent between data sets and among statistical methods. The authors found little evidence of synchrony in population dynamics within assemblages, and therefore little support for the use of indicator species.

Population assessments for marine mammals are increasingly focused on spatially explicit habitat modeling. These efforts generally employ remotely sensed habitat information along with data collected during line transect surveys to develop empirical models of marine mammal habitats. In addition to improving abundance estimation, these tools are used to assess the risks to marine mammals associated with human activities. For example, a spatially explicit model of Northern Right Whale calving habitat was used to evaluate the risk of interactions between whales and large vessels in the southeastern United States (Garrison 2007). Similar habitat modeling approaches are being applied by SEFSC in the Gulf of Mexico. For example, Paula Moreno is looking at assemblage structures in the Gulf of Mexico. The goal of this project is to investigate abundance and distribution patterns of several species (marine mammals and fish), initially restricted to the continental shelf. At this stage, she is preparing archival biological and environmental data from several sources, including the SEFSC surveys, USGS data and remote-sensed data from several sources. She will use a combination of GIS (ArcGis 9.2) and statistical tools (S-plus with spatial module). Analyses include “hot-spot” techniques and generalized linear/additive models. For the marine mammal abundance models and environmental predictors, she plans to use the software Distance to compute a density surface model. Cluster analysis may be used for identifying species based on their trophic habits or habitat usage.

Josh Sladek Nowlis and colleagues are estimating the preliminary status of large assemblages of shallow water Hawaiian reef fishes (Sladek Nowlis et al, in review). This work measures abundance using visual surveys of fish in the extensively fished main Hawaiian Islands (MHI), and compares these estimates to unfished reference values obtained from the essentially unfished Northwestern Hawaiian Islands (NWHI). Many species are unsuitable for the analysis because they are too infrequently or inappropriately sampled by this technique, while still others were deemed inappropriate because they showed latitudinal bias in their distributions across this island chain (thus indicating that the more northerly NWHI were not a suitable reference point). Dozens of species cleared these filters, though. These species were examined to identify patterns relating preliminary status estimates to biological, ecological, and fishery characteristics. The results identified a strong pattern in the data that separated large mobile predators targeted by the primary fishery (for food consumption) and in poor condition from small site-attached low-trophic-level species not targeted by the primary fishery and in relatively good condition. In addition to providing preliminary estimates of stock status for 55 species, this study identified biological and ecological characteristics correlated with poor status.

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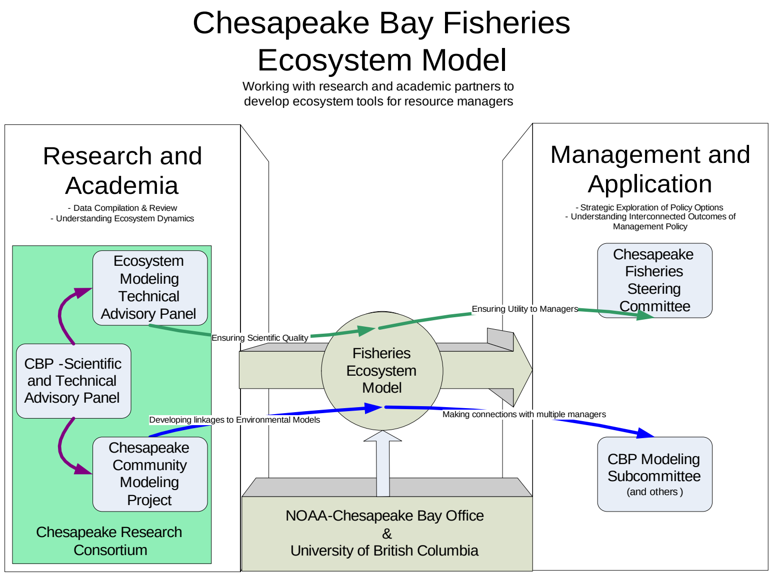
NCBO

Howard Townsend, Hongguang Ma, and Maddy Sigrist

The NOAA Chesapeake Bay Office (NCBO) has been involved in a number of projects related to ecosystem-based management, including guiding the development and publication of the book “Fisheries Ecosystem Planning for Chesapeake Bay” (FEP). Further, NCBO funded the development of several multispecies approaches to fisheries research to aid the attainment of FEP goals. One such approach was the initial development of a Multispecies Virtual Population Assessment (MSVPA) model, which has now been funded by the Atlantic States Marine Fisheries Commission. The main tactic taken by the NCBO, however, towards implementing the FEP was to begin the development of an ecosystem model of the Chesapeake Bay. NCBO working with the University of British Columbia as well as the Chesapeake Research Consortium developed the Chesapeake Bay Fisheries Ecosystem Model (CBFEM) using Ecopath with Ecosim (EwE) model.



The CBFEM modeling effort was designed to be a collaborative effort with the research and management community in the region. The effort is being led by NCBO modelers and is guided by the Ecosystem Modeling Technical Advisory Panel (EMTAP2). EMTAP 2 is a group of regional scientists and fisheries biologists (from research institutions and academic agencies) who are working to ensure that the best available data is being used for the model and to ensure that it will one day be a viable tool for taking into account ecosystem considerations in fisheries management. In addition, ecosystem modeling can be used to synthesize information on habitat changes and land use practices that influence living resources in the bay. In our ultimate goal to manage bay resources for sustainability, this sort of synthesis is paramount to our success. This work is part of NCBO's overall effort to provide science and services in support of ecosystem approaches to management in the Chesapeake, which is mandated by the Magnuson Stevens Act and NCBO's authorization.

In addition, the need to account for the potential impacts of nutrient and coastal zone use has led NCBO to begin linking the CBFEM with lower trophic level and nutrient/water quality models. NCBO is a part of the larger Chesapeake Bay Program, a unique regional partnership that has led and directed the restoration of the Chesapeake Bay since 1983. The Chesapeake Bay Program partners include the states of Maryland, Pennsylvania and Virginia; the District of Columbia; the Chesapeake Bay Commission, a tri-state legislative body; the Environmental Protection Agency; other federal agencies; and participating citizen advisory groups. As a partner, NCBO has worked with the EPA to link water quality management and ecosystem-based fisheries management goals. This has primarily been achieved by linking a Chesapeake Water Quality Modeling tool with the CBFEM. Chesapeake Bay Program partners are working together to achieve the commitments outlined in The Chesapeake 2000 Agreement (C2K). The C2K set a goal of correcting all nutrient and sediment related problems in order to remove the Bay from the list of impaired waters (under the Clean Water Act) by the year 2010. Additionally, in collaboration with the University of British Columbia NCBO has developed Chesapeake Bay Regional Estuarine Ecosystem Model (CBREEM) to develop a long-term snapshot of primary productivity in the Chesapeake Bay.

Chesapeake Bay Fisheries Ecosystem Model (CBFEM)

NCBO is using the Ecopath with Ecosim (EwE) software to develop the Chesapeake Bay Fisheries Ecosystem Model (CBFEM). The CBFEM was created in response to a management need in the Chesapeake Region for a quantified estimate of trophic pathways in the Bay. This information will be used to understand how one stock affects another within the food web and how the many Bay fisheries impact both target and non-target species. Because the life histories and population dynamics of the thousands of organisms that live within the Bay are complicated, a model is necessary to provide a synthesis of the system.

Currently, the model includes 45 functional groups of organisms, representing all trophic levels. The input data primarily includes assessment results from the Chesapeake Bay and Atlantic Coast stocks (including biomasses, mortality rates, catches, and effort) supplemented with fisheries-independent survey data (fisheries and biological oceanography studies); ecological studies (as available from researchers and institutions in the region); and parameter estimates obtained from literature where necessary to supplement local data. The model has been "tuned" to these time series data; 100+ data sets and assessments to produce 50-yr simulations with a nutrient loading forcing functions, in an attempt to replicate the current status and dynamics of the Chesapeake. Simulations can be run to explore policy options (i.e., fisheries management plans) and familiarize people with ecosystem approaches. Activities are underway to refine the temporal and spatial resolution of the CBFEM and to continue to incorporate water quality, habitat, and hydrographic data.

The CBFEM has been used as an exploratory tool to help understand the Chesapeake Bay ecosystems and data systems. Ecosystem explorations using the model have been focused on menhaden interactions with striped bass (and other predators), potential effects of hypoxia on fisheries species, and submerged aquatic vegetation (SAV) habitat-mediation effects on blue crab stocks. Primary lessons learned from the modeling effort include:

- Though the Chesapeake Bay has historically been a well-studied system, relatively little information on all but a few fisheries species (esp., blue crab, striped bass, oysters) exists.
- Trophic linkages for many important forage species (e.g., Atlantic menhaden) have not been clearly defined – i.e., we know what eats them, but we do not know what they eat and the effects of water quality on production.
- Only limited data is available for lower trophic levels and species/groups that are not targeted for harvest.
- Historical catch data (and biomass data) for some species is not available, or of limited value, so mining of existing data is necessary.
- Connections between habitat, water quality, and fisheries have not been quantified.

Pros: The EwE approach has been useful for pulling together multiple disparate data sets, finding gaps in data, and allowing strategic exploration of ecosystem interactions. Model output systems attract others to look at, and “test,” different ecosystem scenarios.

Cons: Limited data adds to a high level of uncertainty about model outputs.

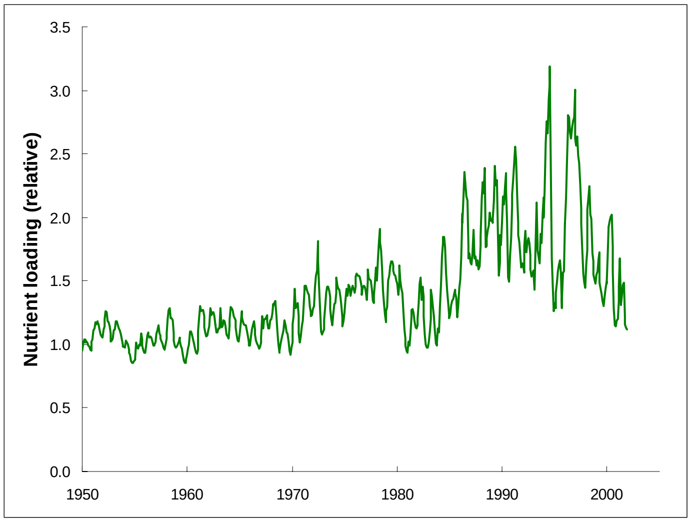
Chesapeake Bay Regional Estuarine Ecology Model (CBREEM)

To better encapsulate the Chesapeake Bay’s ecosystem history, and improve the model’s fit to time series data, a method to capture fluctuations in productivity attributable to primary production was necessary. Preikshot (2004) and others have used hydrological or climate indices to approximate patterns in primary productivity; however, the Chesapeake Bay’s primary production is primarily driven by nutrient loading from the watershed. Currently, no indices to encapsulate 50 years of primary production in the Chesapeake Bay exist.

To create a nutrient loading index to drive primary productivity, we developed the Chesapeake Bay Regional Estuarine Ecosystem Model (CBREEM). CBREEM is a simple, linearized, barotropic, two-layer hydrodynamic model; it uses historical climatological, hydrologic, and nutrient loading data to estimate historical patterns in primary productivity for a regional estuary. The objective in developing this modeling system for the Chesapeake estuary was to integrate information on physical, chemical, and ecological processes into a model for predicting temporal and spatial changes in key indicators of interest to environmental managers. These processes involve variables that can change on various time and space scales, from minutes/meters up to years/kilometers. When faced with such disparate scales in a complex system, modeling generally involves defining a space/time ‘window’ of primary interest. Dynamic variation that is very fast compared to this window is modeled in terms of time-varying equilibria and averages, and variation that is very slow is represented through constant ‘parameters.’ The window of primary interest for CBREEM is a seasonal variation on spatial scales of one to two kilometers. A model time step of one month was used by the CBREEM to capture this seasonal variation. Based on this window, we elected to treat most physical and chemical processes, such as diurnal variation in wind-driven currents and associated chemical concentration fields, which come to equilibrium on time scales of hours, by calculating equilibrium spatial fields of these variables and then averaging the equilibria over monthly time steps. Longer-term variations, such as decadal trends in sea level heights, are treated as constant parameters for any one run of the model that focuses on the window of primary ecological concern.

CBREEM solves for equilibrium velocity fields on a Richardson grid (i.e. Arakawa E-grid) in a one-month time-step. It then solves for wind forcing and other water forcing to determine water mass flow, which is used for making chemical mass-balanced calculations in the grid. The chemical part of the model is very simple. Initially the developers aimed to use non-steady state hydrodynamic models to drive the chemical part of the CBEM, but did not do so because the velocity fields failed to satisfy mass-balance. Instead, a linearized hydrodynamic model was used for most calculations.

The model uses a grid placed over the entire tidal portion of Bay. Freshwater inputs were added with a one-month time-step. Wind was used to drive surface flows. Monthly hydrodynamic velocity fields were calculated in two layers: shallow and deep water. Layer thickness changes due to baroclinic effects. Transport patterns produced by this model fit well with observational data and feed the equilibrium chemical model.



The equilibrium chemical model solves partial differential equations, setting $\frac{\partial}{\partial t}$(concentration) = 0. It was assumed that the equilibrium concentration was equivalent to the monthly average. This was tested in Tampa Bay and seemed to fit these chemical patterns well (unpublished). This methodology was first developed by John Hunter in Australia in the 1980's, and the programming code from Hunter (unpublished) was used and carried forward to present day models.

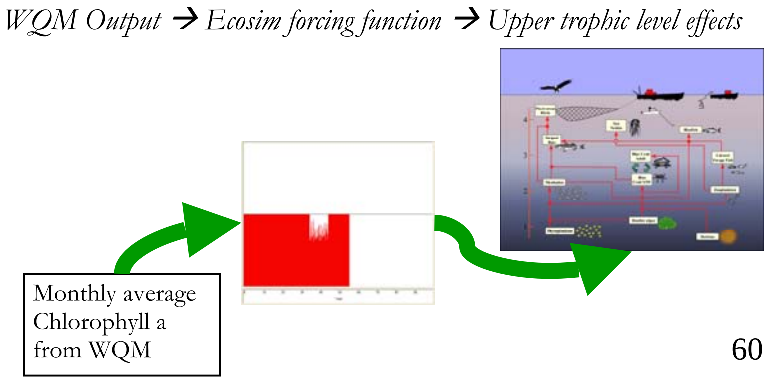
The approach for hydrodynamic modeling is similar to the one used by Wright et al. (1986) for the Gulf of Maine. It first solves for total flows. It then solves for vertical structure, based on Hunter and Hearn (1991)'s methodology. It then performs chemical calculations to set-up PDEs for spatial and temporal change. The model is subdivided into physical and chemical submodels that work in combination to generate monthly time series of ecological parameters of concern. The submodels and supporting data are described in more detail in a manuscript currently being developed for publication. The historical patterns in chlorophyll-a concentration computed by CBREEM, are used as a nutrient loading forcing function for the CBFEM.

Pros: This effort has enabled development of a long-term, primary productivity index for the bay, which can be used for ebfm models and other ecosystem based management tools.

Cons: Monthly averaging of physico-chemical variables may result in the loss of some information.

Chesapeake Water Quality Model

The Chesapeake Bay Water Quality modeling suite includes the linked Airshed Model, Watershed Model, Estuarine Hydrodynamic Model, Estuarine Water Quality Model, and Living Resources Model. The Watershed Model estimates nutrient and sediment inputs to the Bay by



simulating nutrient cycling and hydrology. The Estuarine Hydrodynamic and Water Quality Models simulate the movement patterns of the Bay water cause by winds, tides, freshwater runoff, and changes in water quality changes (such as chlorophyll-a concentration and dissolved oxygen) attributable to nutrient inputs and cycling.

In the current Chesapeake Bay Program modeling suite only a few key living resources of lower trophic levels are simulated with the Water Quality Model (WQM). Water quality affects oyster filtering rates and biomass through temperature, suspended solids, salinity, and dissolved oxygen, and, in return, the simulated oyster biomass removes particulate organic and inorganic material from the water column through filtration and subsequent biogeochemical processes.

The Water Modeling output is linked to the CBFEM using forcing functions (see Figure). These linkages allow dynamic exploration of the effects of nutrient reduction on the fisheries ecosystem of the Chesapeake.

Pros: This effort has drawn attention to the fact that reduced nutrients may result in reduced system productivity.

Cons: Because the linkage is unidirectional and effects of hypoxia have not been well-quantified, the detrimental effects of eutrophication have not been completely incorporated.

NEFSC

Jason Link, Bill Overholtz, Greg Lough

Single species add-ons: predation removals

As a suite of models related to the minimum realistic family of models, these models seek to include predation removals into a stock assessment model. These have been both age/stage structured and bulk biomass/production models. These have ranged from providing context of stock biomass, tuning indices, sources of other mortality, to explicit estimates of additional (i.e., predation or M2) mortality.

Examples of species where this has occurred are predominately forage stocks, including Atlantic herring, Atlantic mackerel, longfin squid, and northern shrimp. One model has been through a formal stock assessment review while the others are in various stages of development and research.

Predation is generally added into these models as an additional fleet and explicitly treating it as another source of removals. The data required are abundance of predators that eat the stock of interest, stomach contents, consumption estimates, and diet composition estimates (in addition to the usual survey and fisheries catch data).

The positives of this approach is that they are relatively simple conceptually and operationally, they use extant data, they are done in a familiar assessment and management context, they provide familiar (albeit modified) model outputs amenable to calculating biological reference points (BRPs), they improve the biological realism of assessment models, and they help to inform and improve stock assessments for species that may have had modeling challenges. The negatives of this approach is that they run the risk common to all minimally realistic models (MRMs), namely that they may be missing a suite of complex interactions and non-linear responses from not including the full suite of interactions in an ecosystem. They also have the potential to be controversial by producing more conservative BRPs and emphasizing the potential for competition between predators and fleets that target these stocks without having a fuller modeling capability to fully address these tradeoff issues.

Single Species Add-ons: Ecological Footprints

As a suite of models related to the minimum realistic family of models these models account for the amount of food eaten by a stock. Estimates of energetic requirements (aka consumptive demands) for a stock at a given abundance level are contrasted to estimates of the amount of food known to be available in the ecosystem from surveys and mass-balance system models. In many ways this is the same calculation as noted above for predatory removals; the difference here is that instead of summing across all predators of a stock, here we sum across all prey for a specific stock.

These have been calculated for a wide range of groundfish, elasmobranch, and pelagic fish species. One set of stocks (the skate complex) has had these estimates go through a formal stock assessment review; the others are in various stages of development and research or else have been calculated as part of predatory removals of forage stocks (noted above).

The data required are abundance of predators that eat the stock of interest, stomach contents, consumption estimates, and diet composition estimates (in addition to the usual survey and fisheries catch data).

The positives of this approach is that they are relatively simple conceptually and operationally, they use extant data, they are done in a familiar assessment and management context, they improve the biological realism of assessment models, and they help to inform and improve stock assessments for species that may have had modeling challenges. The negatives of this approach is that they run the risk common to all MRMs, namely that they may be missing a suite of complex interactions and non-linear responses from not including the full suite of interactions in an ecosystem. They also have the potential to be controversial by addressing tradeoffs among species and emphasizing the potential competition between these stocks and fleets targeting their prey.

Single species add-ons: environmental considerations

As part of Fisheries and the Environment (FATE) and similar programs, we have begun to incorporate environmental considerations into population models. These include changes in carrying capacity (K), growth rates (r), stock-recruitment relationships, or stock distribution relative to environmental conditions.

These have been done or are being done for a wide range of fish, mammal and invertebrate species. Currently none of these models have been through a formal stock assessment review nor explicitly incorporated into a review process that directly informs management. All remain active areas of research and development.

In addition to the standard stock assessment data needs, these approaches require appropriately spatio-temporal scaled environmental data such as temperature, depth, salinity from various monitoring sources.

The positives of this approach are that the environmental data are usually available and relating them to stock dynamics typically utilizes commonly established statistical methods. These approaches also improve the biological realism of assessment models and allow for dynamics to be driven by factors typically outside of usual assessment considerations. The chief negative of this approach is that the data are often usually quite correlative without definitive causal mechanisms; the data are also usually quite collinear and short of exhaustive multivariate analysis are difficult to parse out into factorial weightings useful in stock projection.

MSVPA-X

This multi-species virtual population analysis is an expanded version of the ICES MSVPA model, which is in effect a series of single species VPAs linked together via a feeding model. The model also has the ability to provide short-term forecasts. Typically the model examines the stock dynamics of multiple species that are both predators and prey of one another, and particularly explores the role of predatory removals of stocks relative to one another and to fishery removals.

These have been done for two-subsystems in this region. One is in conjunction with colleagues in the SEFSC and emphasizes menhaden as prey with three main predators in the mid-Atlantic region. The other is for the Southern New England-Georges Bank-Gulf of Maine ecosystem (NEUS), has 19 species, and emphasizes herring and mackerel as the major prey. The mid-Atlantic MSVPA-X has gone through extensive review in the ASMFC and SARC context. Outputs from that model have informed the single species assessments, particularly by providing time-series of M2s for the assessment of menhaden. The NEUS MSVPA-X is still in research and development, with results anticipated to inform single species assessments for herring and mackerel.

The data required are abundance of predators that eat the stock of interest, stomach contents, consumption estimates, and diet composition estimates (in addition to the usual survey and fisheries catch data).

The positives of this approach effectively mirror those of the single species add-on with predation; namely it uses extant data, it is done in a familiar assessment and management context, it improves the biological realism of assessment models, and it helps to inform and improve stock assessment outputs. The key negative of this approach is that it is quite data intensive, with many factors required for each species to parameterize the model. Other limitations of MSVPA are being addressed in the MSVPA-X version (software continually being updated), particularly adding in biomass (i.e., not age structured) predators.

MS-PROD

We have developed a multispecies extension of the Schaeffer production model to include predation and competition terms. The software development is ongoing, with a GUI and mathematical simulation engine available. This model seeks to simulate the relative importance of predation, intra-guild competition, between guild competition, and fisheries removals.

The model has been parameterized for 25 species from the Georges Bank region and has not yet been through a formal review. The model currently does not fit or tune to time series of survey or catch data; the model currently is a simulator, parameterized with empirically based values that can then explore sensitivities and scenarios for different considerations. Right now this is a research tool and will not be used in a management advice context until we develop the capacity to fit to time-series data.

The data required are initial biomass estimates, carrying capacities, predation and competition interaction terms, growth rates, and fishery removals.

The positives of this approach are that it explicitly accounts for ecological processes in addition to fisheries. The other positive is that lower trophic level processes can be directly linked to estimates of carrying capacity. The negatives are that some of the parameters, although empirically derived, are difficult to estimate. The other negative is that it does not currently fit to time series data. Like most multispecies models, it is parameter intensive but less so than many other multispecies models given the simplicity and elegance of the model equation structure.

Agg-PROD

This is effectively the same as the MS-PROD model noted above, but initialized for aggregate groups of species. These groups have been parameterized both as functional guilds and taxonomically related species.

The one distinction is that the model simulates BRPs and a more systemic level production at a group, rather than at the species level. This will be useful if we move towards a two-tier quota system.

The data needs, pros, and cons are the same as MS-PROD, with the amalgamation of parameters across groups a notable caveat.

MSYPR

A multispecies yield-per-recruit (YPR) model was developed to model technological interactions in the New England groundfish fishery. The impact of fishing by a single fleet and multiple fleets on a complex of fish was studied with a YPR analysis. The study was designed to measure the simultaneous impact of changes in effort and mesh selectivity for groundfish on Georges Bank. Data requirements include aggregated fishing effort, catchability coefficients, mean weight data, and mesh selectivity data for the set of fish species being modeled. For Georges Bank these species included cod, haddock, yellowtail flounder, and winter flounder. Equilibrium yields were estimated as a function of aggregate effort and mesh selectivity. Outputs included total and individual species yields, exploitation rates, and individual fish weights. The model was used to study growth underfishing and overfishing by using total yield as the measure of optimality.

MS Bioeconomics

We have developed two models that explore the bioeconomics of multiple species. One is a portfolio approach, while the other is an age structured multispecies model that incorporates a market evaluation of the stocks. Both are research tools/products and not generally used in providing management advice or in the stock assessment review process. However, the multispecies model was used to develop advice for a groundfish amendment for the New England groundfish fishery. The former is a research and development tool and the latter is now a software package. Neither is actively being pursued at this point.

The multispecies bioeconomic model was designed to evaluate management strategies and scenarios. The model uses age-structured data for a multispecies complex of fishes and is driven with aggregate fishing effort apportioned to stock areas. The original application was developed to investigate selected biological and economic implications of effort control on groundfish in New England. A variety of biological and economic performance measures were used to assess the impact of effort reductions in a benefit-cost framework. Increases in catch, standing stock biomass, and catch-per-unit effort were projected when aggregate fishing effort was reduced. Increases in consumer surplus, net present value of revenue, and average fish prices due to size increases were also suggested. The model was also used to evaluate how management strategies with time horizon interventions would impact revenue and consumer surplus.

EMAX

The Energy Modeling and Analysis eXercise (EMAX) is a focused ecosystem study being conducted by the NEFSC. It is a network analysis model (aka a more nuanced energy budget) of the entire food web. It includes the entire northeast US continental shelf, broken into 4 subregions with 36 network “nodes” or biomass state variables across a broad range of biology. The emphasis is on the role of small pelagic species with some pseudo-dynamic scenarios executed. Interactions among targeted and protected species are explicitly included. This work is highly interdisciplinary and involves personnel from most of the Center's Divisions.

The primary work has been to calculate a balanced energy budget for the four regions: mid-Atlantic, Southern New England, Georges Bank, and the Gulf of Maine. Once these networks were balanced, a suite of network analyses and outputs were executed. This work has not gone through a formal model review process; however there has been an interdisciplinary team meeting regularly in workshops to review and revise the work as it has progressed. The rigor and degree of quantitative data used to input and balance these networks has been atypical in comparison to much of the published literature on the subject. This modeling approach was designed to compile and catalog information, identify data gaps, and serve as the basis for future dynamical system modeling. As such it was a research tool. But the model was also designed to evaluate the relative role of specified nodes in the ecosystem; as such it provides contextual and strategic management advice.

EMAX used two energy budget software packages: Econetwrk and Ecopath. There were five main elements critical to the construction of each node for the four NEUS regional networks. We estimated biomass, production, consumption, respiration, and diet composition for all nodes. Additionally, for some nodes we also estimated other sources of removals- namely fisheries.

The positives of this approach are its inclusion of a wide range of biota and associated processesand its ability to holistically examine an ecosystem to ascertain the relative importance of simultaneous processes. Also positive is the ability to examine tradeoffs in biology and fishing in an integrated fashion. Negatives include the data intensiveness for this many nodes, the lack clarity on detrital dynamics, and the complexity of possible dynamics given the myriad of pathways in the full system. Yet the data intensiveness is the same or less than for many MSVPA and multspecies models; the challenge is that for many of the lower trophic level nodes the information is under-determined.

Biophysical coupled models

As part of the synthesis phase of GLOBEC (in collaboration with colleagues at the Institute of Marine Research, Bergen) comparative biophysical coupled model studies are being developed for transport and growth of larval and early juvenile fish in the two marine ecosystems Georges Bank and the Norwegian shelf/Barents Sea (the northern and southern extremes of the distribution of Atlantic cod). These studies will contribute to basic understanding of the interactions between fish populations and zooplankton and how these interactions are influenced by climate variability and change. Realistic physical conditions are being developed to hindcast selected years using the Regional Ocean Modeling System (ROMS) forced by a common set of variables with increased resolution within the regional domains. Lagrangian (particle tracking) models and Individual-based trophodynamic models for larval and early juvenile fish growth are embedded in the regional circulation models.

The core of the trophodynamic model is the standard bioenergetic supply-demand function, in which growth is represented as the difference between the amount of food absorbed by a larva and the metabolic costs of its daily activities. The formulation includes: (i) variable composition of prey fields; (ii) effect of turbulence, swimming behavior and satiation on encounters and ingestion of larval fish and their prey; (iii) light limitation on ingestion rates at low and at high light intensities and (iv) effects of temperature on metabolic costs, ingestion rates and growth.

Data collected during selected years will be used to examine the space-time variability of the larval fish feeding environment. The distribution and evolution of the zooplankton fields will be specified based on the observed structures. If available, evolving prey (zooplankton) fields will be computed from NPZ models.

Comparative basin-scale, spatially explicit simulations can be made (e.g. north Atlantic ocean high vs low years), but full model implementation requires extensive data fields. ROMS forced with CORE or ERA data sets have significant spin-up time before good solutions are realized.

EcoGoMAgg

We are currently constructing a model of the Gulf of Maine (GOM) ecosystem based on results from our Ecopath modeling exercises- Ecosystem Gulf of Maine Aggregate (EcoGoMAgg). We have structured the system based on 16 aggregated biomass nodes spanning the entire trophic scale from primary production to seabirds and marine mammals for the Gulf of Maine. Parameters from our Ecopath model of the GOM system were used to construct a simulation model using recipient controlled equations to model the flow of biomass and the biomass update equation used in Ecosim to model the annual biomass transition. Various performance measures and metrics such as throughput, total flow, biomass ratios (i.e. pelagic fishes to zooplankton), and trophic reference points (i.e. marine mammal biomass to pelagic fish biomass) can be monitored over the simulated time horizon. The model will be used to evaluate how the GOM ecosystem responds to large and small scale changes to the trophic components and system drivers. Specifically events such as climate change, various fishing scenarios, and system response to changes in the biomass of lower and upper trophic levels could be evaluated.

ATLANTIS

ATLANTIS is by far the largest, most complicated model we are using. It was developed by colleagues at CSIRO of Australia and includes a modeling environment with: a virtual ocean with all its complex dynamics, a virtual monitoring and assessment process, a virtual set of ocean-uses (namely fishing), and a virtual management process. The dynamics include solar radiation, hydrodynamics, nutrient processes, growth (with age structure), feeding, settling, sinking, migration, fishery capture, fleet dynamics, market valuation, and regulation which then feed back into the various libraries of the model as appropriate.

We have developed ATLANTIS for the NEUS continental shelf ecosystem with 30 boxes, 5 depth layers per box, 45 biological groups, ,16 fisheries, and 12 hour time steps for 50 years. The parameterization and initialization has required over 60,000 parameters and 140,000 initial values to estimate. We have done a first level of calibration to ensure basic bio-physical processes are realistic. We are in the process of a second level calibration (to time-series fishery dependent and independent data) to ensure fishing processes are reasonable. Future scenarios of different management strategies are planned next.

The model is a primarily a full system simulator. Although parameterized, initialized and loosely tuned to empirical values, ATLANTIS is too complex and was not designed to provide specific tactical management advice for a particular stock (e.g. a quota or effort limit). Rather, ATLANTIS is not only a research tool but a simulator to guide strategic management decisions and broader concerns. For instance, it has been used in other contexts (not yet at the NEFSC) to provide multispecies fishery advice and multi-sector ocean-use advice. The NEUS rendition of ATLANTIS has not been through a formal model review.

The model requires a wide range of data to parameterize and initialize. A listing is best noted from the literature, with the caveat that with many unknown values for a particular system can be generally estimated from first principles and basic physio-chemical laws.

The positive of ATLANTIS is the other side of its negatives: it is exhaustive and inclusive. The positives more specifically are that it can incorporate multiple forms of myriad processes, it explicitly includes numerous processes, it can emphasize those considerations and processes that are most appropriate for a given system, and it can virtually evaluate management decisions without having to actually implement them in a real system. Another positive is that it covers a wide range of biota and is quite flexible or adaptive to a range of key factors. The chief negative of ATLANTIS is that it is unwieldy in its complexity, takes an inordinate amount of time to parameterize, initialize, calibrate, and run any particular application set up for the model. Additionally, the validation routines and capabilities of ATLANTIS are minimal at best, requiring much further improvement.

Recommendations

1. Formally support or even expand dedicated EM efforts at Centers

Most EM work is done on an ad hoc, individual or crisis driven basis. Only 2 of 7 Centers have formal EM groups. There was a notable debate about how “bold” a request this should be, with some in favor of a more strongly worded request for specific groups and others wanting it to be more flexible. It was agreed that given the variations in Center organizational structures, local ecosystems, resource management, and similar needs, that this recommendation be clear in its call for further support but flexible as to what form that might take from Center to Center.

2. Adopt a National Standards of EM use

It was agreed that we adopt a common approach for EM applications. See list in Appendix A for further details. What was noted was that we did not wish to be too prescriptive to the point of stifling innovation, but rather needed to provide general guidance.

3. Adopt a set of EM best practices

Following the FAO template, we modified a list of factors to consider when implementing EM approaches. See Appendix B for further details. The discussion again ranged around how prescriptive we should be, with an agreement that this might be viewed as a corollary- to establish minimal acceptable practices for EM.

4. Implement an MSE framework for contextualizing EM

It was noted that most Centers are doing so informally now for the LMR and EM efforts. Codifying this would adopt international best practices, would allow for a clear timeline of the process, and would more formally involve stakeholders at several steps in the process.

5. Establish regular NEMoWs

The participants strongly noted the benefits of idea sharing, “support” groups, exchanging tools & tips, etc. at national fora such as NEMoW. Becoming aware of what other Centers are or will be doing will facilitate more standardized and (more importantly) better quality EM approaches.

It was suggested that future NEMoWs focus on more specific, topical working groups whereby an issue is tabled and several EM approaches are applied during the meeting on that topic.

6. Establish an expert training capacity

There was a recognized need to build capacity and expertise for EM. Partnering with academic colleagues and institutes familiar with NMFS LMR needs would help develop the personnel that we foresee will be required to continue and expand EM efforts in NMFS. Items such as the NMFS-Sea Grant Fellowships program could be adapted to have a focus on EM (e.g., 5 pop dy, 5 econ, 5 EM). Similar partnerships and joint institutes could also be modified to emphasize developing expertise to fill this need.

7. Although feasible, a National EM Toolbox is not necessarily needed

It was noted that many tools are commonly used and are shared among NMFS EMers already. There was concern that an EM toolbox might constrain regional application and impede future development. A key conclusion from the workshop was that no single model or approach should be exclusively adopted or avoided, and that multi-model inference is often preferable.

It was also noted that a webpage of links pointing to extant tools would be helpful. But in some respects, such a webpage already exists as part of the EBM tools network. It was noted that NMFS could partner with this effort or establish its own webpage, but there was no need to duplicate tool development and or coordination efforts at some levels.

8. (Yet) Establish "Toolbox list" of efficiencies

Having a loosely organized, broadly applicable toolbox was noted, similar to the stock assessment toolbox, as a way to gain efficiencies in EM review. Having a centralized repository of vetted, routinely-used models would gain efficiencies in application of the models. If NMFS establishes a toolbox of ecosystem models that have undergone thorough review and vetting, it could recommend them as one approach to address a set of EM issues. In so doing, it would save time by allowing users to apply an already vetted tool.

What was also noted here was the need for a nationally coordinated effort to develop common support tools. For example, visualization tools or model output presentation/formatting were noted as item that would gain efficiencies across Centers.

The sum of points 7 and 8 is that a toolbox is not required or even needed, yet having a centralized listing of vetted approaches and support tools would allow EM efforts to be more efficient.

9. Establish mechanisms for feedback between EM and Monitoring

It was noted that for EM efforts to fully assist the broader efforts of the NMFS, they need to usefully identify and suggest areas of data gaps in which to fill. There have been several data gaps noted but how and whether to usefully fill them, at appropriate temporal and spatial scales, or more so when they are not necessarily needed, is something that models can uniquely assist in. By developing mechanisms whereby model identified data gaps are included in monitoring design should help the Agency to more effectively monitor the nation's LMR.

10. Identify areas of disciplinary/expert weaknesses

There was a wide ranging discussion on this topic, with the conclusion that as NOAA moves towards a multiple sector, IEA context, there are areas in which we are not going to have adequate expertise. A common point was that even with the economics expertise, better incorporation of those experts into EM efforts would be beneficial.

11. Engage external (to NMFS) partners

Related to points 10 and 5, it was recognized that we need to engage our external partners and stakeholders more effectively as we continue to develop EM efforts. By including broader and earlier perspectives, we will obtain "buy-in" to model outputs. Other NOAA line offices and governmental agencies may also be of assistance as we begin to address EM issues not solely driven by biological or fisheries related processes.

Appendix A - Proposed National Standards for Ecosystem Modeling

From the workshop discussions, here we propose a set of standards as guidance for use of EM and to serve additionally as review criteria (Table A.1).

Table A.1. Proposed national standards for ecosystem modeling.

1. Adequate Documentation

2. Clearly Stated Objectives

3. Peer Review

4. Best Practice Use

5. Uncertainty Characterized

1. Adequate Documentation

It is proposed that all Ecosystem Models should be fully documented. This would include descriptions of input data and parameterization (Table A.2), model structure and equations; major modeling “tweaks” and tips to allow for functionality and execution of the model; model assumptions; specific model implementation and/or application to a particular system; and key diagnostics.

It was noted that NOAA technical memoranda, Center reference documents, and webpages should be more fully utilized for this purpose.

The need for a “data warehouse” is already recognized within the agency given the copious number of databases that the NMFS manages and maintains. A “parameter warehouse” might also be an emergent property from such extensive documentation over time, whereby routinely used constants and parameters would be vetted and stored. Finally, a list of “approved” models as part of a nascent EM toolbox would also be an emergent factor after several of the models are reviewed (discussed later in item #3) and extensively documented.

Table A.2. A proposed template for documenting model input data and parameters. The rows would be the state variables, parameters, or similar input properties to the model, which would then have major properties (columns) described.

	Input Value	Units	Description	Type (State Variable, constant, etc.)	Origin (Including Species From Which Parameter Was Derived)	Multiple Measures?	Timeframe for Derivation of Value	Type of Review	Reliability/ Confidence	References
Parameter 1										
Parameter 2										
Parameter 3										
Parameter 4										
Parameter 5										
etc.										

2. Clearly Stated Objectives

It is proposed that all Ecosystem Modeling activities have clearly stated objectives. Although a seemingly obvious consideration, often the purpose of a modeling exercise is not forthrightly stated, leading to confusion about intent and application of results. Particularly for those EMs used in a LMR management context, the objectives should be clearly stated. Additionally, if EMs are not to be used in a particular context, these limitations should be clearly identified if they are for primarily research/heuristic purposes.

Additionally, there were several common issues of why EM is invoked. These are listed in Table A.3. We also note the generic model classes (Plaganyi 2007) with model types in that table. Using the rows and columns, we provide a list of recommended model uses for particular applications. These are to help guide that the generic model classes are appropriately applied to the major, common issues facing LMR issues for which EM is invoked.

We want to be clear; this table is not intended to be too prescriptive or to limit innovation. Rather it provides guidance on established approaches for common sets of issues such that a novel use would need a strong justification to be used outside of the recommended objective-model mapping given.

Table A.3. Major model classes as typically applied to common objectives of model use.

Model Classes (Plaganyi 2007) / Major Topics			*Extended SS Assessment Models*	*Minimal Realistic Models*			*Dynamic Systems Models*				*Whole Ecosystem Models*
	Generic Model Types / Common Issues & Objectives	Single Species	Single Species w / add-ons	Multi-species	Aggregate Biomass	Food Web	Habitat	Biophysical	Biogeochemical	Bioeconomic	Full System
Technological Interactions	technological interactions		x	x	x	x				x	x
	bycatch	x	x	x	x	x				x	x
Trophic / Ecological Interactions	protected species and species of interest	x	x	x	x	x		x		x	x
	commercial fishing on forage species		x	x	x	x				x	x
	trade-offs among predators being targeted		x	x	x	x					x
	predation of targeted species		x	x	x	x		x			x
Physical / Climate Drivers	effects of fishing on habitats						x		x		x
	habitat effects on stocks		x	x	x	x	x	x			x
	climate		x	x	x	x	x	x			x
	cumulative effects					x	x	x			x
	toxins / bioaccumulation					x			x		x
Spatial Features	MPA efficacy, structure, placement						x	x		x	x
	range shifts		x				x	x			x
	habitat restoration strategies						x		x		x
System Considerations	invasive species										
	"ecosystem health"—sustainability, resilience				x	x					x
	ecosystem status				x	x		x			x
	biodiversity				x	x					x
	underlying system carrying capacity				x	x	x	x			x
	regime shifts							x			

Table A.3 (continued).

Socioeconomic Drivers & Management	economic issues	x			x	x				x	x
	trade-offs among fleets			x						x	x
	determining reference points- systemic				x	x		x	x		x
	determining reference points- SS assessments	x	x	x							
	cumulative management effects				x	x				x	x

3. Peer Review

It is proposed that all NMFS EM used for LMR management be peer reviewed. This statement was viewed as imperative by the NEMoW participants. Although perhaps obvious, it merits stating outright.

This peer review would entail a review of the: model structure; model behavior & sensitivity analysis; software & code; and for a particular application a review of the: parameters & input data; calibration, validation & verification; and model outputs.

Such a peer review would be performed at several levels of model construction, with a preference for the model structure, behavior and software to be in the peer reviewed literature. Related to item #1 above, the particular application would also need to be documented in an appropriate venue. The model output as applied to a particular LMR management issue would also need to be reviewed by a panel of experts, *sensu* the CIE or some similar body.

4. Best Practice Use

It is proposed that all NMFS EM modeling efforts adopt a “best practices” approach (see Appendix B). This would effectively entail using the FAO (or variant thereof) “checklist” when initiating an EM application.

The discussion ranged widely on this topic, but there was consensus that this “Best Practices List” not be an absolute requirement but a set of guidelines of approaches to best address common modeling caveats. The converse of a “Best Practices List” was suggested as having a minimum standards of use, which is in effect another view of the checklist.

By ensuring that minimum EM standards are met, we mean to ensure that the data are sufficient for each generic model type and specific model (meet minimum requirements). We also mean to ensure that the data and model class are sufficient to specific issue being addressed (Item #3 above).

5. Uncertainty Characterized

It is proposed that each EM effort needs to explicitly characterize uncertainty. Although this is a large part of the best practices noted in #4 above, a clear, transparent set of statements of where a model may not perform adequately is needed. A transparent set of statements of what data or inputs or parameters are sensitive or highly variable, and how this might affect model behavior, is needed.

Although this point could be included in item #4 above, the NEMoW participants conveyed strong enough opinions on the matter to warrant it being noted as a separate item.

Characterization of model uncertainty would take into account structure, implementation, and parameter uncertainty as a key set of reported diagnostics. There should be a suite of standard, model-specific diagnostics in each EM application, but some form of uncertainty characterization would be mandatory for EM use in a LMR management context.

Appendix B - Proposed Ecosystem Modeling Best Practices List

(Editor's Note: this text and section was adapted heavily from a forthcoming FAO report. The FAO report was the result of an Ecosystem Modeling meeting held in Triviso, Italy. We thank G. Watters, E. Plaganyi, K. Aydin and B. Fulton for alerting us to it and allowing us to utilize and modify the text.)

A best practice approach to ecosystem modeling must include specification, implementation, evaluation, reporting and review steps. Model scoping undertaken during model specification must include the iterative construction of conceptual models that are used to define the relevant subsystem to be modeled. Once this subsystem is identified, the final model representation must be defined based on the question being considered, available data, the important system features and the appropriate scales (regarding space, time, taxonomic and human impacts resolution) and process representations.

Table B.1 shows best practices for modeling. These are not benchmarks but rather are an achievable set of practices that should guide thinking as to the importance of different model attributes and suggested approaches for handling each of these. These practices should be followed to the extent possible. This list summarizes some of the key attributes to be considered in model development and suggests the current best practice for handling each of these, noting that this may not be practically achievable in most circumstances.

The list is intended as a set of considerations to be addressed when developing ecosystem models. However, it is not anticipated that these practices will be achievable or required in every case.

Consideration in Model Development	**Best practice approach**
Setting up a model	
How many species or groups?	Aggregate based on shared characteristics of the species and omit the least important to keep food web tractable
Include age, size or stage structure of the species of interest?	Include if there are major shifts over the course of the life history of (harvested) species of interest
Include spatial structure?	Include where there are major shifts in the location of the species of interest over the course of its life history
Include seasonal and temporal structure?	Where there are large differences in the seasonal dynamics in species movement or production
Defining boundary conditions	Basing boundaries on biological/geological rather than anthropogenic considerations such as national boundaries.
Is fishery harvesting more than one stock of a particular species?	Model needs to distinguish such different stocks when the harvesting practice is such as might impact these stocks to different extents; this may necessitate spatially structured models
Distinguish different fleets?	Important in the context of provision of advice at the tactical level, if for the same mass of catch, they make substantially different impacts on target and bycatch species or on the habitat.
Explicitly represent primary productivity and nutrient cycling	May only be necessary when bottom-up forces or lower trophic levels are of key concern. Inclusion of these processes can be highly informative for some strategic modeling exercises.
How to model recruitment?	Recruitment may be included either as an emergent property or as a derived relationship (which should not be based on uncritical correlation studies of recruitment and environmental parameters). Recruitment variability is likely to be important for tactical and risk analyses, but is not a strict requirement in many strategic models.
How to model movement?	This involves testing sensitivity to a range of movement hypotheses. Where possible, best practice involves parameterizing movement matrices by fitting to these data. If decision rules are used to drive movement, attention should be focused as to whether the resultant changes in distribution are sensible.
Explicitly consider fleet dynamics?	Important to consider if substantial changes to the spatial distribution of fishing may result from, for example, the declaration of an MPA. The population model must include of spatial component in these circumstances, and it may be necessary to develop a model of the manner in which fishing effort patterns will change in response.
How much detail in representing predator-prey interactions?	Represent as bi-directional unless it can be strongly demonstrated that it is adequate to include a one-way interaction only in which the predator ration is fixed and changes in prey abundance have no effect on predator populations.

Which functional response?	Test sensitivity and robustness to alternative functional relationships.
Include environmental forcing?	Only if it is an absolute requirement for capturing system dynamics. When it is included there must be some means of generating future forcing for use in predictions and closed loop simulations and a clear understanding of probable mechanism
Other anthropogenic forcing?	Their influence on shallow coastal and estuarine systems should be considered in conceptual models and if they are found to be significant pressures on the system then they should be empirically included (e.g. simply as a forcing term) in any strategic models and management strategy evaluations for the system.
Alternative stable states?	Strategic models in particular need to ensure forecasting the consequences of environmental change, contain the capacity (e.g. functions) which allow for phase shifts, either directly (in accordance with past observations), or as an emergent property of the functions in the model. Even if such a functional form is used, it must be recognized that, until a threshold is crossed in the data, it may not be possible to parameterize the threshold point: uncertainty reporting should evaluate possible thresholds either on a theoretical or empirical basis.
Dealing with uncertainty	
Model structure uncertainty	Identify alternative qualitative hypotheses for all of the processes considered likely to have an important impact on the model outputs and then formulate these hypotheses mathematically (or as the values for parameters of a general relationship).
Implementation uncertainty	Implementation failures introduce biases in fishery data which will impact assessment and tactical models. It also creates biases in the expected impacts of simulated management measures within an MSE. Implementation uncertainty needs to be linked to consideration of fleet dynamics and is largely driven by, and must be included in, economic considerations.
Other process error considerations	Other process error, arising from natural variation in model parameters, needs to be included in projections, whether they be strategic or tactical, when that variation contributes substantially to uncertainty in the model outcomes.
What features to include in closed loop simulations?	As many as are feasible to parameterize for addressing the question at hand.
Should the model be fit to data?	Fitting to data is best practice, and this requires careful specification of likelihoods.
Taking account of parameter uncertainty	Include clear statements about uncertainties in model parameters; Bayesian methods and bootstrapping are considered best practice for quantifying parameter uncertainties in extended single-species models and MRMs; Improving current practices requires 1) that there is an

	explicit accounting of the number of parameters that are being estimated and fixed, 2) qualitative estimates of the uncertainty in every parameter, and 3) **sensitivity analyses.**
Taking account of parameter uncertainty for mass balance / static models	To develop and fully document a formal data pedigree (quality ranking), and if possible include error ranges for estimates, with input from data providers as to potential biases. Sensitivity analyses may be conducted using available routines. For dynamic models, best practices is to fit to as much data as possible using appropriate likelihood structures, while being clear about both potential biases arising from fixing parameters, as well as fully reporting error ranges resulting from freeing parameters. In case of fixing parameters, additional sensitivity analyses (e.g. resampling, Monte Carlo routines) should be used to assess model sensitivity to the assumptions. An important component is using results of sensitivity analyses to guide future data collections and the continuation of critical time series.
Use and outputs	
Should code be freely available?	Documentation and source code must be freely available to allow for review and understanding of the model. Using existing models can be of great help in learning, but careful thought is required when using a pre-existing model so that the tool is not misused.
Social and economic outputs	Have economic experts collaborating with fisheries ecologists when designing a model implementation of economic factors.
Ease of modularization	Best is object-oriented design

Appendix C - Workshop Observations

Bjarte Bogstad
Institute of Marine Research, Bergen, Norway

The NeMoW in Santa Cruz gave a very useful summary of ongoing ecosystem modeling work. Also the classification of model groups (based largely on FAO Fisheries Technical paper 477 edited by Eva Plaganyi) is very useful when planning future work. This year, 2007 seems to be the year on summing up the 'state of the art' of ecosystem/multispecies modeling. In addition to NeMoW and the Plaganyi paper, there is also the ICES Working Group on Multispecies Assessment Methods in October 2007, which has as one of its terms of reference to "examine the status of multispecies modeling efforts throughout the ICES region". (Editor's note, there was also a FAO workshop and will be a DFO workshop on a similar topic).

I agree with the general line of thinking of using different models for different purposes.

Some points for further work that I'd like to make:

It is important to emphasize that modeling work needs to be well integrated with ongoing biological research. It is easy to underestimate the effort needed to bridge the gap between the modelers and 'the others'. Increasing the biological realism of models requires new equations and parameter values to be included, and if not this is specifically asked for, it may be difficult/impossible to obtain from the publications being made in ongoing biological research.

Note also that, at least initially, putting effort into this integration may hamper the publication rate of the people doing the ongoing biological research.

Easy access to relevant data sources is also very important, and much more of a challenge than for single-species models. One needs to make it as easy as possible both actually getting access to the data as well as extracting the data on the spatial/temporal/biological resolution required for a particular model.

Alida Bundy
Fisheries and Oceans, Canada, Bedford Institute of Oceanography, Canada

Overall Comments

I would first like to thank the organisers for the invitation to NEMoW – it was a very well organised and enjoyable workshop. Although I was invited as an external participant, I gained a lot from the discussions, the presentations and meeting NMFS scientists. Furthermore, the atmosphere was collegial, enthusiastic and positive. I am impressed by the number of NMFS scientists engaged in ecosystem modelling, and by the amount and quality of ecosystem modelling work. Clearly, this is through the foresight and interest of individual scientists rather than a grand plan for ecosystem research. Luckily for NMFS there are some very talented and dedicated scientists among its ranks, most of whom are younger than 50!

Ecosystem Models and NMFS

It is as difficult to define an ecosystem model as it is to define the boundaries of an ecosystem. Fortunately, this workshop was able to benefit from the imminent FAO Tech Rep 477, “Models for an ecosystem approach to fisheries” (Plaganyi 2007) which has classified a wide range of ecosystem models into 4-5 categories. It was demonstrated during the meeting that NMFS scientists are using and developing models across the range described in Plaganyi (2007). Actually the breadth of applications within NMFS is impressive. Also impressive are the innovations that NMFS scientists have brought to some of the methods, such as the developments of EwE by Aydin and Gaichas (AFSC) and of MSVPA by Garrison (NEFSC).

There are a large number of ecosystem models in use, and there is the clear potential to develop more models (tailor made to specific systems?). During plenary and breakout group discussions, we discussed modelling gaps or insufficiency, such as chaotic models, migration models, larval models, etc. While it is useful to be aware of gaps, I think in the short term (3-5 years) it will be more useful for NEMoW to focus on what it is doing, and doing well, and build strength and capacity here, while keeping track of where it needs to go in the future. This was reflected in my breakout group discussion where we agreed that we should work with the major classes of model identified at NEMoW, (ie., there was no point in reinventing the wheel), but that room should also be allowed for innovation.

Having said this, one area which requires more focus is incorporating economics and bio-economics into ecosystem models. We were told that NMFS does have economists, but how are economics currently included in NMFS? Are the economists involved in any of the modelling work? It is important that biologists, modellers and economist, social scientists talk with one another!

There was little to no discussion of how complex we want these models to be. Some are very unwieldy, take a lot of time to get running and can only be run by a few people. I think that there needs to be some hard-nosed thinking about the pay-offs for the time invested in these super large models versus the time it would take to use a different, simpler modelling approach. This is not a question of strategic versus tactical (see below), but how to explore strategic questions, possibly within MSE, when there are limited resources.

In terms of the models/approaches that are being undertaken by NMFS scientists, and the objectives of NEMoW, I wonder whether the habitat and water quality related models are a good fit in this scheme (those presented were mostly related to salmon)? To my knowledge, there were only 2-3 scientists working with these models at the meeting, so I felt that they were underrepresented in terms of user participation and these models were discussed less than models such as EwE, MRM and ESAM which are used in many of the Centres. This was articulated at one point in the meeting when it was suggested that in the salmon world there is a focus on anthropogenic influences whereas in marine shelf world focus is on foodwebs. I chatted with a couple of the scientist using these models and they indicated that they found the workshop useful, finding both commonalities and scope for cross fertilisation of ideas. However, the idea of applying National Standards to models which are not well represented in the room is a little worrisome. Note that in the FAO report (Plaganyi 2007), habitat models were not well covered either and I think that this reflects both a more common focus on marine/shelf fisheries (amongst those at the workshop) and a separate literature for habitat models.

There was no mention of the role of qualitative modelling, although this can be very useful for conceptualising problems and can also be used in MSE.

Given the extent of ecosystem modelling that is already taking place at various NMFS Centres, it would be useful to take a formal hierarchical modelling approach to one or more systems. This would both further understandings of the system and also allow the evaluation of models of different complexity and their utility to the management process.

Strategic versus Tactical Models and setting of priorities.

People were too hung up on this discussion. Clearly both are needed, there is a synergy between the two, and data, resources, expertise, problems to be addressed will determine the distribution of effort between the two.

I liked the idea of proactive modelling and NMFS taking the initiative to use models to explore issues/questions that it thinks is important, while also consulting with stakeholders. While there will always be cases where we can only be reactive (we cannot anticipate everything), a proactive approach has the potential to increase response time from a greater base of understanding.

In terms of identifying modelling objectives, there were several suggestions that stakeholders should be involved in this process. Not sure that this was agreed by all and no process was discussed for doing this.

Generic Modelling Objectives

As always when you get a group of scientists together, some got hung up on semantics and classification when we discussed whether there are common modelling objectives across the NMFS Centres. Here are some thoughts:

- Is it useful to identify a set of generic modelling objectives?
    - I think so, because it underscores the fact that similar issues are faced in each Centre and that these are more efficiently addressed when there is agreement on the best way(s) to address these issues.
- Does it matter whether there are 5 or 10?
    - No, what matters is that the main modelling objectives are covered. Two different lists were proposed.

List 1:	List 2:
Trade-off between predators	Ecological Interactions
Technical interactions	Technical Interactions
Exploitation of commercial forage species	Spatial Dynamics
Concern over species of interest	Physical/environmental Drivers
Bycatch issues	Management/societal implications
MPAs	
Ecosystem Status (resilience etc)	
Habitat Effects	
Establishing biological reference points	
Habitat restoration questions	
Land-sea interactions	
Water quality issues	

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Which list is better? I think that List 1 is more useful for (a) it is more specific (b) it will allow clearer mapping to models and (c) it is a living list that can be extended as required (Editor's note: this discussion resulted in large part the tables seen in Appendix A).

Standardisation and an Ecosystem Modelling Toolbox

I was not too surprised by the dichotomy of opinion expressed concerning both the development of National Standards for ecosystem modelling and the EM toolbox: on the one hand these will hopefully lead to consistency of models use, good bug-free code and facilitate the assessment process. On the other, they could be seen to limit freedoms to explore and develop new models. I do not believe that the latter is the intent, and I do think that a centralised approach, with a toolbox of used and approved methods, within a National Standards for EM framework, would facilitate greater interest and participation in ecosystem modelling by NMFS scientists. There is no reason why models should be esoteric and only available to those who can write code. A National Standards approach may require more accountability, but that it a good thing, and will ensure proper use of the models.

I found it interesting that everyone essentially agreed on developing a toolbox of sorts for visualisation of model output and communication with stakeholders/management and other users. This was a recognised deficit.

Peer Review of Models

This is an excellent approach and there already seems to be a process in place for review of fisheries models in NMFS that can be used/adapted for ecosystem models, e.g.,: CIE – Centres of Indepdent Expert Review; SAW- Stock Assessment Workshop; SARC; STAR Reviews, etc.

Degree of review should depend on what the model is used for (eg, tactical , theoretical or MSE type model). One concern though is that there is a danger of tying ourselves in knots of our own making if the process for model review is overly cumbersome and onerous. There may be too few reviewers available, if the review process is made too detailed. The advantage of a toolbox approach would be that many models would already be reviewed, and thus the application of the model would be reviewed, not the model itself.

Data Needs
There was some focus on data needs for EM, and in particular diet data and seasonal data. The problem is, we always want more data and I am not sure how much NMFS administrators want to hear this. I would not overly emphasise this point

Communication

All Centres use foodweb models of some sort, and many use other common approaches, but it was not clear how much communication there is between Centres concerning methods and uses of models.

It was useful to have scientist from some different backgrounds because the diversity brought some interesting perspectives to the discussions, which were mostly useful. However, what proportion of those engaged in ecosystem modelling at NMFS was represented at the meeting? Was the meeting representative of NMFS ecosystem modelling efforts?

Break-out groups – these worked well and interestingly, there was a lot of consistency between groups as well as independent thought. Sometimes questions were a bit repetitive but they were generally useful since they provided structure for the discussion.

Parallels with Canada
There are lots of commonalities with the EM modelling situation in Canada – e.g., we are also in the process of trying to develop a dedicated ecosystem modelling group across the country for exchange of ideas and to develop a common approach to EM, we have concern over being able to hire people with sufficient expertise, there is little connection between ecosystem modelling and stock assessment, although we too are trying to bridge this gap and we are trying to raise the profile of EM. It will be useful to keep an exchange of ideas across the border as well as in Canada and the US.

Additional Thoughts

What are the resources available for EM in NMFS (i.e, $ and people)? This not clearly outlined. What are the limitations? What can realistically be done? What are the time lines?

Concerns about recreating SS problems in MS world – it’s a good point!

Purpose of NEMoW
In addition to the objectives of NEMoW identified in the TOR, I would suggest that one of the main benefits of this meeting has been the opportunity for the participating scientists to engage in discussion, and exchange ideas with colleagues about EM.

The Future
Ecosystem Modelling WGs as a common part of the fisheries/ecosystem assessment process.

Villy Christensen
University of British Columbia, Fisheries Centre

The world-wide move toward ecosystem-based management of fisheries resources has manifested itself through numerous international agreements and through the emphasis the topic has received in fisheries research organizations and academia in many countries. Important aspects of the move have been to address how we establish the scientific underpinning to inform the process, notably related to how we evaluate alternative management scenarios and the trade-off's that inevitably will be called for when incorporating system-wide effects. It is clear that ecosystem modeling has a very important role to play in this context, and the NEMoW-initiative must on this background be lauded for being timely and highly relevant. While there are many activities around the world that are related to ecosystem modeling and its use as part of the EBM process, such initiatives are typically low-key ones where researchers use sparse funds of opportunity to get introduced to the topics and engaged in the process, often without it being clearly defined in the terms-of-reference for the researchers. It is indeed rare that EM is more than an appendix on the activities in fisheries research and management institutions. Here, NEMoW is one of the first initiatives where institutional backing for the process has received a level that seems to recognize that effort will need to follow intentions, even if it means picking up additional workload. Considering what it will take to carry forward the momentum gained through NEMoW-1, I'd especially point to the need to support the cooperative element that NEMoW represents. There are, as was clear from the workshop, a large number of EM - EBM activities in the NMFS centers across the United States, and care (i.e. effort) should be given to ensure that such activities develop in concert. This concern is rooted in recognition of the unfortunate observation of how single-species fisheries assessment in North America largely has been divided in two, radically different schools, west coast versus east coast. Through cooperation, such as what NEMoW may well lead to, we can hopefully build a cooperative environment where researchers through regular communication recognize the need to use a suite a tools, rather than being entrenched with what happened to be 'customarily' used. I think it would be beneficial for NMFS to consider how best to support this cooperation and perhaps to set up a structure that will help coordinate tool development and training, among others by arranging methods workshop. Having said this, I finally noted at the workshop that the tool I'm mainly involved in development of, EwE, is being used (to some degree at least) at all NMFS centers. The level at which the tool is used varies between centers, but I note that only few colleagues actually are involved in developing the tool further. We have through a new version (which is fully re-programmed in an OOP-environment) facilitated a much wider involvement of developers in the further development, e.g., by creating center-specific software versions tailored to the use in the individual centers. I'd very much like to be involved in and support such an activity in the future.

Beth Fulton
Commonwealth Scientific and Industrial Research Organisation, Marine and Atmospheric Research, Hobart, Tasmania, Australia

The first NEMoW workshop is timely, given it comes during a year where much of the resource modelling world is taking stock of where ecosystem modelling has reached and what needs to be done to make the best use of it. The practical limits on the available resources for this work versus the increasing demand means that it is an important and wise decision to evaluate what is already being done, what resources exist and how to best make use of them by identifying commonalities, data requirements and modelling standards.

Ecosystem modelling within the US, and more generally around the world, has often been caste as an opportunistic exercise typically driven by specific ecological (or economic) research questions. The body of work presented within the workshop indicates that despite this impression an impressive body of research spanning the spectrum of ways in which ecosystem processes can be modelled in resource models (extended single species through multispecies to whole of ecosystem models). What this diversity of effort should highlight is that there is an immense body of creativity within NOAA's science centres and that the scientists on the ground are already making significant advances towards addressing the range of questions that need to be addressed for immediate management action or may be needed into the future under changing conditions. The biggest advantage to building on the existing body of work is to be well prepared for future questions, an important step to make given the lead time many of the methods require. The size of the existing body of work also underlines why anything that could constrain that breadth of effort and ideas should be avoided, the more models used the better for understanding, confidence and for ensuring the correct models are used for the specific question being addressed. As has been said many times before, all models are imperfect representations of reality and that "the truth is the intersection of independent lies" (Levins 1966). Most of all it must be stressed that the different model types complement rather compete with each other. For instance, ecosystem models can be used to direct strategic decisions, to help navigate the best path through the turbulent waters that are the highly complex mix of levers, motivations and drivers of resource management.

One particularly useful tool in that context is the management strategy (or management procedure) approach (Butterworth and Punt 1999, Sainsbury et al. 2000). It is a method that has been used with great success in other countries to check many aspects of the adaptive management cycle, from specific assessment methods, monitoring schemes or harvest rules to region-level multiple use management (IWC 1992, Punt and Butterworth 1995, de la Mare 1996, Mapstone et al. 2004, Goldsworthy et al. 2001, Gray et al. 2006, Fulton et al. 2007). Another lesson that can be learnt from experience overseas is not to overlook the contributions and involvement of the many stakeholders in natural resource systems. The inclusion of stakeholders from the earliest stages has lead to greater engagement and success in work in (for example) Australia. The stakeholders have a greater feeling of ownership, it is often easier to communicate results and they can also provide sources of information when there are no alternative ways of filling information gaps. This is particularly important when it is recognised that there are some significant system components that need to be incorporated in to, at least some of, the modelling exercises (e.g. habitat, disease, larval supply, climate impacts, and social and economic drivers). To date the prioritisation of resource use has typically overlooked these drivers, but they can be as important (if not more so) than some of the more typically included processes; in particular economic drivers can be as strong a force in a system as ecological or climate drivers (e.g. Fulton et al 2007) and as such should be integrated into analyses from the earliest steps, not added in a patchwork fashion at a later date.

Given the potential for models that need to consider this growing list of factors, at least at the conceptual if not final implementation stages, it is imperative that best practice model construction and use methods be used. Fortuitously the timing of this workshop can build on the experience and efforts of the other groups going through a similar process of defining guidelines and shape them further with the wide range of US experience to form a very useful set of best practices (and a very good draft of such practices has been produced by workshop members). Research into model complexity and the implementation of multiple use management strategy evaluations has shown the value of building quantitative models only after conceptual or qualitative models have been used to refine objectives and model structure. This makes the choice of model type easier and allow for a more transparent consideration of the many dimensions of model construction, including: trophic, anthropogenic, spatial, temporal and process resolutions. Another key factor of the best practice use of models is to make sure there is maximum transparency (chiefly via documentation, freely available source code or software and peer review). These best practices are fairly typical of all kinds of modelling, but they are particularly important for multispecies and ecosystem models as their very nature makes it a non-trivial exercise to repeat analyses; uncertainty is often large but hard to refine, represent or communicate; and a lot of research remains to be done into the best means of parameter estimation, calibration, handling uncertainty, judging model skill (performance) and most effectively linking that to advice for management bodies. The size of these tasks will not diminish under the non-stationarity imposed on systems by climate change.

Ecosystem modelling is a relatively new and rapidly developing field with much to be done. Nevertheless many research initiatives are underway and communication is probably currently the single most important key to making the most of the current research momentum and resources. Communication is key to conveying results (with new technologies like web and visualisation tools presenting a key way of tailoring results to the audience's needs), preventing needless duplication of effort, dissemination of experience and the kind of advance that comes hand-in-hand with a critical mass of intellect directed at common problems. Further workshops, training exercises or grants (which will help bring in new talent and increase resources) and collaboration with external bodies are likely to be amongst the best means of communication. Some of this has happened already without more formal frameworks, but dedicated support and resources will allow for more rapid advances. In particular it is strongly encouraged that engagement with international peers, particularly those sharing common resources and facing similar problems (e.g. researchers in neighbouring countries), would be mutually beneficial and a strong value-adding exercise. All nations engaged in EBFM have reached the point of assessing what ecosystem models currently have to offer and what they need to do into the future to most usefully contribute to management. The US is currently well placed to move beyond this stage of taking stock and going forward to make some world leading advances in the areas of model use and model-management links. By building on current activities, building strong communication channels, implementing best practice methods and ensuring all stakeholders and major fields (especially economics) are included from the outset, NOAA researchers have very good prospects for following through on this potential.

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Eva Plaganyi
Department of Maths and Applied Maths, University of Cape Town, South Africa

Some comments on the NEMoW:

The development and application of fisheries ecosystem modeling approaches is important both in the U.S. and worldwide. It was impressive to see the wide range of different ecosystem modeling approaches being developed at the various centres. The Workshop was clearly extremely useful in bringing together these different groups to share ideas and take stock of progress to date.

The range of ecosystem models described suggested that these models had been constructed to address a wide variety of topical questions. It may be useful to assess the issues addressed against a broader framework in which all ecosystem issues are listed. Given that practical constraints have typically limited the focus of these ecosystem models, it is important to bear in mind that wider ecosystem issues such as those pertaining to social, economic and governance considerations can be highly important in some contexts.

The workshop highlighted the considerable progress that has been made nationally in the development of ecosystem models, but it was clear that much work still needs to be done before the results of these studies contribute directly to the management process. Examples that were presented highlighting success stories in this regard will undoubtedly contribute to strengthening efforts in this regard. There appears to be substantial differences between work being conducted on the west versus east coasts of the U.S., highlighting the need for better communication and integration of research in this area. It was interesting to note that there was considerable overlap in ecosystem modeling issues across all regions and management problems, even those pertaining to different systems such as salmon habitat considerations. This workshop was both essential and successful in moving forward ecosystem modeling with relevance to fisheries.

Summary Observations, NEMoW Steering Committee

NEMoW provided the opportunity to compare technical aspects of ecosystem modeling as well as issues related to the construction and use of models. Discussion among workshop participants yielded a number of commonalities among Centers and Offices (hereafter, Centers). Here, we highlight what appeared to be approaches, strengths and concerns shared among the Centers.

I. Observations about the types of models used or being developed

A. Food-web or energy models were a tool that most (if not all) of the Centers and Offices (hereafter, Centers) have developed. For instance, EcoPath with Ecosim (EwE) was a ubiquitous tool. Additionally, Atlantis seems to be a tool gaining some use in various locations (e.g. the Northeast and Northwest). The degree of sophistication of these models appears to vary greatly among regions, with some regions extending far beyond its “stock” capabilities. This variable level of complexity may result from the degree to which management is directly concerned with foodweb issues, and thus the need for rigorous models that can immediately inform management action.

In addition to entire food web models, most centers have extended single species models so that issues involving predation on commercially targeted species can be addressed. These models appear to differ philosophically from food web simulation models (such as EwE) in that extended single species models are largely developed to improve single-species stock assessments, while food web models, thus far, appear largely geared toward exploring the ecosystem-level consequences of different management strategies.

B. MRM or multispecies models are intermediate in complexity between foodweb models and extended species models. Many (4 of 7) Centers have some form of MRM or multispecies models. As with extended-single species models, MRMs predominately evaluate the effects of predation on targeted species. Thus, these models are geared toward fisheries goals, rather than broader ecosystem goals.

C. In addition to models focused on trophic interactions, most Centers have models that link aspects of the environment to fish ecology or biology. For instance, there appear to be a number of efforts to statistically use physical conditions (e.g., sea surface temperature) to improve recruitment estimates. In other cases complex models have been or are being developed to predict or better understand aspects of movement, migration and/or carrying capacity.

D. Many (4 of 7) Centers also have developed or are building habitat-based models. Two general types of habitat models were discussed. In some systems in which degraded habitat is a key management concern, models linking management actions to changes in habitat quantity or quality were common. In such models, the management action might be to restore the geological / ecological processes that produce important fish habitat, and simulations allow determination of how much is enough. Secondly, habitat models are used to link physical, biological or chemical habitat attributes to fish production. These models are often related to or embedded in the models discussed above. In combination, these models provide a means for estimating the effects of habitat restoration / preservation on the dynamics of fish stocks. Research in the Gulf of Mexico on how habitats function for juvenile fishery species is now being translated into mechanistic habitat models that are directed towards simulating consequences of further habitat loss and supporting the design of habitat restoration projects. These models were particularly prominent in estuarine dominated ecosystems as well as for watersheds in the Pacific Northwest.

II. Additional observations

A. The concept of adaptive management is now engrained in fisheries science, and it became clear from the presentations and discussions that most Centers have adopted a “Management Strategy Evaluation” (MSE) framework to simulate the adaptive management cycle. Generally, MSE involves assessing the consequences of a range of management strategies or options and presenting the results in a way that exposes tradeoffs in performance across a range of management objectives. MSE might be formally conducted using simulation techniques, but even those Centers that do not yet use simulation models to conduct MSEs use this framework implicitly to contextualize their ecosystem modeling efforts.

B. Outputs from ecosystem models typically do not have routinely high “uptake kinetics”. That is, it appears that few model outputs currently find their way into the management process. In those limited cases were outputs from ecosystem models have been directly used in the management of living marine resources, workshop participants indicated that such uptake was associated with a lawsuit or similar controversy.

C. Ecosystem models, especially more complex models, can require an immense amount of data. Thus, it is not surprising that all Centers have clearly identified data needs. For target species, data gaps include diet information, as well as details about spatial and temporal variation of natural mortality, reproductive output and growth. In many instances, data for ecologically important species (e.g., krill, shrimp, mesopelagics, benthic invertebrates, macroalgae, gelatinous zooplankton at mid trophic levels) are lacking. Even basic abundance data for ecologically important species is absent. While some Centers have greater data gaps than others, the type of data needs were similar among Centers.

D. All Centers noted a shortage of staff and resources to execute ecosystem models. Workshop participants noted that currently ecosystem modeling is performed in somewhat of an ad hoc basis. With more resources, participants felt model outputs could more routinely be integrated into the LMR management process. There was a clear consensus that to execute or implement significant levels of ecosystem modeling while continuing to address other duties requires either new resources or a shift in the frequency of executing other duties.

E. There clearly was a lot of enthusiasm and a surprising amount of concurrence among practitioners on most of the ecosystem modeling topics. The advantages and disadvantages of different models or modeling approaches were clearly laid out, and rather than argue about what model was “best”, discussion centered around what modeling approaches were best suited to particular sorts of problems.

F. Despite a shortage of resources, NMFS clearly has an active ecosystem modeling community. Given limited resources and the relative youth of the field, the level of activity is nothing short of “impressive”, as was noted repeatedly at the meeting. Additionally, there is clearly a great deal of interest in NMFS ecosystem modeling activity by external constituents.

Appendix D - Participants List

Ned Cyr	Ned.Cyr@noaa.gov	ST
Kenric Osgood	Kenric.Osgood@noaa.gov	ST
Howard.Townsend	Howard.Townsend@noaa.gov	NCBO
Jason Link	Jason.Link@noaa.gov	NEFSC
Kerim Aydin	Kerim.Aydin@noaa.gov	AFSC
George Watters	George.Watters@noaa.gov	SWFSC
Phil Levin	Phil.Levin@noaa.gov	NWFSC
Josh Sladek-Nowlis	Joshua.Nowlis@noaa.gov	SEFSC
Jeff Polovina	Jeffrey.Polovina@noaa.gov	PIFSC
Sarah Gaichas	Sarah.Gaichas@noaa.gov	AFSC
Mike Dalton	Michael.Dalton@noaa.gov	AFSC
Jim Ianelli	Jim.Ianelli@noaa.gov	AFSC
Buck Stockhausen	William.Stockhausen@noaa.gov	AFSC
Chris Harvey	Chris.Harvey@noaa.gov	NWFSC
Mark Scheuerell	Mark.Scheuerell@noaa.gov	NWFSC
Mary Ruckelshaus	Mary.Ruckelshaus@noaa.gov	NWFSC
Tim Beechie	Tim.Beechie@noaa.gov	NWFSC
Tom Wainwright	Thomas.Wainwright@noaa.gov	NWFSC
Isaac Kaplan	Isaac.Kaplan@noaa.gov	NWFSC
Evan Howell	Evan.Howell@noaa.gov	PIFSC
Bert Harting	harting@mcn.net	PIFSC
Frank Parrish	Frank.Parrish@noaa.gov	PIFSC
Russell Moffitt	Russell.Moffitt@noaa.gov	PIFSC
John Field	John.Field@noaa.gov	SWFSC
Christian Reiss	Christian.Reiss@noaa.gov	SWFSC
Jonathan Phinney	Jonathan.Phinney@noaa.gov	SWFSC
Andy Leising	Andrew.Leising@noaa.gov	SWFSC
Todd Gedamke	Todd.Gedamke@noaa.gov	SEFSC
Lance Garrison	Lance.Garrison@noaa.gov	SEFSC
Tom Minello	Tom.Minello@noaa.gov	SEFSC
John Carlson	John.Carlson@noaa.gov	SEFSC
Joan Browder	Joan.Browder@noaa.gov	SEFSC
Kevin Friedland	Kevin.Friedland@noaa.gov	NEFSC
Heather Haas	Heather.Haas@noaa.gov	NEFSC
Chris Legault	Chris.Legault@noaa.gov	NEFSC
Bill Overholtz	William.Overholtz@noaa.gov	NEFSC
John Manderson	John.Manderson@noaa.gov	NEFSC
Greg Lough	glough@whsun1.wh.whoi.edu	NEFSC
Hongguang Ma	Hongguang.Ma@noaa.gov	NCBO

External Observers

Villy Christensen	v.christensen@fisheries.ubc.ca	UBC
Beth Fulton	Beth.Fulton@csiro.au	CSIRO
Alida Bundy	BundyA@mar.dfo-mpo.gc.ca	DFO
Eva Plaganyi	Eva.Plaganyi-Lloyd@uct.ac.za	UCT
Bjarte Bogstad	bjarte.bogstad@imr.no	IMR
Mike Uhart	Michael.Uhart@noaa.gov	OAR
Marc Mangel	msmangel@soe.ucsc.edu	UCSC

Appendix E - Steering Committee

Howard Townsend	NCBO
Kerim Aydin	AFSC
Ned Cyr	ST
Kenric Osgood	ST
Josh Sladek-Nowlis	SEFSC
Jeff Polovina	PIFSC
Phil Levin	NWFSC
George Watters	SWFSC
Jason Link	NEFSC