Northeast Fisheries Science Center Reference Document 11-23

An Overview of the NEFSC's Ecosystem Modeling Enterprise for the Northeast US Shelf Large Marine Ecosystem: Towards Ecosystem-based Fisheries Management

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EXECUTIVE SUMMARY

As we move towards Ecosystem-based Fisheries Management (EBFM) in the Northeast [US] Shelf Large Marine Ecosystem (NES LME), ecosystem modeling will be a critical element of doing so. As such, it is valuable to describe current and ongoing ecosystem modeling efforts in the NES LME, with a particular emphasis on how they are being used in a living marine resource (LMR) management context. We provide a description of the major ecosystem models and salient information associated with their use in the NES LME. We discuss how such models could be used to advance EBFM in the near term with a focus on the appropriate application of classes of models for addressing specific types of high priority research and management questions. We also note those areas of improvement that could be considered to enhance ecosystem modeling efforts for the NES LME. We finally highlight some of the major lessons learned from our modeling endeavors in an LMR context in the NES LME, so that we and other regions around the world can continue to move towards the implementation of EBFM.

LIST OF ACRONYMS

AAC	Atlantis Availability Calculator
Agg Prod	Aggreate Production
AMO	Atlantic Multidecadal Oscillation
ASMFC	Atlantic States Marine Fisheries Commission
B_{MSY}	Biomass at Maximum Sustainable Yield
BRP	Biological Reference Point
CanCorr	Canonical Correlation
CCA	Canonical Correspondence Analysis
DFA	Dynamic Factor Analysis
DFO	Department of Fisheries and Oceans (Canada)
EcoAP	Ecosystem Assessment Program
EBM	Ecosystem-based Management
EBFM	Ecosystem-based Fishery Management
EFH	Essential Fish Habitat
EM	Ecosystem Model
EMAX	Energy Modeling and Analysis eXercise
ESAM	Extended Stock Assessment Model
EwE	Ecopath with Ecosim
F_{msy}	Fishing rate (or Mortality) at Maximum Sustainable Yield
FMC	Fishery Management Council
GARM	Groundfish Assessment Review Meeting
GOMAGG	Gulf of Maine Aggregated Dynamic Model
GUI	Graphical User Interface
IEA	Integrated Ecosystem Assessment
K	Carrying Capacity
LeMans	Length-based Multispecies Analysis by Numerical Simulation
LMR	Living Marine Resource
LTL	Lower Trophic Level
M2	Predation Mortality
MAFA	Min-Max Factor Analysis
MDS	Multi-dimensional Scaling
MRM	Minimal Realistic Model
MS	Multispecies
MSE	Management Strategy Evaluation
MS-PROD	Multispecies Production
MSVPA	Multispecies Virtual Population Analysis
MSY	Maximum Sustainable Yield
MSYPR	Multspecies Yield-Per-Recruit
NAO	North Atlantic Oscillation
NEFSC	Northeast Fisheries Science Center
NES LME	Northeast [US] Shelf Large Marine Ecosystem
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
PCA	Principal Components Analysis
PSA	Productivity-Susceptibility Analysis

r	Growth Rate
SARC	Stock Assessment Review Committee
SAW	Stock Assessment Workshop
SPMW	Surplus Production Modeling Workshop
SS	Single Species
SSC	Science and Statistical Committee
TL	Trophic Level
TOR	Term of Reference
TRAC	Trans-boundary Resource Assessment Committee
UTL	Upper Trophic Level

INTRODUCTION

There have been numerous calls for implementing an ecosystem-based fisheries management approach (EBFM) (Larkin 1996, Link 2002a, 2002b, Garcia et al. 2003, Browman and Stergiou 2004, 2005, Pikitch et al. 2004, Link 2010a). The justifications and rationales for adopting EBFM have been previously noted (Larkin 1996, Botsford et al. 1997, NMFS 1999, Link 2002a, Garcia et al. 2003, Link 2010a), with clear benefits of considering a broader array of factors that influence living marine resources (LMR). For instance, EBFM: (1) addresses effects of fishing on nontarget species, habitat, ecological interactions, and system-wide processes; (2) recognizes that marine ecosystems provide "goods and services" other than fishery harvest; (3) explicitly addresses biomass tradeoffs (in our view the key to the entire issue); (4) increases leverage from new stakeholders brought to the process not normally involved in single sector, fisheries focused issues; and (5) can actually change the burden of proof, particularly in determining and evaluating impact of various ocean uses and ecosystem dynamics on the fisheries and LMRs, and vice versa. Even if classical LMR approaches were executed entirely correctly (as some have argued as all that is required for EBFM; e.g. Mace 2004, Hilborn 2004 (in Browman and Stergiou 2004), Eagle 2008 (in Leslie et al. 2008)) there are still many factors that would not be adequately addressed. Although the debate continues (e.g., Mace 2004, Hilborn 2004 (in Browman and Stergiou 2004), Eagle 2008 (in Leslie 2008)), there is an emerging recognition that EBFM is necessary. There is a clearly recognized need to be holistic, coordinated, and integrated in our approach to LMR management.

There have been relatively few instances where such an approach has been implemented (Pitcher et al. 2009), but the number is growing as fisheries scientists, managers, and stakeholders grapple with the specific details of executing EBFM (Pitcher et al. 2009). As a discipline and as a practice, fisheries scientists and managers are now clearly beyond the whys and whats of EBFM (Murawski 2007) and squarely in the middle of the hows. That is, we are now well underway in the transition towards novel ways of assessing and managing LMR. While some have noted (Pitcher et al. 2009) that a full implementation of EBFM is still distant, steps to that end are extant.

There are many methods, tools and approaches that can be used to implement EBFM, including a wide range of analytical, indicator, framework and governance considerations. One of the more important tools among these approaches is the use of models.

The Value of Ecosystem Models

As noted, there are numerous methodological approaches that can facilitate the scientific basis for the implementation of EBFM. These include: (1) development of systemic fisheries indicators, particularly those empirically based on longstanding fisheries and oceanographic monitoring surveys; (2) statistical evaluation of these surveys, both from a time series and multivariate perspective; (3) process-oriented studies to more fully elucidate those ecological and environmental relationships to LMRs of interest; (4) ecosystem comparisons to determine unique and general marine ecosystem properties; (5) exploring the range of EBFM options in a process that is adaptive (e.g., Integrated Ecosystem Assessment (IEA), Management Strategy Evaluation (MSE), Risk Analysis, etc.); and (6) implementing the full range of ecosystem modeling endeavors. This latter item can be thought of as "*in silico*" virtual studies that explore the relative importance of ecosystem processes and the robustness of various management strategies. Ecosystem models are clearly an important part of implementing EBFM, and many of the other approaches noted above utilize ecosystem models (and their outputs) as a key component of those efforts.

The use of models has recognized value in marine science, particularly for living marine resources (Fennel and Neumann 2004, Megrey and Moksness 2009). Modeling approaches provide a means to: (1) collate and integrate a broad array of data; (2) evaluate the relative importance of several concurrent processes; (3) test hypotheses concerning ocean system structure and functioning; (4) formalize hypotheses; and (5) produce predictions of both scientific and resource management interest.

There have been very useful summaries of the range of ecosystem models that are germane for EBFM (Hollowed et al. 2000, Whipple et al. 2000, Plaganyi 2007, Townsend et al. 2008, FAO 2008). These models cover the gradient noted in Link (2002b; his Figure 1) from SS to full system models, with numerous modeling options along that gradient of complexity and realism. At various points along that gradient, multiple models can address a range of questions or issues. As noted in Townsend et al. (2008, their Table A.3), the types of model classes being employed need to correspond to the appropriate set of questions and issues. One of our objectives in this document is to amplify and expand this model classification (Figure 1 and Table 1) and explore the utility of these models for the broad context of LMR management issues in the Northeast [US] Shelf Large Marine Ecosystem (NES LME).

The NES LME has been the subject of a number of modeling efforts. These include considerations ranging from physico-chemical features (e.g., Chen et al. 2001, Franks and Chen 2001, Townsend et al. 2006, Hu et al. 2008) to socio-economic uses (e.g., Holland and Sutinen 1999, Edwards et al. 2004) of the ecosystem. We also note that there have been many excellent efforts at LMR population modeling in this region[1], but do not focus upon those solely single species models here. Further, we recognize that many of our academic colleagues in the NES LME region have produced or are continuing to develop some excellent multispecies and ecosystem models (e.g., Collie and DeLong 1999, Tsou and Collie 2001, Steele et al. 2007) that have complemented or informed some of the works noted herein and have represented key collaborations with NEFSC staff. To contextualize how all these models are related, we provide a taxonomy of model types used in the NEFSC EM enterprise, as applied to the NES LME (Figure 1).

Context for the Application of Ecosystem Models in the NES LME

There are several major applications planned or ongoing for LMR related ecosystem models in the NES LME. We briefly note them here and discuss how they can be addressed by the EM activities we have undertaken thus far. Our aim in doing so is to provide more specific context for why we are executing the models we have chosen to use, evaluate their appropriateness for use, and thus focus the universe of a wide range of possible models and uses to those of higher priority for this region.

Our first rationale for executing EMs is to estimate fishery production potential, ultimately to the end of evaluating system-level Biological Reference Points (BRPs; e.g. MSY and related). These aggregate estimates of fishery production are based upon the underlying

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[1] See http://www.nefsc.noaa.gov/nefsc/saw/
http://www.nefsc.noaa.gov/read/protspp/mainpage/

theory of production potential for an entire ecosystem. The technical basis and key assumptions for estimating such systemic or aggregate BRPs is founded on the following observations: (1) The energy available to all LMR fish and invertebrates from lower trophic levels is limited and shared by the entire LMR community (Pauly and Christensen 1995, Pauly et al. 1998, Pauly et al. 2002); therefore an aggregated approach may be warranted. That is, the production potential for LMRs for any given area of the ocean is, within ranges of natural variation, relatively fixed due to and certainly constrained by lower trophic level production; (2) Fish stocks have different productivities, making it difficult to simultaneously attain single stocks objectives in multispecies fisheries. Therefore an average or aggregate quota may be more appropriate (May 1975); (3) Due to biological and/or technological interactions that may not always be able to be directly accounted for, an aggregate quota may be more appropriate for managing suites of stocks (May 1975, Pope 1975, Fukuda 1976, Pope 1979, Mayo et al. 1992); and (4) In mixed stock fisheries the effective catchability of each stock is different, therefore aggregate approaches are probably justified (Garrod 1973). Such systems-thinking has value as outputs and emergent properties at a systemic, or even aggregated level, tend to be more stable than at the population level. Using existing BRPs, simply applied to an aggregate grouping of species, capitalizes on the familiarity LMR managers have with such approaches. Further, we note that the Science and Statistical Committees (SSCs) of both regional Fisheries Management Councils (FMCs) associated with the NES LME are in need of this information and both Councils and their SSCs have explicitly asked for such information. Evaluating the production potential of a given region is critical for the further adoption of an EBFM; we note that this is complementary to but distinct from evaluating the status of all component stocks individually in a given region. Before evaluation of the outputs of such aggregated models (used to provide estimates of system level production) can be done for any given application, the validity of the modeling approaches to estimate such outputs warrants examination.

The second and related major rationale for conducting EM is to establish ecosystem overfishing thresholds and criteria. Similar to SS BRPs, these systemic or aggregate BRPs take advantage of the emergent properties of LMR communities and provide markers for evaluating the status of the system or fish communities from a broader perspective. The rationale and value of doing so has been copiously noted previously (Murawski 2000, Jennings 2005, Link 2005, 2010a, Samhouri et al. 2010, Shin et al. 2010). Briefly, the major reasons for executing such an approach is that it provides a way to detect major changes that can lead to irreversible regime shifts in ecosystems and food webs much more rapidly than by examining a suite of distinct SS indicators separately; it coordinates across a broader range of LMRs that are being targeted, and it allows for factors associated with other ocean-use sectors to be directly considered. In addition to the typical MSY-types of BRPs as applied to aggregate groupings of LMRs, there are also a range of other possible system-level indicators that could be considered (Tudela et al. 2005, Libralto et al. 2006, 2008, Coll et al. 2009, Link 2010a, Link et al. 2010d, Samhouri et al. 2010, 2011, Shin et al. 2010). The challenge with this wider range of ecosystem indicators has been to establish limits and thresholds beyond which control rules are invoked (Murawski 2000, Fulton et al. 2005, Link 2005, Samhouri et al. 2010). Additionally, these indicators provide a useful context for SS approaches and have also usefully informed systems-focused management strategy evaluations (Fulton et al. 2005, Samhouri et al. 2010, 2011). In any of these uses of system-level BRPs, EMs are needed to generate estimates, test and identify thresholds, and evaluate projections based upon various threshold scenarios. Thus, a review of any models used to assist in the development of system-level BRPs is also warranted.

A third reason we execute EMs for the NES LME is to provide support for tactical LMR management advice, particularly with respect to ecosystem considerations that are becoming common terms of reference (TOR) in the assessment of LMRs. Thus, we plan to continue the development and use of Minimal Realistic Models (MRMs[2]) in our current SS modeling assessment efforts and review processes (e.g., Stock Assessment Review Committees, Stock Assessment Workshops, Trans-boundary Resource Assessment Committees, Groundfish Assessment Review Meetings; SARCs, SAWs, TRACs, GARMs, etc.). The use of these MRMs has expanded beyond providing simple context to actually being integral data streams in a stock assessment context, if not as lead assessment models themselves. We anticipate the continuation of estimating predation mortality (M2), especially for key forage stocks. We are also continuing to increasingly explore environmental factors that are important factors influencing stock assessment models, especially for growth and stock-recruit relationships. The role and use of multispecies (MS) model outputs also remains an option, but is less clear as to how such outputs will be directly utilized or prioritized. The example for Atlantic menhaden in the Atlantic States Marine Fisheries Commission (ASMFC) is a good example; results from a multispecies virtual population analysis (MSVPA) are used to produce a matrix of annual, age-specific M2s which are then used as inputs into the SS assessment model. As many of these approaches and models have been executed and reviewed in existing review venues (NEFSC 2007a, b, 2010a, b, 2011, DFO 2010, Deroba et al. 2010), we anticipate that they will continue to be appropriately evaluated in that context. As such, we do not emphasize them in this report. Yet we do note that such efforts form an important part of the broader NEFSC EM enterprise.

Another reason we are developing and using EMs is the consideration of multisector uses. As the Presidential Executive Order of July, 2011[3] noted, the key tenets of those newly established regional ocean councils will involve ecosystem-based management and serve as a venue to mitigate among all the tradeoffs across multiple ocean use sectors. To address all the potential tradeoffs, clearly questions such "what would such a multijurisdictional venue look like?" and "what are the best frameworks and approaches to do so?" all need to be, and are in the process of, being sorted out. Yet we anticipate that some form of Integrated Ecosystem Assessment (IEA; Levin et al. 2009) will be invoked to do such evaluation among various ocean use sectors. And regardless of the specific format of what such a process would look like, we anticipate that EMs will be an important part of simulating and structuring various scenarios to evaluate the viability among various tradeoff options. Thus, the development of EMs and how to review their outputs in this anticipated context is again significant justification for evaluating the underlying EM models that will provide such outputs.

Finally, we note that across levels of the biological hierarchy, across various LMR management contexts, across marine spatial planning, and across the range of probable ocean-use sectors, the use of management strategy evaluation (MSE) is apt to be an important tool (e.g., Smith et al. 1999, 2007, Sainsbury et al. 2000). Recognizing that EMs will be an important facet of MSE, we also want to review the utility of specific models for use as operating models in an MSE framework.

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[2] By minimal realistic models, we do not mean to imply at all that the modeling is minimized or of inferior quality, nor that other models are not realistic. Rather, we are using the international convention for those models that focus on specific aspects of a system to address particular questions, in this context usually extended stock assessment models and multispecies models that do not have as their main objectives inclusion of all potential processes that could affect LMRs.

[3] See http://www.whitehouse.gov/files/documents/2010stewardship-eo.pdf
http://www.whitehouse.gov/administration/eop/oceans/policy

Given these major rationales for why the NEFSC is conducting EM efforts, we also want to explicitly note that we are strong proponents of multimodel inference. That is, in most specific application contexts to-date, we often execute and apply at least two models to ensure that any underlying analytical biases, assumptions, calculation methods, or overall approaches are not skewing any model outputs. If multiple but distinct models provide common responses, the confidence in the general outputs collectively is heightened. Thus our philosophy of developing and, where feasible, applying multiple model approaches and tools within a given model class or for a given issue is worth noting. This may partially explain the broader range of models provided herein than what typically might be applied for a given set of specific issues. This approach is analogous to ensemble modeling common in atmospheric and climate sciences (Krishnamurti et al. 2000, Gneiting and Raftery, 2005, Tebaldi and Knutti 2007).

Certainly within both the broader MSE, IEA, and related systemic contexts and within the usual LMR management advice there will be both tactical and strategic applications of these models outputs. We aim to note how each model can be used in any given context on any given question (Table 2). For each model (or groups of related models), we will: (1) review data requirements requisite for the model; (2) discuss the adequacy of input data as applied for the NES application of this model; (3) highlight the strengths and weaknesses of analytical methodologies; (4) highlight how model structure, parameterization, calibration/tuning, validation/verification, and intended uses have been documented; (5) compare how the NES LME application of these EMs are being addressed with respect to the strengths and weaknesses of assumptions, example estimations, and sources of uncertainties, especially with compared with known best practices in the field; and (6) identify the types/levels of use for model outputs, especially with respect to adequacy of modeling relative to major topical issues.

The intention of this work is to provide the background description, data adequacy, utility of these models and an entry point to the fuller literature that has been developed for the NES LME EM LMR applications (Table 1). In particular we highlight specific, selected models, reference their documentation, provide a brief description of key assumptions and structures, and note progress to date. Many of these have been summarized in the form of tabular compilations (Tables 1, 3-9), with data needs for each specific model, uses for each specific model, and the pros and cons for each specific model distilled into a format designed to be amenable to and to facilitate comparison. The remaining text herein amplifies the contents of these tables and is followed by summarizations and observations.

NEFSC ECOSYSTEM MODELS

Examining the models to support implementation of EBFM in the NES LME (Table 1) would be well informed by first considering how single-species management approaches have been adapted for this purpose and then moving on to consider multispecies methods. Integrated aggregative and ecosystem-level frameworks that may play a significant role in the future of EBFM are subsequently considered. Although extensive, again we do not describe the solely single species approaches that have had a long history in the NES LME. We note that ecosystem models vary in complexity from extended single-species models (i.e., single species models with add-ons such as an environmental factor or predation-caused mortality) to complex models that encompass selected aspects of the entire ecosystem. We have noted these in various model classes below. Where appropriate, we briefly describe the intent (sensu Table 2), main assumptions (Table 1) and key inputs (Tables 3-9) along with some commentary on the strengths of each approach.

Minimal Realistic Models (MRMs): Extended single-species assessment models (ESAMs)

A number of extended single species assessment models have been developed in the NES LME (Plagányi 2007, Townsend et al. 2008) through add-ons to single species formulations to account for predation, consumptive demands, or the environment in a single species assessment model. These have been both age- or stage-structured and bulk biomass or production models. The purpose of these ESAMs has ranged from providing context for stock biomass estimates, providing tuning indices, serving as sources of other mortality, informing modifications to key parameters, serving as "reality checks" for estimates of magnitude of population estimates, and even providing explicitly modeled estimates of predation mortality.

Single-species Add-ons: Predation

These models describe the impact of predation and its effects on a stock in a single species assessment model. These models have been developed predominately for forage stocks, including Atlantic herring (*Clupea harengus*), Atlantic mackerel (*Scomber scombrus*), longfin squid (*Loligo pealei*), butterfish (*Peprilus triacanthus*), several species of hakes, and Northern shrimp (*Pandalus borealis*) (NEFSC 2007a, b, Overholtz and Link 2007, Overholtz et al. 2008a, Link and Idoine 2009, Moustahfid et al. 2009a, b, Deroba et al. 2010, NEFSC 2010b, 2011). Several of these models have been used as part of formal stock assessment reviews, usually to provide context and estimates of predation mortality (M2). For the most part, predation in these models is considered as an additional "fleet". That is, predation by other species (than the target stock) is treated collectively, but explicitly, as another source of removals. The data required, in addition to the usual survey and fisheries catch data, are abundance of predators of the stock of interest, predator stomach contents, estimated consumption rates, and diet composition estimates (Table 3).

The positive aspects of this approach are that such models are relatively simple conceptually and operationally, use extant data, are implemented in a familiar assessment and management context, provide familiar (albeit modified) model outputs amenable to calculating biological reference points (BRPs), improve the biological realism of assessment models, and help to inform and improve stock assessments for species that may have been difficult to assess in the past. The negative aspect is that, like all minimal realistic models, they may be missing a suite of non-linear responses caused by not including the full suite of complex interactions involved in a real-world 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. Further, they do not have the fuller modeling capability to completely address these trade-off issues.

Single Species Add-ons: Ecological Footprints

The models in this category attempt to account for the amount of food eaten by a fish stock. These estimates of energetic requirements (i.e., consumptive demands) at a given abundance level are then 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 feeding on a stock of fish, here it is summed across all species serving as prey for the fish predator. The point being is that if an estimate of stock abundance would imply feeding demands (i.e. consumption) above what is feasible as estimated from an ecosystem context, then some reevaluation of model parameters would be merited.

These models have been developed for a wide range of groundfish, elasmobranch, and pelagic fish species (Link and Garrison 2002, NEFSC 2007b, Tyrrell et al. 2007, Link and Sosebee 2008, DFO 2010, NEFSC 2010a). Estimates for a few sets of stocks (e.g., the skate complex, NEFSC 2007b, Link and Sosebee 2008; spiny dogfish, DFO 2010; Pollock and goosefish, NEFSC 2010a) have gone through a formal stock assessment model review[4]; others, including for marine mammals, are in various stages of development. In addition to survey and fisheries catch data, the data required are abundance of the focal stock, stomach content and diet composition estimates, and consumption estimates (Table 3). The positive and negative aspects of this approach are similar to those outlined above for predatory applications of this approach.

Single Species Add-ons: Environmental Considerations

The NEFSC has begun to incorporate environmental considerations into population models, but not yet in a fully operational mode. These include changes in carrying capacity (K), population growth rates (r), stock-recruitment relationships, or stock distribution relative to environmental conditions (Keyl and Wolff 2008). These have been done or are being done for a wide range of fish, mammal and invertebrate species. With environmental terms in population models, it is possible to forecast the response of a population to climate change, thereby providing a long-term forecast that can inform EBFM (Fogarty et al. 2008a, Hollowed et al. 2009, Hare et al. 2010). Currently, none of these models have been through formal model review nor explicitly incorporated into a review process that directly informs management. Such modeling remains an active area of research and development.

In addition to the needs of a standard stock assessment, these approaches require appropriately (spatio-temporal) scaled environmental data such as temperature, depth, and salinity and the associated monitoring data products (Table 4).

The advantages of this approach are that the environmental data are usually available and relating them to stock dynamics typically takes advantage of commonly established statistical methods. These approaches also improve the biological realism of assessment models and allow for consideration of dynamics driven by factors typically outside of usual assessment considerations. The chief drawbacks of this approach are that the data are often auto-correlated without definitive causal mechanisms; similarly, environmental correlates have a noted history of decoupling with additional data; and the data may also often be collinear, and, short of exhaustive multivariate analysis, are difficult to untangle for useful stock projection. Yet although the debate over the utility of using environmental factors in assessments will undoubtedly continue (e.g., Walters and Collie 1988, Rose 2000), there are now clear links among physiological and metabolic factors and key environmental variables (e.g. temperature) that should be robust (Keyl and Wollf 2008, Hollowed at al. 2009, Hare et al. 2010).

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[4] Here and throughout when we note that a model has not been through a “formal model review” we mean that although the model may be in the peer-reviewed literature, the model has not been evaluated by a review panel as to its behavior, dynamics, diagnostics, and implementation all to determine even if it is suitable for use in a LMR management context in the first instance (i.e. the review panel associated with this document) and its results for an actual implementation applied to a particular situation thereafter.

MRMs: MS Models

Multispecies Virtual Population Analysis (MSVPA)

MSVPA is one of a suite of multispecies models that focuses on age-structured populations of commercial importance. The MSVPA approach was developed within the ICES context in Europe (ICES 1991) and is in effect a series of single species VPAs linked together via a feeding model. The modeling approach has the ability to provide short-term forecasts. Most typically, the model examines the stock dynamics of multiple species that are both predators and prey, particularly exploring the role of predatory removals of stocks relative to fishery removals.

An ‘extended’ version of MSVPA has been developed in the NES LME (MSVPA-X), which among other improvements, includes predators without age-structured assessment data and has multiple forms of VPAs for each species, thus enhancing the flexibility of the approach. MSVPA-X models have been applied to two-subsystems in the NES LME (Garrison and Link 2004, NEFSC 2006, Tyrrell et al. 2008, Garrison et al. 2010). An MSVPA-X model for the mid-Atlantic region emphasizes menhaden (*Brevoortia tyrannus*) as prey with three main predators and has gone through extensive and formal model review (NEFSC 2006). Outputs from that model have informed single species assessments, particularly by providing time-series of predation mortalities for the assessment of menhaden. A second MSVPA-X model applies to Southern New England-Georges Bank-Gulf of Maine ecosystem (Tyrrell et al. 2008). It involves 19 species and emphasizes herring (*Clupea harengus*) and mackerel (*Scomber scombrus*) as the major prey. The results have contextually informed single species assessments for herring and mackerel.

The data required for this approach include abundance estimates for predators that eat the stock of interest, stomach contents, consumption estimates, and diet composition estimates (in addition to survey and fisheries catch data; Table 5).

The positive aspects of this approach mirror those of the single species add-on with predation; namely it uses extant data, is implemented in a familiar assessment and management context, improves the biological realism of assessment models, and helps to inform and improve stock assessment outputs. The key negative facets of this approach is that it is quite data intensive and there is no feedback loop between predator and prey.

Multispecies Yield-Per-Recruit (MSYPR)

Murawski (1984) applied a multispecies extension of yield-per-recruit theory that explicitly accounted for technical interactions through by-catch in the Georges Bank multispecies groundfish fishery. Cases in which species groups (assemblages) were exploited by one fishery, and when several fisheries (defined by gear type, seasonal changes in species mix, etc.) exploit the same species concurrently and/or sequentially were considered. Equilibrium fishery yields (in aggregate and for individual species) were computed as functions of standardized effort levels and size-selective characteristics of the gear. The multiple fishery model allowed for variable harvest strategies with respect to gear selectivity and effort levels among component fisheries.

Data requirements include estimates of natural mortality rate, mean-weights-at-age, gear selectivity coefficients for each age class, and relative recruitment levels for each species (Table 5). Additional fishery-related information included standardized fishing effort levels, and species-specific catchability coefficients. Seasonal fishing patterns were simulated in some of the analyses.

Total and individual equilibrium species yields, exploitation rates, and mean fish weights in the catch for all fisheries combined and separately were evaluated. The potential for either growth underfishing or overfishing of individual species/stocks was demonstrated when total system yield is the optimization criterion.

Advantages of the model include its relative simplicity and its direct evaluation of the effects of simultaneous harvesting of co-occurring species, a critical consideration in multispecies fisheries. Species included in the analyses are assumed to have negligible trophic dependence. The method shares the general disadvantage of all yield-per-recruit analyses in that it does not address fishing effects on recruitment nor does it consider interspecific interactions.

Multivariate Time Series Models

Two forms of multivariate time series models have been applied in the NES LME with the objective of assessing predictive capability and examining covariance patterns among potentially interacting species or species groups. These simpler models can often outperform more complex mechanistic models in forecast skill.

Linear state space models have been applied to research vessels survey biomass estimates for aggregate species groups on Georges Bank (Fogarty and Brodziak 1994). State space models comprise a state equation and an observation equation (which represents measurement error in the data). The state equation is centered on a transition matrix describing the relationships among the observed variables. In the NES LME application, aggregate species groups broadly defined by taxonomy and history of exploitation were analyzed and significant interactions among system components were identified.

The second major class of state space models applied in the NES LME is nonlinear time series analysis (Sugihara & May 1990, Sugihara 1994). These models represent a flexible class of nonparametric models for identification of system complexity (e.g. dimensionality and nonlinearity). The application in the NES LME involved an assessment of co-predictability among 26 fish populations on Georges Bank using research vessel survey data (Liu et al. in review). Results of this analysis indicate relatively high levels of co-predictability among pair-wise combinations of this multispecies assemblage related to both biological interactions among some species and common forcing mechanisms related to natural and anthropogenic factors.

Advantages of both the linear and nonlinear multivariate time analyses include the relatively simple model structures, explicit consideration of serial dependence in the data, and often high forecast skill for short-term projections. The linear form suffers if any underlying processes cannot be effectively treated by transformation. The nonlinear form is much more flexible and explicitly addresses the issue of the potential for complex dynamics in the abundance time series. It is specifically designed to determine the effective dimensionality of the system and to test for dynamic complexity in the observed time series.

Multispecies Surplus Production Modeling Workshop Approach

Production models based on work executed at an international surplus production modeling workshop have been constructed (Link et al. 2010b). These models are based on the general frameworks of extended Schaefer-types of models that explicitly include species interactions (e.g., Collie and DeLong 1999, Prager 1994, Mueter and Megrey 2006) and have been employed for functionally analogous species across over 10 northern hemisphere ecosystems (Stockhausen et al. unpubl. data).

As in all production models, the main inputs are time series of biomass estimates and landings (fishery removals) (Table 5). Additional information includes known predator-prey relationship and initial values for growth rates, carrying capacity and interaction terms from which the model seeks to optimize a solution.

The main strengths of this approach are its relative simplicity, minimal assumptions, requirement of readily available data, and relative portability of the approach for ease of use on different data sets. The drawbacks are those usually associated with production models (e.g. missing internal stage or age related dynamics, concerns over equilibrium assumptions, and obfuscating across life history). This work has not been reviewed in a formal context and is currently a research application.

Multispecies Production Models: MS-PROD

A multi-species extension of the Schaefer production model has been developed to include both predation and competition. The model is a simulation tool and incorporates a wide range of what are primarily ecological processes (Link 2003, Gamble and Link 2009). The chief aim of this model is to simulate the relative importance of predation, intra-guild competition, inter-guild competition, and fisheries removals.

An MS-PROD model has been parameterized with empirically-based values for 24 species from the NES LME region that can be used to explore sensitivities to fishing pressure and species interactions. It was not designed to be directly used for management advice. Nonetheless, it has proved useful in providing contextual information for ecosystems influenced by fisheries and for simulating options for LMR management. The data required are initial biomass estimates, carrying capacities, predation and competition interaction terms, growth rates, fishery removals, and – optionally – spatial overlap parameters between each set of species, providing a rudimentary way to consider some spatial resolution (Table 5).

Some of the simulation results have been used to provide context to management of LMR (NEFSC 2008). A stochastic model has been added, allowing the growth rate of each species to vary at the start of a run, or at each time step. Adding environmental effects and a fitting algorithm to routine data are the planned next steps.

The desirable aspects of this approach include explicitly accounting for ecological processes in addition to the effects of fisheries and inclusion of lower trophic level processes that can be directly linked to estimates of carrying capacity. Limitations include the fact that some of the parameters, although empirically derived, are difficult to estimate. Another negative is that, like most multispecies models, it is parameter intensive but less so than many other multispecies models given the simplicity of the modeled equation structure.

Aggregate Production Models

Agg-PROD v of MS-PROD

This model is effectively the same as the MS-PROD model noted above, but initialized for aggregate groups of species (i.e., species are not individually represented). The interactions with other ecosystem components in these groups have been parameterized both as functional guilds and as taxonomically related species. The one distinction from MS-PROD is that this model simulates biological reference points (BRPs) and production at a more systemic or group level rather than at a species level. This model could be useful for considering two-tier quotas by which there are both limits per stock individually and for a full group of stocks collectively. The data needs, pros, and cons are the same as MS-PROD, with the caveat that amalgamation of parameters across groups warrants examination. Again, simulation results have been used as contextual information for management of the U.S. fisheries influence on LMRs in the NES LME (NEFSC 2008).

Annual Surplus Production- Surplus Production Modeling Workshop Approach- Deterministic and Dynamic

Production models based on work executed at an international surplus production modeling workshop have been constructed (Link et al. 2010b). These models are again based on the general frameworks of extended Schaefer-types of models (e.g., Prager 1994, Collie and DeLong 1999, Mueter and Megrey 2006, Gamble and Link 2009) and have been employed for all fished species in over 10 northern hemisphere ecosystems (Mueter & Bohaboy unpubl. data).

As in all production models, the main inputs are time series of biomass estimates and landings (fishery removals) (Table 6). Additional information includes initial values for growth rates and carrying capacity from which the model seeks to optimize a solution. Here the distinction is that instead of fitting for a species and its fishery removals, this is done in aggregate groupings or for all the fished biomass (systemic levels) in an ecosystem.

The main strengths of this approach are its relative simplicity, minimal assumptions, requirement of readily available data, and relative portability of the approach for ease of use on different data sets. The drawbacks are again those usually associated with production models (e.g. missing internal stage or age related dynamics, concerns over equilibrium assumptions, and obfuscating across life history). This work has not been reviewed in a formal context and is currently a research application.

Aggregate Production Version of a Surplus Production Model Incorporating Covariates (ASPIC)

This model is based on the general frameworks of extended Schaefer-types of models that explicitly include covariates (e.g., Prager 1994, Collie and DeLong 1999, Mueter and Megrey 2006), but particularly the tool develop by Prager (1994), ASPIC. A comparable, simple linear code has also been developed in SAS (Overholtz unpubl. data).

As in all production models, the main inputs are time series of biomass estimates and landings (fishery removals) (Table 6). Additional information includes a suite of covariates, as applied in the NES LME, largely as the AMO, NAO and similar broad-scale forcing factors (Overholtz et al. 2008b). Initial values for growth rates and carrying capacity from which the model seeks to optimize a solution were derived from surveys, landings data, and compared to disaggregated (but then summed) stock assessment estimates. Here the distinction is that instead of fitting for a species and its fishery removals, this is done in aggregate groupings or for all the fished biomass (systemic levels) in an ecosystem.

The main strengths and weaknesses of this approach are the same as noted above. The one particular addition is that this approach has had environmental covariates explicitly included in it. This work has been reviewed in a formal context (GARM III; NEFSC 2008, Overholtz et al. 2008b) as context compared to sums of SS estimates of MSY and associated BRPs. Further updates are ongoing.

Management Strategy Evaluation for Aggregate-Species Production Models (Aggregate Testing of MS-PROD)

Species with different life histories and vulnerabilities to ecological interactions (predation and competition) will be affected differently at varying levels of harvest. Application of an aggregate-species model requires special care because differential life history characteristics of the species within the aggregate can result in marked differences in vulnerability to exploitation. To explore the development of effective assembly rules for aggregate groups to minimize the potential depletion of vulnerable species, Gaichas et al. (unpubl. data) conducted simulations using MS-PROD for a ten species system using species-specific parameter estimates and interaction coefficients based on results provided in Gamble and Link (2009). The value of this type of exercise is that it can: (1) determine likely levels of aggregation that are appropriate for a marine ecosystem, and (2) determine which species might need to have special considerations applied in addition to simply setting an aggregate level F_{msy}.

Individual species trajectories were simulated over a 100 year time frame and then combined according to three assembly rules. The effects of aggregating over the entire ten species assemblage and for subsets of the whole defined by taxonomic affinity and habitat characteristics (demersal vs. pelagic) were examined. Although definition of aggregate groups defined by taxonomic relationships entailed less overall risk, differences among even closely related species in their intrinsic rate of increase are sufficient to put some species at risk. Precautionary exploitation rates that entail relatively little loss in yield can be identified that sharply reduce the probability of stock collapse for more vulnerable species.

It is important to note that we don’t recommend that MS-PROD/Agg-PROD be used to determine species or aggregate BRPs. Rather, as a simulation tool, it can be used to evaluate the robustness of aggregate BRPs regarding how species in the system would likely respond to those BRPs and which species could become overfished at various levels of aggregation.

Energy Transfer Models

Linear and Stochastic Production Potential

We explored the applicability of simple energy transfer models of the type developed by Ryther (1969) and extended by Ware (2000) to estimate fishery production potential for this ecosystem. Ware (2000) further developed the Ryther model to consider energy pathways though both the microbial food web and the classical grazing food chain, accounted for retention and transport, and accounted for differences in transfer efficiency at the lowest trophic levels relative to tertiary consumers. Fogarty et al. (2008b) developed estimates for the fishery production potential of the NES LME based on estimates of primary production (partitioned into net and nanoplankton components), ecological trophic transfer efficiencies (Table 7), and the specification of harvest extraction policies for different trophic levels in a Bayesian framework (the linear version is simply the deterministic outputs without distributions about the parameters). Prior distributions were placed on (1) the level of primary production for the two major phytoplankton compartments based on satellite-derived estimates, (2) transfer efficiencies derived from north temperate marine network analyses, and (3) mean trophic level of the catch. Output consisted of the posterior distribution of fishery production potential.

Advantages of the approach include the relative ease in explaining the underlying concepts to stakeholders and managers and its ability to readily accommodate shifting patterns in productivity in a non-equilibrium setting. Disadvantages include its highly aggregated structure and the potential to obscure important underlying nonlinear processes. This work was formally reviewed as part of the GARM III exercise (NEFSC 2008, Fogarty et al. 2008b).

Ecopath and Econetwrk

The Ecopath with Ecosim (EwE) model has been widely used to describe aquatic systems and to explore the impacts of fishing ecosystems (Christensen and Pauly 1992, 1993, Christensen et al. 2005). It is composed of a mass balance model (Ecopath; Polovina 1984, Pauly et al. 2000, Kavanagh et al. 2004, Christensen et al. 2005) from which temporal (Ecosim) and spatial (Ecospace) dynamic simulations can be developed (Walters et al. 1997). Mass balance (Ecopath) models have been developed for many regions across the NES LME: especially for the Gulf of Maine, Georges Bank, Southern New England and Middle Atlantic Bight ecosystems (Link et al. 2006, 2008a, b). These ecosystems were similarly modeled using the Econetwrk software (Ulanowicz 2004, Dames and Christian, 2006), which functionally sought to balance the network and energy budget.

Data requirements for these models include estimates of biomass, production and consumption rates, catch and diets (Table 7). These food web models in the NES LME have been developed under a specific project, EMAX (The Energy Modeling and Analysis eXercise).

These models have been used to further our understanding of ecosystem structure and functioning, explore hypotheses concerning ecosystem change, used as a basis for comparative studies (spatial and temporal), used to provide ecosystem indicators, and used in various simulated perturbation experiments. Performance measures and metrics such as throughput, total flow, biomass ratios (e.g., pelagic fishes to zooplankton), and trophic reference points (i.e., marine mammal biomass to pelagic fish biomass ratios) can be tracked and compared with empirical information over the simulated time horizon. The use of these models remains an active area of research. Some results have been used as contextual information in a LMR management context (NEFSC 2008, Overholtz et al. 2008b, Gaichas et al. 2009) and planning is underway to use these models in a management strategy evaluation (MSE) context in the NES LME.

The major advantages of this approach are that it encompasses the whole ecosystem and is conceptually simple, versatile, accessible and adaptable. The cons of this approach are that because of the widespread availability EwE, it can be misused. It also requires a plethora of data and parameters to initialize the model that are not routinely collected, either in terms of process or taxa group, in a fisheries context.

Topological Webs

Food webs are essentially maps of connections among species. There is significant information able to be gleaned from such network properties (Odum, 1964, Patten and Odum, 1981). A topological (network of connections, without measured flows) food web has been constructed for the NES LME food web (Link, 1999, 2002c). This construction depends heavily upon food habits data to detect and identify major linkages (or interactions) among species. The outputs of such an approach can elucidate major features of the ecosystem and ultimately address community stability (May, 1972, 1973). Adequate construction of food webs requires copious diet composition data (Table 7). Further, food webs are static depictions and do not typically convey the dynamics of the communities they are capturing.

Many network properties can be insightful into the structure and function of an ecosystem, but are not routinely used in an LMR management context. The outputs have been calculated for the NES ecosystem and compared to the other such food webs (Link et al. 2005, Gaichas et al. 2009) but are not planned for direct use for management in this region.

Gulf of Maine Aggregated Dynamic Model (GOMAGG)

A dynamic simulation model of the GoM ecosystem has been constructed, with the system partitioned into 16 aggregated biomass nodes spanning the entire trophic scale from primary production to seabirds and marine mammals (Overholtz and Link 2009). Parameters from the EMAX Ecopath model of the GoM ecosystem 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. As with EwE, GOMAGG produces performance measures that can compared with empirical information over the simulated time period. The model has been used to evaluate how the GoM ecosystem might respond to large and small scale changes to the trophic components and system drivers, specifically events such as climate change, fishing scenarios, and system response to changes in the biomass of lower and upper trophic levels.

Data and inputs include initial biomasses, diet compositions and flows between taxa groups (Table 7). Various rate parameters (growth, P/C, other mortality) are also needed to initialize the model. In the NES LME instance, these were largely developed from the EMAX established ecological network information (Link et al. 2006, 2008a, b).

GOMAGG has not been through a formal model review. This remains a research tool and has not yet been used in informing management, but GOMAGG simulation results have informed other modeling efforts. The pros of this approach are that it examines the food web dynamically and utilizes extant model structures and data. It has the ability to simulate a wide range of scenarios. The chief negatives of this approach are that it is not entirely user-friendly and is can be difficult to validate some scenarios and inputs.

Full System Models

ATLANTIS

ATLANTIS (Fulton et al. 2004, 2010) is by far the largest, most complicated model in use for the NES LME. Generically, ATLANTIS integrates physical, chemical, ecological and fisheries dynamics in a 3D spatially explicit domain. In addition to ecological interactions, it contains environmental components, including a simulated ocean with complex dynamics, a simulated monitoring and assessment process, a simulated set of ocean-uses (namely fishing), and a simulated management process. The dynamics represented in the model range from solar radiation to hydrodynamics, and it includes nutrient processes, growth (with age structure), feeding, settling, sinking, migration, fishery captures, fleet dynamics, market valuation, regulation, and feedback among the various components of the model as appropriate.

The ATLANTIS application of the NES ecosystem (Link et al. 2010c, 2011c) is composed of 30 regional boxes, up to 4 depth layers per box, 12 hour time steps for 50 years, 45 biological groups, and 18 fisheries. Processes at the ocean surface and at the epibenthic sediment are also modeled. Model parameterization and initialization required estimation or setting of over 60,000 parameters and 140,000 initial values (when spatially and temporally allocated; cf. Table 8). A first level of calibration ensured basic bio-physical processes matched observed dynamics. Second and third level calibrations ensured that fishing processes (catch and effort, respectively) were reasonable. These calibrations have been completed, and future scenarios of different management strategies and ecosystem dynamics/responses can now be explored. Examples of management strategies which can be explored in ATLANTIS include area closures (any combination of dynamic/static and seasonal/yearly), effort and technical controls, and catch limits. Removals on individual species/groups can be explored to determine indirect effects throughout the system. Ecosystem dynamic scenarios can be explored separately or in conjunction with any of the above scenarios to provide information on the robustness of management actions in the context of climate change, ocean acidification, or similar phenomena.

The data and inputs needed to parameterize and calibrate the ATLANTIS application of the NES LME are too numerous to list in detail here, but we provide a general outline. Flowfields and physical forcing time series (temperature, salinity, etc.) are required for the hydrodynamics. Nutrient inputs and primary productivity estimates are required for the lower trophic levels. Geographically proportioned biomass, catch, effort and discard time series are required, as are vital rates (growth, consumption, etc.) for each of the functional groups. More detailed information on parameterization, calibration and scenario testing is described elsewhere (Link et al. 2010c, 2011c).

Although parameterized, initialized and loosely tuned to empirical values, the ATLANTIS application of the NES LME 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 a research tool and a simulator designed to guide strategic management decisions and broader concerns. For instance, it has been used in other contexts to provide multispecies fisheries and multi-sector ocean-use advice in support of EBFM (Smith et al. 2007, Fulton 2010, Fulton et al. 2011). The NES LME ATLANTIS application has not been through a formal model review, although documentation of key parameters and calibration is available (Link et al. 2011c). It will likely serve as a key operating model in future MSE applications.

The advantage of ATLANTIS is that it can incorporate multiple forms of myriad processes, can emphasize those considerations and processes most appropriate for a given system, and can be used to evaluate management decisions to provide insight into what might happen in a real system; i.e., as an operating model in an MSE context. Another advantage is that it covers a wide range of biota and is flexible or adaptive to a range of key factors. The chief negative aspect of ATLANTIS is that it is unwieldy in its complexity and takes an inordinate amount of time to parameterize, initialize, calibrate, and run any particular application. Additionally, the validation routines and capabilities of ATLANTIS are minimal at best, requiring much further improvement. Further exploration of appropriate model skill metrics to validate calibration is still quite rudimentary.

Miscellaneous Models

Atlantic Availability Calculator

The ATLANTIS Availability Calculator (AAC) is a utility developed to calculate, rather than estimate, an important parameter in ATLANTIS (Gamble, unpubl. data). Using relatively easily measurable parameters, this utility calculates the availability values (similar to α_{ij}s in Lotka-Volterra models or generic species interaction terms) in the Type II feeding functional response used in ATLANTIS for predation by many of the functional groups. The inputs required are the biomass of each prey and predator, the growth rates and assimilation efficiencies on live food for each predator, the consumption rate for each predator, and the diet composition (proportion of each prey in the diet of each predator) (Table 9). While specifically developed for ATLANTIS, this could be utilized to provide availability terms for other versions of a Type II (or adapted for other types of) functional response.

Donut Selectivity Model

The rank proportion algorithm, or more commonly known as the donut model (Link 2004), is a tool designed to provide selectivity terms for a suite of models, especially MS models. If relative abundances of the prey field are available, then estimates of diet composition are also produced. The logic is based upon Holling's components of predation and using first principles simply ranks the prey in their suspected or known order of preference for a given predator. There is even an "icing" factor whereby a user can reinforce the weightings of a particular prey. When testing the model it performed at ~80-90% accuracy in predicting diet compositions, a useful outcome for those situations where diet compositions are not readily obtainable.

There are no data required *per se* to initialize the model, again other than any material to inform the relative proportions of the prey field if diet compositions are desired (Table 9). Another possible input is spatio-temporal overlap if it is known to be an important consideration in particular predator-prey interactions. If actual stomach content data are available to validate the model regarding diet compositions, that is helpful but not necessary. The pros are its simplicity, ease of use, and intuitiveness. The cons are its reliance on the components of predation philosophy.

Productivity-Susceptibility Analysis (PSA)

In general terms, risk assessments for data-poor stocks usually follow some type of semi-quantitative methodology. Previous examples of semi-quantitative risk assessments have addressed the fishery impacts on bycatch and targeted species (Francis, 1992, Lane and Stephenson, 1998, Stobutzki et al., 2001a,b), extinction risk (Musick, 1999, Roberts and Hawkins, 1999, Cheung et al., 2005, Mace et al., 2008), and ecosystem viability (Jennings et al., 1999, Fletcher et al., 2005, Astles et al., 2006). These approaches allow for the inclusion of less quantitative information and a wider range of factors, and can complement both stock and ecosystem assessments.

In the United States, the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NMFS) recently developed a risk assessment to assist its managers and scientists in evaluating the vulnerability of its stocks to overfishing (Patrick et al. 2009, 2010). The productivity and susceptibility analysis (PSA) focused on easily obtainable and readily rankable information. Overall, vulnerability is a composite measurement of a stock's productivity and its susceptibility to a fishery. Productivity refers to the capacity of the stock to produce optimal levels of yield (e.g. MSY) and to recover if the population is depleted, and susceptibility is the potential for the stock to be impacted by the fishery. In general, vulnerability is an important factor to consider when organizing stock complexes; developing buffers between target and limit fishing mortality reference points; and determining which stocks should be managed under a fishery management plan. The main inputs are categorical ranking scores among a set of productivity and susceptibility measures, most loosely related to life-history characteristics and relationship to the fishery, respectively (Table 9). These scores are assigned by regional experts and were only done for the groundfish complex in the NES LME (Patrick et al. 2009, 2010).

The main benefits of this approach are that it provides semi-quantitative evaluations of risk without requiring detailed and sophisticated information. It is also potentially quite useful in a triage exercise. The main negatives of this approach are that it can lead to a false sense of security in data-poor situations, and it can minimize the use of some data where such data are extant and routinely collected.

LeMans

LeMans (Length-based Multispecies Analysis by Numerical Simulation) is a size-structured multi-species model of a fish community with a realistic distribution of life-history attributes (Hall et al. 2006). This approach differs from that reported from most other size-based models in that it maintains both the identity of the species in the system and the size structure of the individual populations. To maintain a level of realism and to help ensure internal consistency, it was loosely based on a single real fish community. The aim of LeMans is to structure and parameterize a general model in a realistic manner, using the Georges Bank community as a template. This model is a simulation tool to test various factors that can influence common BRPs. LeMans is a tool to particularly evaluate the behavior of various multi-species metrics under various fishing regimes.

The main inputs are a variety of biological parameters related to growth, feeding, and fecundity (Table 9). Realistic initial biomasses and fishing rates were also key inputs. As the model is a simulating tool, it was not fit to particular data *per se*, but again was tuned to loosely match some of the key features of a known fish community (i.e. Georges Bank). This model has not been through a formal review process and is used largely for context or heuristic explorations.

The main strengths of this approach are its adherence to realistic size-based life history constraints, its modularity, and its ability to explore various parameter spaces associated with most “typical” temperate fish communities. It main drawbacks are that it is not well known, widely distributed, and it takes a large amount of time to initialize and tune.

Size Spectra

Simple size spectra have been constructed for the NES LME fish community (Link 2005, Methratta and Link 2006). These rely solely on survey biomass, as binned into distinct size groups. Spectra have been produced over the time series and salient parameters (i.e., the intercept and slope) estimated. The patterns of spectra have shown a distinct steepening over time, particularly in the late 1970s and early 1980s when the fish community had experienced intense fishing pressure.

These spectra have been constructed largely in the context of ecological indicator development (Link and Brodziak 2002, Link 2005, Methratta and Link 2006). They have not been used, nor are they planned for use, directly in LMR management. The main benefit of this approach is that it is relatively simple and has minimal assumptions (Jennings 2005, Duplisea et al. 2007). The main drawbacks are that it can obfuscate key dynamics associated with specific taxa and it was not designed to detect or represent a broader set of factors that can influence fish communities.

Multivariate Ordination Techniques

Largely in the context of evaluating ecosystem indicators or comparative analysis across ecosystems, several multivariate methods have been explored for the NES LME. Principal components analysis and multidimensional scaling (PCA/MDS; Link et al. 2002, Methratta and Link 2006), canonical correlation or canonical correspondence analysis (CanCorr/CCA; Link et al. 2002, EcoAP 2009, Link et al. 2010d), and min-max factor analysis and dynamic factor analysis (MAFA/DFA; Link et al. 2009, Nye et al. 2010, Shin et al. 2010) have all been applied to large, composite data sets for the NES LME. These efforts have centered around dimensional reduction and redundancy identification in indicator selection, identification of common patterns and processes, and heuristic pattern detection.

These methods are all highly empirical and have relatively robust assumptions. Data inputs have included a vast array of survey, age, landings, food habits, oceanographic, climatological, social, and economic data (Table 9). These approaches have not been directly used, nor are they planned for direct use in a LMR management context. Rather they have provided broader context to help identify the relative prominence among major processes in the ecosystem.

NES LME ECOSYSTEM MODELING SUMMARIES

A range of ecosystem models are extant in the NES LME, from MRMs to Energy Transfer Models to Atlantis (Table 1). We are cognizant of modeling tools and packages that are not employed here but may be used or developed in other regions (see listings in Hollowed et al. 2000, Whipple et al. 2000, Plaganyi 2007, Townsend 2008). Additionally, although not described in detail in this work, habitat and biophysical models address yet other sets of issues (Chen et al. 2001, Franks and Chen 2001, Townsend et al. 2006, Hu et al. 2008, Ji et al. 2008, Cogan et al. 2009, Smith et al. 2009) and are being conducted. Collectively the use of all these ecosystem models is increasing with time, as the data to support (i.e., initialize, parameterize, calibrate and validate) them is quite extensive for the NES LME, the computing power to execute models that can handle increasing ranges of complexity is readily available (Megrey and Moksness 2009), and the need to consider more than one isolated species is readily apparent.

What has been interesting to note is that in an LMR context, many of these models have advanced well beyond the research tool stage and are being applied to inform management advice (e.g., Link et al. 2010a, ICES 2007, 2009, 2010). Many of the proof of concepts, feasibilities, identification of robust functional forms, and basic model sensitivities have been undertaken. What remains is to take the gamut of ecosystem models and characterize their uncertainties and utilities (Link et al. 2010a) for further inclusion in LMR management and to better support EBFM. Exactly how such models shall be used is an important consideration. Equally important is a discussion on the strengths and weakness of EMs in use at the NEFSC.

Appropriate Uses of Ecosystem Models in the NES LME

Ecosystem models in the NES LME have been used to further our understanding of ecosystem structure and functioning, as central pieces of broader comparative studies (spatial and temporal), to develop ecosystem indicators, and in “virtual” perturbation experiments (Table 2). While these models continue as an active area of applied and basic research, some have been used in a LMR management context (e.g., such as for the groundfish carrying capacity issue (NEFSC 2008)). Others (e.g., MRMs) are now explicitly used in a stock assessment context. Given the wide array of ecosystem models developed an in use in the NES LME, the question begs, “What is the most appropriate use of these models for any given situation?”

The management of LMRs requires both tactical (i.e., what is the value and level of a BRP to determine stock status or set quotas?) and strategic advice (i.e., what management strategies are feasible, viable, and likely to best achieve management objectives?). Certain models are better suited to address some questions better than others; prior efforts (Plaganyi 2007, Townsend et al. 2008) have attempted to map the type of model to its best use for research and management applications. We note this mapping as applied to example models from the

NES LME (Table 2). We assert that a generic "ecosystem modeling" activity if applied to the wrong type of question for which a particular ecosystem model class was not designed, could actually dampen further efforts to implement these models, destroy any gained credibility, and thus hamper their ability to better support EBFM, and ultimately lead to potentially spurious or negative management implications.

Models like the ESAMs and multispecies approaches noted above better address issues such as specific physical/climate drivers, trophic interactions, or technical interactions as they relate to stock assessment contexts. Some of the aggregated approaches can also explore these types of questions, but may be better suited to the examination of system carrying capacity and related systemic issues. Food web models such as EwE or Econetwrk can explore trophic issues and can be used to explore management tradeoffs among species. And by their nature, full system models such as ATLANTIS can explore a wide range of questions but are best suited to explore a range of tradeoffs among multiple system components beyond solely the biota, particularly elucidating the relative prominence among a myriad of processes; all as applied across a range of management strategy evaluation exercises.

So, returning to our major intended uses and rationales for executing EMs in the NES LME, are we applying best practices regarding appropriate use of ecosystem models (Table 2)? Are the models we are using being applied to the appropriate types of questions and issues?

For evaluating system production potential (i.e., MSY for a system-level) and ecosystem overfishing, the models we are using span a range of aggregate production, energy transfer, and full system approaches. We assert that based upon recent reviews (Plaganyi 2007, Townsend et al. 2008), these approaches are appropriate for those questions. Not all specific models we have explored in each broad model class can address those issues; as such we have begun to de-emphasize some of them with our focus upon stakeholder demands for outputs that address system level production and system-level overfishing. The full system models provide context and simulations to support the other model results, but are not planned to be used for providing tactical outputs. From the energy transfer and aggregate production approaches, we can certainly produce tactical outputs for direct use in LMR management. These have been done previously (GARM III; NEFSC 2008) and are even more poised to do so now.

Definitively we can continue to use a plethora of MRMs in a stock assessment context. We are well positioned to continue examining trophic ecology ESAMs (i.e., namely consumptive removals) as they influence stock dynamics, particularly for forage fishes. Environmentally focused ESAMs likely remain an area for continued research until more solidified environmental-biotic response relationships and mechanisms can be documented. MS models similarly will likely serve in a contextual role. We note that all these MRMs can provide tactical LMR management advice, but presently only the ESAM Ecology models are in a position to do so.

Certainly the use of any of these models as operating models within an MSE context is possible, but our expected use of MSE will likely be to evaluate tradeoffs. We are well positioned to do so across species, fleets and common fisheries management options, but less so for multisector ocean uses. There is a relative shortage of analytical models to explore issues across multisector ocean uses. Certainly some of our full system models could be applied to this end, as could more categorical types of approaches such as PSA or other risk analyses. These likely will be embedded in a broader decision-support framework and in the context of MSE provide a range of possible, viable options for consideration. We suspect that these more strategic outputs will require distinct or novel venues for use (discussed below), but assert that the range of full system models and many of the other, miscellaneous models we have noted should clearly not be used to provide specific, tactical LMR advice.

Strengths and Weaknesses of Ecosystem Models in the NES LME

Here we pose key questions in the context of a broad review of the NEFSC EM enterprise, largely to identify areas where we think we could improve our efforts. We attempt to address these questions, but also specifically solicit objective evaluations via responses to this document to ensure that we are not omitting any major features that could further enhance our efforts. Simply posing such questions serves to capture the concepts and the need to routinely evaluate our EM endeavors.

Data Adequacy for Ecosystem Models

Collectively across our EMs, what are the main data needs, data gaps, and data adequacy concerns for the models we have identified for use? Certainly all the models build upon the excellent, world-class data sets found at the NEFSC. Multiple seasonal bottom trawl survey data, food habits data, zooplankton data and physical oceanographic data—from over half a century of sampling—all form a powerful set of databases (NEFSC data dictionaries[5]) from which many of our EMs can be constructed and tested. Many derived data sets, such as length, age, growth, recruitment, feeding, trophic level, and mortality can also be readily accessed. Fisheries dependent data, especially for landings, similarly is well established and documented[5]. Bycatch and discard information and data are perhaps not to the most optimal levels one might like, and are often challenging to allocate at certain scales of spatial resolution, but are also comprehensive and among some of the better estimates of such information, globally speaking. In terms of spatial extent and resolution, taxonomic resolution, and process coverage, these databases likely represent a rather optimal tradeoff between cost and coverage (e.g., we could extend surveys into the winter and summer seasons, but would have minimal time or resources to support doing so). These core fisheries and oceanographic data sets represent a foundational strength of the NEFSC EM modeling endeavor.

If one looks at Tables 3-9, particularly for the system level determinants of overfishing and production potential applications, a suite of common data gaps is implied. To support what has been reported elsewhere (e.g. EMAX, Link et al. 2006, Hare pers. comm., NEFSC unpubl. data) and as it pertains to input data requirements for these models, a key observation is that many groups are undersampled and understudied but could have significant influence upon the flow of energy in this ecosystem. These include a synoptic and broad-scale data of the macrobenthos (across a range of taxa), micronekton (e.g. mesopelagic fishes, euphasiids, etc.) data, seabird data, any data (as it pertains to abundance, biomass or distribution) on gelatinous zooplankton, and any quantitative information (again as it pertains to abundance, biomass or distribution) on the microbial loop (e.g., Johnson et al. 2011).

Of particular note and need for these EMs are estimates of primary production. Although estimates of satellite-derived primary production are extant and available, they do not extend to the full length of the time series as compared to other NEFSC databases. Further, phenological issues related to the timing and duration of spring and fall blooms, as mediated by a plethora of factors, also challenge assumptions about the "average" levels of production. Similarly, concerns

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[5] See http://nova.wh.whoi.edu/datadict/

over sub-surface chlorophyll maxima, the most appropriate algorithm to convert chlorophyll *a* estimates into production units, and various issues of color detection as it pertains to the phytoplankton community are important issues to consider and warrant further future work. We have attempted to address such issues by averaging across broader scales and color spectra. Conversely, the spatial and temporal resolution and extent since the inception of these satellite programs is highly valuable and available. We should also note that many of the data gaps we have identified as important to do ecosystem modeling in support of EBFM in the NES LME are not quintessentially fish or fisheries *per se*, but center upon lower- or mid-trophic levels. As we move towards EBFM, it will be critical to understand the production limitations of fish and fisheries from the base of the food web. Of all the potential data gaps or perceived needs, those associated with primary production and those lower trophic level (LTL) taxa noted above are apt to be most immediately critical for our intended EM uses.

Many of the physical forcing features of the NES LME are broad-scale. For instance, measures like the NAO, Atlantic multidecadal oscillation (AMO), and position of the Gulf Stream wall are readily available and have usefully served as covariates and context in many of our EMs (EcoAP 2009). Fine scale physical flow fields are extant, particularly as outputs from hydrodynamic models, and the thermal, saline, pH, wind stress, and stratification conditions of the NES LME are at least generally understood. How phenological changes influence those factors from year to year are important issues, but we tend to take mean flows at a rather coarse scale when considering these physical factors. Riverine inputs, tidal flows, and similar, more localized features are not as well documented, but they are also not that widely utilized for many of the EMs we have noted. Nutrient concentrations can be important, especially in some of the full system models. Although snapshots of information are available for some of the major nutrients (Townsend et al. 2006, see listings in Link et al. 2011c), there is nothing extant that is synoptic or provides good, routinely-measured coverage for this information.

Socio-economic data are also important for the use, parameterization, and contextualization of these EMs, particularly as they related to evaluating and tracking specific socio-economic outcomes. In a fisheries context, we have a reasonable data stream with which to parameterize models for landings, catch, and effort. Clearly more spatial resolution would be beneficial, but what we currently have is sufficient at least for broad spatial areas. Additional socio-economic data are required to varying degrees depending upon the type of model (Tables 3-9), but are also extant for many of the possible needs (EcoAP 2009, Link et al. 2011c).

Finally, many of the important rate processes (e.g. consumption, production, or respiration) are only known at a rudimentary level for many of the taxa in this or really any LME. Transfer rates between trophic groups or trophic levels are also only outputs of models, not directly estimated. Clearly more research into vital rates across a range of conditions is warranted. For most of the NES LME EMs, we have generally taken a rigorous approach to populating these rates using local data, literature values, qualitative rankings and categorizations, and in some instances Bayesian re-sampling techniques to at least bound what are the feasible ranges of some of these parameters. These vital rate parameters are likely the second most important data or information gap for improved EM in the NES LME after the LTL information noted above.

Best Practices for NEFSC Ecosystem Modeling

Are there areas of model use or assumptions that are being misapplied? We trust, as seen in Table 2 (and above), that we are applying these models to appropriate uses and to examine appropriate questions. But more germane, are the main assumptions for these models being violated (Table 1) in our execution of them for the NES LME? We have endeavored to document the inputs and tuning of these EMs that are generally applicable for each of the specific models. We trust that we have done so in a good faith effort to capture major initialization and parameterization choices. Even more appropriate, in order to address the main questions and uses we have intended for them (Table 2), have we violated any assumptions of these particular models? Looking at Table 1, the most common assumptions in these models are related to the functional forms of various processes or aggregation (and hence possible amalgamation) across taxa. We have endeavored to address the first main assumption by exploring multiple functional forms and evaluating the ramifications for functional form selection (as well as sensitivity analyses on associated parameters) on model outputs (e.g., Moustahfid et al. 2010). We have attempted to address the assumptions associated with aggregation via various simulation tests, sensitivity analyses, and differences from baselines due to various types of aggregation. Our collective results for both of the main assumptions is that for most issues our approaches tend to be robust to choice of forms or aggregations, with specific exceptions that have been duly caveated and noted in very particular instances (e.g., NEFSC 2006, 2007b, Moustahfid et al. 2010, Link et al. 2011c, Gaichas et al. unpubl. data, Fogarty et al. unpubl. data). Certainly we will continue to examine other assumptions beyond these two main ones, but our categorical approach has been to bound the issue and examine choices that address the assumption in an objective manner. Finally, we note that our use of multimodel inference adds further robustness to our assumptions for any particular application (NEFSC 2008, Link et al. 2010a).

Has there been adequate documentation for the collective NEFSC EM enterprise? Similarly, has there been adequate consideration of calibration, verification, initialization and parameterization steps in model construction? For many of our MRMs, these are embedded in stock assessment reports and the methodologies and details are noted (see ESAM sections above). For one of our MS models, there has been an extensive review (NEFSC 2006). For some of our key energy transfer and food web models, we have a fairly detailed and rigorous set of descriptions for the food web (Link et al. 2006, 2010b) and related energy-based approaches (as used in a recent GARM; NEFSC 2008) to document important methodological and calibration details. Other applications have begun to be applied in the region for other issues at different scales (Byron et al. 2011 a, b) from this basis. For one of our main full system models, a fairly detailed set of methodologies and calibration has been documented (Link et al. 2010c, 2011c). For these and many other models, specific applications have also appeared in the peer reviewed literature, with general summaries noted for specific contexts (ICES 2007, 2009, 2010, Townsend et al. 2008, Link and Bundy in press, Link et al. 2011a, b). Some such models have had methods reviewed and have been documented to the point that some emerging best practices have been proposed and disseminated in the primary literature (e.g., Tyrrell et al. 2011, Link 2010b). Although there are undoubtedly features remaining that have been inadvertently omitted in any such documentation, we trust that there has been enough evidence of a good faith effort to provide ample and rigorous documentation. How such documentation compares to other EM efforts elsewhere in the world warrants ongoing evaluation, but we suspect that what we have done is a reasonable start and conforms to many of the best practices suggested for EM in a LMR context (Plaganyi 2007, Townsend et al. 2008, FAO 2008, Link et al. 2010a).

Are best practices being used in the NES EM enterprise; are there any more that should be used (Plaganyi 2007, Townsend et al. 2008, FAO 2008, Link et al. 2010a)? As we have been involved with many of the efforts to establish global EM best practices, we have endeavored to apply them to our EM efforts in the NES LME. It is certainly possible that we have been biased against certain considerations, particularly regarding simpler ecosystem models or a broader use of models explicitly emphasizing more of the environmental, bio-physical couplings and associated processes (as is more commonly applicable in eastern-ocean boundary ecosystems). Yet acknowledging this potential bias, we have endeavored to systematically and categorically address the items in FAO (2008, their Table 2), and Townsend et al. (2008, their Table B.1 and associated Appendix B). We trust that this document further contributes to that end.

Have all the uncertainties of the NEFSC EM enterprise been adequately characterized and addressed? Based upon the report by Link et al. (2010a; their Table 4), clearly not every one of them have been for all of our EM classes. Of particular omission have been efforts to improve communication and visualization of model outputs. Doing so remains an area for improvement, despite some recent efforts at stakeholder outreach; this is identified again in discussion of possible review venues noted below. Many of the tradeoffs among model (structural) complexity uncertainty vs. basic data uncertainty are currently being explored and documented (c.f. Link et al. 2010a, their Tables 4, 7, 8 and ICES 2010), particularly via the use of multimodel inference, sensitivity analyses and MSEs.

Are there major analytical approaches the NEFSC EM enterprise is missing? Are there major EM classes that the NEFSC EM enterprise is missing? We pose these questions not necessarily to add further modeling capacity to our existing model tools, but rather to ensure that for the main model uses we have identified (Table 2), have the most appropriate general approaches been considered. Again, we clearly recognize that there are a host of other EMs we could use, but will they help us to address for example delineations of ecosystem overfishing, ecosystem fisheries production potential, or tradeoffs among ocean uses? We suspect what we have employed thus far represents a reasonable start towards addressing those questions, but readily admit that there is room for much further improvement.

Appropriateness of Review Venues for Various Model Classes

It is relatively easy to see the value of MRMs as tools to assist in the application of EBFM. Yet somewhat surprisingly, even though the applications are growing the information from MRMs have only rarely been utilized in a fisheries management context specifically as incorporated directly into stock assessments; this despite the large amount of effort applied to that end (e.g., NEFSC 2006, 2007 b, 2010b, 2011, Deroba et al. 2010). Essentially the information is there, the underlying mechanisms are mostly understood, and the data are mostly no less certain than other data used in the assessment and management process. Certainly there are aspects of estimation and precision uncertainty that can increase by including additional data on other considerations, but these are largely outweighed by the decreases in process, magnitude and accuracy uncertainty that are associated with including this extra information (Link et al 2010a). We suspect that differing expectations (especially with respect to precision), a lack of full characterization of (and familiarity with) input data dynamics and associated properties, and generally a healthy respect for the limits of modeling— both single and multi-species alike—are factors for the less than entire inclusion in the stock assessment process to date. We also suspect that, particularly for models that include environmental factors, the challenge of predicting future states has limited their use. However, the skill of environmental models is improving and the ability to couple climate, environmental and population models is developing rapidly (Hollowed et al. 2009, Hare et al. 2010, Fulton 2010).

All of that said we are encouraged that such “ancillary” information has been evaluated in the stock assessment process to provide “contextual” assessments that are reviewed along with the primary assessment. Certainly more research is required, but what is encouraging is that much of this work is now at the stage of focusing on sensitivity analyses, further quantifying uncertainty or model diagnostics, having already accomplished proof of concept and understanding of basic, underlying mechanisms.

From these and related observations, it has become apparent to the authors that distinct venues for evaluating ecosystem models beyond MRMs are required (NEFSC 2008, Link et al. 2010a). Perhaps a bigger factor is management institutions structured along single species lines that cannot easily accommodate multi-species advice. This highlights a dimension of EBFM that has not been raised herein – the need for management institutions to adapt to accommodate EBFM. Certainly some of the MRMs could and have been incorporated into existing stock assessment review frameworks. Yet many of the more aggregative, food web, and full system modeling approaches need to be evaluated by a subtly but importantly different set of expertise. These models are quite distinct from those for solely SS protected species or targeted species approaches currently used to support LMR management. Additionally, the sources and types of uncertainty are distinct and require review panels more familiar with the nuances of this broader array of considerations. Further, the outcomes of these models, being either largely strategic or highly aggregated, are addressing different terms of reference than what are currently evaluated in typical SS LMR assessment review venues. Distinct review processes with parallel processes similar to current SS-oriented LMR reviews, yet with distinct TORs and emphases that focus on broader ecosystem issues, would be beneficial. We assert that general familiarity with these models is nascent but growing, and we support efforts to develop modeling capacity as well as standardized and codified use of ecosystem models in this context (e.g., Plaganyi 2007, Townsend et al. 2008, FAO 2008, Link et al. 2010a, Link 2010b).

Strategic Considerations and Possibilities for the Future

We trust that the full range of models presented herein demonstrates a wide range of existing tools available to begin implementing EBFM in the NES LME. We discuss some of the lessons learned from these models as observed in their application for the NES LME. We partially do so to perhaps shed insight into how they could be more fully used and be further developed. We certainly desire to identify major areas of weaknesses that need to be addressed and have attempted to identify those items that could improve the NEFSC EM enterprise. Thus, here we provide a few observations for consideration in that longer-term, broader context.

Importantly, these models have elucidated a better understanding of what we do not know. In many respects, these modeling efforts have served as a veritable catalog of disparate datasets, from which we can identify major data gaps, a valuable outcome of these efforts (as noted above). For instance, we reiterate that it is sobering that a taxa group such as gelatinous zooplankton, which has typically not received much attention in LMR contexts, can potentially influence total LME system dynamics, including dynamics of LMRs of interest. Identifying key properties of the system that we do not know as fully as we could is an important outcome of the EM exercises.

We reemphasize a critical point of EBFM and the use of these models; confronting tradeoffs. We have begun to do so but need to further expand the use of these models to explore the range of feasible ecosystem configurations relative to national policies, laws and objectives in the NES LME. What has emerged from the modeling thus far is that EBFM is not apt to be an optimization exercise but rather an approach to avoid undesired ecosystem states and to identify those management approaches that are most robust for LMR management. Ignoring tradeoffs amongst objectives is not prudent; doing so could result in unanticipated consequences as a consequence of unexamined tradeoffs among the biota of, or sectors exploiting, an ecosystem. We assert that ecosystem models provide a tool to explicitly state and explore the range of viable options among potential tradeoffs in species, harvest, and management tools. As we have noted, this will likely require establishment of new institutional and formal processes to express and discuss these tradeoffs, which is as important as the actual modeling. Having an appropriate venue to explore such tradeoffs seems warranted, as does utilizing it on a routine basis.

In the context of tradeoffs, there are also plans to apply management strategy evaluation (MSE) to at least the fisheries sector in the NES LME sub-ecosystems. MSE (Smith et al 1999, 2007, Sainsbury et al. 2000) takes what we know now, places that information in an adaptive framework, simulates a range of management options or "scenarios" from a wide range of operating models, and then reports the outcomes of these virtual "*in silico*" experiments. The goal of doing this is to identify management options that are robust to uncertainty and will meet as many of the legislative mandates as possible while affording managers the flexibility to adapt to changing conditions. In the NES LME, several preliminary discussions have occurred with the regional fisheries management councils (both in the Mid-Atlantic and New England) and their supporting Scientific and Statistical Committees (SSC). We have also held similar discussions with the Atlantic States Marine Fisheries Commission (ASMFC) and the NMFS Northeast Regional Office. All said parties, and particularly the Councils' SSCs, have a keen interest in ecosystem approaches as doing so affords the opportunity for enhanced coordination across all managed species, as well as holding the prospect for actually simplifying the (assessment) process, particularly if a more aggregated production approach is considered. Many of the models noted herein could serve as the "operating model" in an MSE context. Using an MSE approach allows those management institutions to "test drive" various options before actual implementation of them.

Further, the US is moving towards some form of integrated management, with formal Coastal Marine Spatial Planning (CMSP) efforts beginning and several Integrated Ecosystem Assessments (IEAs) planned for many U.S. marine ecosystems, including the NES LME. At their core, IEAs seek to assess the status of an ecosystem, cognizant of the major drivers or pressures influencing that system, and that status relative to pre-established thresholds (Levin et al 2009). Ecosystem modeling is an integral part in the support of IEAs. IEAs are meant to be inclusive of the wider range of factors and processes that influence large marine ecosystems and their component LMRs, but a major distinction from EBFM and a primary focus on just fisheries is that these approaches have a much broader inclusion of other ocean-use sectors beyond fisheries. It is clear that much further work is required to support these multi-sectoral efforts, but some of the preliminary full system models described above could be adapted to address these more inclusive considerations. It is also clear that without many of these models, implementing IEAs will be severely hampered.

Exploring the use of model outputs at the aggregate or systemic levels is something that is sorely needed and requires much greater attention in the near future. This is an excellent example of needing to address biological tradeoffs. For instance, a recent assessment meeting for the NES LME groundfish community noted that the sum of all species B_{MSY} was greater than that as modeled in aggregate, for the system (NEFSC 2008). This confirms several prior studies (Garrod 1973, May 1976, Pope 1975, Fukuda 1976, Brown et al. 1976, Pope 1979). Exploring the use of system level or aggregate group level BRPs remains an important feature of many of these models. How productive a piece of the ocean is and how that production is partitioned to upper trophic levels seems a critical element of moving towards EBFM. Having an appropriate venue to review and uptake such model outputs again seems warranted, especially since many of our stakeholders are explicitly asking for such information.

As noted, the demand for EMs and their outputs is growing and is likely to continue to increase in coming years. Given national initiatives within the NOAA and the NMFS we anticipate national programs to continue to grow in the support of EM efforts. There does appear to be high demand for this type of work leading to the implementation of EBFM, and we anticipate that continuing to execute EMs will remain an important endeavor for LMR in this region.

It is unclear whether we need to further develop many of our EMs into a standardized toolbox. There are pros and cons of doing so, but nationally the NMFS has recognized that the potential limitations to regional innovation might outweigh any benefits gained from national standardization (Townsend et al. 2008). Certainly for internal use more user-friendly interfaces (e.g. GUIs, canned routines, etc.) and established protocols would be useful for the next generation of model users. How much time and effort we devote to this task of basic model development – as compared to executing particular applications for specific LMR management needs or continuing to develop the science of EM—remains to be determined.

There are many possible strategies for ecosystem modeling at the NEFSC. We could easily move towards more model development or more use of a broader range of models. Conversely, we could move away from our philosophy of multimodel inference and choose just one model to focus upon. And so on, such that we are cognizant that any such choices have longer term programmatic consequences (be they good or bad). Although many of the choices just noted are useful approaches and have their demonstrated benefits, our strategy for implementing and executing EMs at the NEFSC has followed several underlying philosophies: (1) we want to capitalize on the solid data sets that we do have, which means building, testing and using models that can take advantage of such copious data; (2) we want to retain multimodel inference capabilities to ensure we do not inadvertently err from the potential biases of any one model; (3) we want to develop (and collaborate with those developing) models as needed to implement EBFM, but not become "tool-makers" as an end in itself; (4) we want to work closely with our stakeholders and clients to ensure we are addressing the questions they have raised (or that we can reasonably anticipate that they will raise); (5) although we recognize and value the scientific importance and discovery that comes from the use of these models, we want to apply our EMs directly to solve LMR management relevant topics as a primary consideration; and (6) our focus has been and will be for the near-term future modeling and estimating that information useful for dealing with the tradeoffs in the NES LME. It is this latter point that has led us to have as our main EM foci on several of the intended ecosystem model uses that have been noted throughout this document, particularly estimating production potential, delineating ecosystem overfishing, and evaluating strategies to address these tradeoffs. Had we identified another priority, our choice of EMs would naturally represent a different emphasis and set of EMs. As we move towards addressing these tradeoff issues, we also desire to maintain efforts in support of MRMs in a tactical, stock assessment context and also desire to maintain the flexibility to develop novel tools and applications for future (both anticipated and as yet unanticipated) EM uses.

We conclude by noting that what happens with respect to EMs at the NEFSC has larger benefits beyond just our Center. Clearly this is true as it pertains to enhanced LMR management advice and moving towards a fuller implementation of EBFM. Yet within the Agency, it is clear that any capacity building to implement and execute EMs in the NES LME ultimately has widespread utility for the NMFS for several, obvious reasons. Certainly we have benefitted from interacting with other elements of the NMFS and NOAA, and certainly we have benefitted from interacting with our colleagues in the much broader, LMR-focused ecosystem modeling community. Yet based upon feedback we routinely obtain from this broad array of colleagues, we suspect that the NEFSC EM endeavor is also at least minimally contributing such benefits to the global LMR ecosystem modeling efforts. It is our aim for the NEFSC to be one such nexus of excellence for LMR-focused ecosystem modeling. We trust that the material documented herein demonstrates that we have begun to take steps to be such a nexus.

REFERENCES CITED

Astles, K.L., M. G. Holloway, A. Steffe, M.Green, C. Ganassin, and P. J. Gibbs. 2006. An ecological method for qualitative risk assessment and its use in the management of fisheries in New South Wales, Australia. Fish. Res. 82: 290–303.

Botsford, L. W., J. C. Castilla, C. H. Peterson 1997. The management of fisheries and marine ecosystems. Science, 277:509-515.

Browman, H.I. and K.I. Stergiou. 2004. Perpectives on ecosystem-based approaches to management of marine resources Mar. Ecol. Prog. Ser 274:269-303.

Browman, H.I. and K.I. Stergiou. 2005. Politics and soci-economics of ecosystem-based approaches to management of marine resources Mar. Ecol. Prog. Ser 300: 214-296

Brown, B.E., J.A. Brennan, M.D. Grosslein, E.G. Heyerdahl, and R.C. Hennemuth. 1976. The effect of fishing on the marine finfish biomass in the Northwest Atlantic from the Gulf of Maine to Cape Hatteras. ICNAF Research Bulletin 12:49-68.

Byron, C., J. Link, D. Bengston, B. Costa-Pierce. 2011a. Modeling Carrying Capacity of Shellfish Aquaculture in Highly Flushed Temperate Lagoons. Aquaculture. 314:87-99

Byron, C., J. Link, D. Bengston, B. Costa-Pierce. 2011b. Calculating Carrying Capacity of Shellfish Aquaculture Using Mass-Balance Modeling: Narragansett Bay, Rhode Island. Ecol. Model. 222:1743-1755

Chen, C., R. C. Beardsley, and P. J. S. Franks, 2001. A 3-D prognostic model study of the ecosystem over Georges Bank and adjacent coastal regions. Part I: physical model. Deep Sea Research, 48, 419-456.

Cheung, W. W. L., T. J. Pitcher, and D. Pauly. 2005. A fuzzy logic expert system to estimate intrinsic extinction vulnerabilities of marine fishes to fishing. Biol. Cons. 124: 97–111.

Christensen, V. and Pauly, D. 1992. On steady-state modeling of ecosystems. In: Trophic models of aquatic ecosystems. (Christensen, V. and Pauly, D. eds.). ICLARM Conference Proceedings 26, Manila, Philippines pp. 14-19.

Christensen, V. and D. Pauly. 1993. Trophic models of aquatic ecosystems. ICLARM Conf. Proc. 26, 390 p Christensen V., Walters, C. 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecological Modelling, 172(2-4): 109-139.

Christensen, V., Walters, C.J. and Pauly, D. 2005 Ecopath with Ecosim: a User's guide. Fisheries Centre of University of British Columbia, Vancouver, Canada. 154 pp.

Cogan, C.B., B.J. Todd, P. Lawton, and T.T. Noji. 2009. The role of marine habitat mapping in ecosystem-based management. ICES J. Mar. Sci. 2009 66: 2033-2042.

Coll, M., S. Libralato, S. Tudela, I. Palomera, F. Pranovi 2008. Ecosystem overfishing in the ocean. Public Library of Science (PLOS) ONE 3(12): e3881. doi:10.1371/journal.pone.0003881.

Collie, J.S., and DeLong, A.K., 1999. Multispecies interactions in the Georges Bank fish

Community. pp. 187-210. In Ecosystem Approaches for Fisheries Management. Alaska Sea Grant College Program. AK-SG-99-01.

Dames, JK and RR Christian. 2006. Uncertainty and the use of network analysis for ecosystem-based fishery management. Fisheries 31 (7): 331-341.

DFO. 2010. Proceedings of the Transboundary Resources Assessment Committee (TRAC) Spiny Dogfish Review. Proceedings 2010/01. 57 pp.

Debroba, J., G. Shepherd, F. Grégoire, J. Nieland, and J. Link. 2010. Stock Assessment of Atlantic Mackerel in the Northwest Atlantic - 2009. TRAC Reference Document - 2010/01. 59pp.

Duplisea, D.E., Kerr, S.R., Kickie, L.M., 1997. Demersal fish biomass size spectra on the Scotian Shelf, Canada: species replacement at the shelfwide scale. Can. J. Fish. Aquat. Sci. 54: 1725–1735.

EcoAP (Ecosystem Assessment Program). 2009. Ecosystem Status Report for the Northeast U.S. Continental Shelf Large Marine Ecosystem. Northeast Fisheries Science Center Reference Document, 09-11. 34 p.

Edwards, S.F., Link, J.S. and Rountree, B.P. 2004. Portfolio management of wild fish stocks. Ecol. Econ. 49:317-329.

FAO (Food and Agriculture Organization of the United Nations). 2008. Fisheries Management. 2. The ecosystem approach to fisheries. 2.1 Best practices in ecosystem modelling for informing an ecosystem approach to fisheries. FAO Technical Guidelines for Responsible Fisheries, 4 (Suppl. 2, Add. 1), 79 pp.

Fennel, W. and Neumann, T. 2004. Introduction to the modelling of marine ecosystems. Elsevier, Amsterdam, The Netherlands. 297 pp.

Fogarty, M.J., Overholtz, W.J. and Link, J. 2008. Fishery Production Potential of the Northeast Continental Shelf of the United States. GARM WP 3.5 GARM-III-BRP Meeting, NEFSC, Woods Hole, MA.

Fogarty, M. L. Incze, K. Hayhoe, D.Mountain and J. Manning. 2008. Potential Climate Change Impacts on Atlantic Cod (*Gadus morhua*) off the Northeastern United States. Mitig. Adapt. Strat. Glob.Change. 13:453-466.

Fogarty, M.J. and J.T. Brodziak. 1994. Multivariate time series analysis of fish community dynamics on Georges Bank. ICES C.M. 1994/P:3.

Fletcher, W. J., J. Chesson, K. J. Sainsbury, T. J. Hundloe, and M. Fisher. 2005. A flexible and practical framework for reporting on ecologically sustainable development for wild capture fisheries. Fish. Res. 71: 175-183.

Francis, R.I.C.C. 1992. Use of risk analysis to assess fishery management strategies: a case study using orange roughy (Hoplostethus atlanticus) on the Chatham Rise, New Zealand. Can. J. Fish. Aquat. Sci. 49: 922-930.

Franks, P.J.S. and Chen, C., 2001. A 3-D prognostic numerical model study of the Georges Bank ecosystem. Part II: biological-physical model. Deep-Sea Res. II 48:457-482.

Fukuda, Y. 1976. A note on yield allocation in multistock fisheries. ICNAF Research Bulletin 12, 83-87.

Fulton, E.A., Smith, A.D.M. and Johnson, C.R. 2004. Biogeochemical marine ecosystem models I: IGBEM--a model of marine bay ecosystems. Ecological Modelling 174, 267-307.

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

Fulton, E.A. 2010. Approaches to end-to-end ecosystem models. Journal of Marine Systems 81: 171–183.

Fulton, E.A., J.S. Link, I. Kaplan., M. Savina-Rolland, P. Johnson., C. Ainsworth, P. Horne, R. Gorton, R.J. Gamble, A.D.M. Smith, D.C. Smith. 2011. Lessons in modelling and management of marine ecosystems: The Atlantis experience. Fish and Fisheries 12:171-188

Gaichas, S., Skaret, G., Falk-Petersen, J., Link, J.S., Overholtz, W., Megrey, B.A., Gjoesaeter, H., Stockhausen, W., Dommasnes, A. & Aydin, K. 2009. A comparison of community and trophic structure in five marine ecosystems based on energy budgets and system metrics. Prog. Oceanogr. 81:47-62.

Gamble, R.J. and Link, J.S. 2009. Analyzing the Tradeoffs Among Ecological and Fishing Effects on an Example Fish Community: a Multispecies (Fisheries) Production Model. Ecological Modelling 220: 2570-2582.

Garcia, S.M., Zerbi, A., Aliaume, C., Do Chi, T. and Lasserre, G. 2003. The ecosystem approach to fisheries: issues, terminology, principles, institutional foundations, implementation and outlook. FAO Technical Paper 443. FAO, Rome. 71 pp.

Garrison, L., and Link, J. 2004. An expanded multispecies virtual population analysis approach (MSVPA-X) to evaluate predator–prey interactions in exploited fish ecosystems. Version 1.1, Users Manual and Model Description. Atlantic States Marine Fisheries Commission, Arlington, VA. 90 pp.

Garrison, L.P., Link, J.S., Cieri, M., Kilduff, P., Sharov, A., Vaughan, D., Muffley, B., Mahmoudi, B. and Latour R. 2010. An Expansion of the MSVPA Approach for Quantifying Predator-Prey Interactions In Exploited Fish Communities. ICES Journal of Marine Science 67: 67: 856-870.

Garrod, D.J. 1973. Memorandum on the mixed fishery problem in Subarea 5 and Statistical Area 6. ICNAF Research Document. 73/6.

Gneiting, T. and A. E. Raftery. 2005. Weather forecasting with ensemble methods. Science 310(5746): 248-249.

Hall, S.J., Collie, J.S., Duplisea, D.E., Jennings, S., Bravington, M. & Link, J. 2006. A length-based multi-species model for evaluating community responses to fishing. Can. J. Fish. Aquat. Sci. 63:1344-1359.

Hare J.A., M. Alexander, M. Fogarty, E. Williams and J. Scott. 2010. Forecasting the dynamics of a coastal fishery species using a coupled climate-population model. Ecological Applications. 20 (2): 452-464

Holland, D.S., and Sutinen, J.G., 1999. An empirical model of fleet dynamics in New England trawl fisheries. Canadian Journal of Fisheries and Aquatic Sciences 56: 253–264.

Hollowed, A.B., Bond, N.A., Wilderbuer, T.K., Stockhausen, W.T., A'Mar, Z.T., Beamish, R.J., Overland, J.E. and Schirripa M.J. 2009. A framework for modelling fish and shellfish responses to future climate change. ICES Journal of Marine Science 66, 1584-1594.

Hollowed, A.B., Bax, N., Beamish, R., Collie, J., Fogarty, M., Livingston, P., Pope, J. & Rice, J.C. 2000. Are multispecies models an improvement on single-species models for measuring fishing impacts on marine ecosystems? ICES Journal of Marine Science, 57:707-719.

Hu, S., D.W. Townsend, C. Chen, G. Cowles, R.C. Beardsley, R. Ji and R.W. Houghton. 2008. Tidal pumping and nutrient fluxes on Georges Bank: A process-oriented modeling study. Journal of Marine Systems 74(1-2): 528-544.

ICES. 1991. Multispecies models relevant to management of living resources. ICES Marine Sci. Symp. 193. 358 pp.

ICES. 2007. Report of the Working Group on Multispecies Assessment Methods (WGSAM), 15–19 October 2007, San Sebastian, Spain. ICES CM 2007/RMC:08. 134 pp.

ICES. 2009. Report of the Working Group on Multispecies Assessment Methods (WGSAM), 5–9 October 2009, ICES Headquarters, Copenhagen. ICES CM 2009/RMC:10. 117 pp.

ICES. 2010. Report of the Working Group on Multispecies Assessment Methods (WGSAM), 4–8 October 2010, San Sebastian, Spain. ICES CM 2010/SSGSUE:05. 95 pp

Jennings, S. 2005. Indicators to support an ecosystem approach to fisheries. Fish and Fisheries, 6:212-232.

Jennings, S., J. D. Reynolds, and N. V. C. Polunin. 1999. Predicting the vulnerability of tropical reef fishes to exploitation with phylogenies and life histories. Cons. Biol. 13: 1466-1475.

Ji, R., C. S. Davis, C. Chen, D. W. Townsend, D. G. Mountain, and R. C. Beardsley. 2008. Modeling the influence of low-salinity water inflow on winter-spring phytoplankton dynamics in the Nova Scotian Shelf–Gulf of Maine region. Journal of Plankton Research 30:1399.

Johnson CL, Runge JA, Curtis KA, Durbin EG, Hare JA, Incze LS, Link J, Melvin GD, O'Brien TD, Van Guelpen L. 2011. Biodiversity and ecosystem function in the Gulf of Maine: pattern and role of zooplankton and pelagic nekton. PLoS ONE 6(1): e16491. doi:10.1371/journal.pone.0016491

Kavanagh, P., N. Newlands, V. Christensen, and D. Pauly. 2004. Automated parameter optimization for Ecopath ecosystem models. Ecol. Model. 172:141-149.

Keyl, F., and M. Wolff. 2008. Environmental variability and fisheries: what can models do? Reviews in Fish Biology and Fisheries, 18:273-299.

Krishnamurti, T. N., C. M. Kishtawal, Z. Zhang, T. LaRow, D. Bachiochi, E. Williford, S. Gadgil, and S. Surendran. 2000. Multimodel Ensemble Forecasts for Weather and Seasonal Climate. Journal of Climate 13:4196-4216.

Lane, D.E. and R.L. Stephenson. 1998. A framework for risk analysis in fisheries decision-making. ICES J. Mar. Sci. 55: 1-13.

Larkin, P.A. 1996. Concepts and issues in marine ecosystem management. Reviews Fish Biology and Fisheries 6:139-164.

Leslie, H., A. A. Rosenberg, J. Eagle 2008. Is a new mandate needed for marine ecosystem-based management? Frontiers in Ecology and the Environment, 6:43-48.

Levin P.S., M.J. Fogarty, S.A. Murawski, and D. Fluharty. 2009. Integrated Ecosystem Assessments: Developing the Scientific Basis for Ecosystem-Based Management of the Ocean. PLoS Biol 7(1): e1000014. doi:10.1371/journal.pbio.1000014

Libralato, S., V. Christensen, D. Pauly. 2006. A method for identifying keystone species in food web models. Ecological Modelling 195:153-171.

Libralato, S., M. Coll, S. Tudela, I. Palomera, F. Pranovi. 2008. Novel index for quantification of ecosystem effects of fishing as removal of secondary production. Marine Ecology Progress Series 355:107-129.

Link, J. 1999. (Re)Constructing Food Webs and Managing Fisheries. Proceedings of the 16th Lowell Wakefield Fisheries Symposium- Ecosystem Considerations in Fisheries Management. AK-SG-99-01: 571-588.

Link, J.S. 2002a. Ecological considerations in fisheries management: When does it matter? Fisheries, 27(4): 10-17.

Link, J.S. 2002b. What Does Ecosystem-Based Fisheries Management Mean? Fisheries 27(4):18-21.

Link, J.S. 2002c. Does food web theory work for marine ecosystems? Mar. Ecol. Prog. Ser. 230:1-9.

Link, J.S. 2003. A Model of Aggregate Biomass Tradeoffs. ICES Annual Science Conference. Theme Session on Reference Point Approaches to Management within the Precautionary Approach. ICES CM 2003/Y08 28 pp

Link, J.S. 2004. A general model of selectivity for fish feeding: a rank proportion algorithm. Trans. Amer. Fish. Soc. 133:655-673.

Link, J.S. 2005. Translation of Ecosystem Indicators into Decision Criteria. ICES J. Mar. Sci. 62:569-576.

Link, J.S. 2010a. Ecosystem-based fisheries management: confronting tradeoffs. Cambridge Univ. Press. Cambridge, UK.

Link, J.S. 2010b. Adding Rigor to Ecological Network Models by Evaluating a Set of Pre-balance Diagnostics: A Plea for PREBAL. Ecol. Model. 221:1582-1593.

Link, J., and J. Brodziak. (eds.). 2002. Report on the Status of the NE US Continental Shelf Ecosystem. NEFSC Ecosystem Status Working Group. Northeast Fisheries Science Center Reference Document, 02-11, 245 pp.

Link, J.S. and Bundy, A. (In Press). Ecosystem Modeling in the Gulf of Maine Region: Towards an Ecosystem Approach to Fisheries. AFS Gulf of Maine Symposium Proceedings

Link, J.S. and Garrison, L.P. 2002. Changes in piscivory associated with fishing induced changes to the finfish community on Georges Bank. Fish. Res. 55:71-86

Link, J.S. and J.S. Idoine. 2009. Predator Consumption Estimates of the northern shrimp Pandalus borealis, with Implications for Estimates of Population Biomass in the Gulf of Maine. N. Amer. J. Fish. Manag. 29:1567-1583

Link, J.S. and Sosebee, K. 2008. Estimates and implicatons of Skate Consumption in the northeastern US continental shelf ecosystem. N. Amer. J. Fish. Manag. 28:649-662.

Link, J. S., J. K. T. Brodziak, S. F. Edwards, et al. 2002a. Marine ecosystem assessment in a fisheries management context. Canadian Journal of Fisheries and Aquatic Science, 59:1429-1440.

Link, J.S., Stockhausen, W.T. & Methratta, E.T. 2005. Food web theory in marine ecosystems. pp. 98-113 in Belgrano, A., Scharler U.M., Dunne, J. & Ulanowicz, R.E. (eds.) Aquatic Food Webs: an Ecosystem Approach. Oxford Univ. Press, Oxford.

Link, J.S., C.A. Griswold, E.T. Methratta, and J. Gunnard, Editors. 2006. Documentation for the Energy Modeling and Analysis eXercise (EMAX). NEFSC Center Reference Document 06-15. 166 p.

Link, J.S., O'Reilly, J., Dow, D., Fogarty, M., Vitaliano, J., Legault, C., Overholtz, W., Green, J., Palka, D., Guida, V. and Brodziak, J. 2008a. Comparisons of the Georges Bank Ecological Network: EMAX in Historical Context. J. Northwest Atl. Fish. Sci. 39:83-101.

Link, J., Overholtz, W., O'Reilly, J., Green, J., Dow, D., Palka, D., Legault, C., Vitaliano, J., Guida, V., Fogarty, M., Brodziak, J., Methratta, E., Stockhausen, W., Col, L., Waring, G., and Griswold, C. 2008b. An Overview of EMAX: The Northeast U.S. Continental Shelf Ecological Network. J. Mar Sys. 74:453-474.

Link, J.S., Stockhausen, W., Skaret, G., Overholtz, W., Megrey, B.A., Gjoesaeter, H., Gaichas, S., Dommasnes, A., Falk-Petersen, J., Aydin, K., Kane, J., Mueter, F., Friedland K. & Hare, J. 2009. A comparison of biological trends from four marine ecosystems: Synchronies, differences, and commonalities. Prog. Oceanogr. 81:29-46.

Link, J.S., T.F. Ihde, H. Townsend, K. Osgood, M. Schirripa, D. Kobayashi, S. Gaichas, J. Field, P. Levin, K. Aydin, G. Watters, and C. Harvey (editors). 2010a. Report of the 2nd National Ecosystem Modeling Workshop (NEMoW II): Bridging The Credibility Gap – Dealing With Uncertainty In Ecosystem Models. NOAA Tech. Memo. NMFS-F/SPO-102, 72p.

Link, J.S., B.A. Megrey, T.J. Miller, T. Essington, J. Boldt, A. Bundy, E. Moksness, K.F. Drinkwater & R. I. Perry. 2010b. Comparative Analysis of Marine Ecosystems: International Production Modelling Workshop. Biol. Lett. doi: 10.1098/rsbl.2010.0526

Link, J.S., Fulton, E.A., and Gamble, R.J. 2010c. The northeast US application of ATLANTIS: A full system model exploring marine ecosystem dynamics in a living marine resource management context. Prog. Ocean. 87: 214-234.

Link, J.S., Yemane, D., Shannon, L.J., Coll, M., Shin, Y-J., Hill, L., Borges, M.F., Bundy, A. & Aydin, K. 2010d. Relating Marine Ecosystem Indicators to Fishing and Environmental Drivers: An Elucidation of Contrasting Responses. ICES Journal of Marine Science 67: 787-795.

Link, J.S., Bundy, A., Overholtz, W.J., Shackell, N., Manderson, J., Duplisea, D., Hare, J., Koen-Alonso, M. & Friedland, K. 2011a. Northwest Atlantic Ecosystem Based Management of Fisheries. in Belgranno, A. and Fowler, C.W. (eds.) Ecosystem Based Management for Fisheries: Linking Patterns to Policy. pp. 32-112 .

Link, J.S., A. Bundy, W.J. Overholtz, N. Shackell, J. Manderson, D. Duplisea, J. Hare, M. Koen-Alonso, K.D. Friedland. 2011b. Northwest Atlantic Ecosystem-Based Fisheries Management. Fish and Fisheries 12:152-170.

Link, J.S., Gamble, R.J., and Fulton, E.A. 2011c. NEUS – ATLANTIS: Construction, Calibration and Application of an Ecosystem Model with Ecological Interactions, Physiographic Conditions, and Fleet Behavior. NOAA Tech. Memo. NMFS NE-218. 247 p.

Liu, H. Fogarty, M.J., Glaser, S.M., Altman, I. Rosenberg, A.A. and Sugihara, G. In review. Nonlinear dynamic features and co-predictability in the Georges Bank fish community. Mar Ecol Prog Ser.

Mace, G. M., N. J. Collar, K. J. Gaston, C. Hilton-Taylor, H. R. Akcakaya, N. Leader-Williams, E. J. Milner-Gulland, and S. N. Stuart. 2008. Quantification of extinction risk: IUCN's system for classifying threatened species. Cons. Biol. 22: 1424-1442.

May, R.M. 1972. Will a large complex system be stable? Nature 238:413-414.

May, R.M. 1973. Stability and Complexity in Model Ecosystems. Princeton University Press, Princeton, NJ.

May, A.W. 1975. Report of standing committee on research and statistics. ICNAF Seventh Special Commission Meeting – September 1975.

May, A.W. 1976. Report of standing committee on research and statistics. ICNAF Seventh Special Commission Meeting – September 1975. ICNAF Redbook 1976, 5-19.

Mayo, R.K., M.J. Fogarty, and F.M. Serchuk. 1992. Aggregate fish biomass and yield on Georges Bank, 1960-87. JNAFS. 14:59-78.

Methratta ET., Link JS. 2006. Evaluation of quantitative indicators for marine fish communities. Ecological Indicators, 6:575-588.

Megrey, B.A. and E. Moksness (eds) 2009a. Computers in Fisheries Research, Springer, 421 pp.

Moustahfid, H., Link, J.S., Overholtz, W.J. and Tyrell, M.C. 2009a. The advantage of explicitly incorporating predation mortality into age-structured stock assessment models: an application for Northwest Atlantic mackerel. ICES Journal of Marine Science 66, 445-454.

Moustahfid, H., Tyrrell, M.C. and Link, J.S. 2009b. Accounting explicitly for predation mortality in surplus production models: an application to longfin inshore squid. North American Journal of Fisheries Management 29, 1555-1566.

Moustahfid, H., M.C. Tyrrell, J. S. Link, J. Nye, B. E. Smith & R. J. Gamble. 2010. Functional feeding responses of piscivorous fishes from the northeast US continental shelf. Oecologia 163(4):1059-1067.

Mueter, F. J., B. A. Megrey 2006. Using multi-species surplus production models to estimate ecosystem-level maximum sustainable yields. Fisheries Research, 81:189-201.

Murawski, S. A. 1984. Mixed-species yield per recruitment analyses accounting for technological interactions. Canadian Journal of Fisheries and Aquatic Science, 41:897-916.

Murawski, S.A. 2000. Definitions of overfishing from an ecosystem perspective. ICES J. Marine Science 57:649-528.

Murawski, S. A. 2007. Ten myths concerning ecosystem approaches to marine resource management. Marine Policy, 31:681-690.

Musick, J. A. 1999. Criteria to define extinction risk in marine fishes. Fish. 24: 6-14.

NEFSC 2006. 42nd Northeast Regional Stock Assessment Workshop (42nd SAW). Northeast Fisheries Science Center Reference Document, 06-09b, 308 pp.

NEFSC 2007a. Assessment Report (45th SARC/SAW). Northeast Fisheries Science Center Reference Document, 07-16, pp. 13-138

NEFSC 2007b. Assessment Report (44th SARC/SAW). Northeast Fisheries Science Center Reference Document, 07-10, pp. 332-344, 504-547

NEFSC 2008. Report of the 3rd Groundfish Assessment Review Meeting (GARM III), Northeast Fisheries Science Center Reference Document 08-15, 884 pp.

NEFSC. 2010a. 50th Northeast Regional Stock Assessment Workshop (50th SAW) Assessment Report. Northeast Fisheries Science Center Reference Document 10-17, part A, C.

NEFSC. 2010b. 49th Northeast Regional Stock Assessment Workshop (49th SAW) Assessment Report. Northeast Fisheries Science Center Reference Document 10-03. Appendix B1.

NEFSC. 2011. 51st Northeast Regional Stock Assessment Workshop (51st SAW): Assessment Summary Report. Northeast Fisheries Science Center Reference Document 11-01, part A, B, C.

NMFS (National Marine Fisheries Service). 1999. Ecosystem-based fishery management. A report to Congress by the Ecosystems Principles Advisory Panel. U.S. Department of Commerce, Silver Spring, MD.

Nye, J.A. A. Bundy, N. Shackell, K.D. Friedland, & J.S. Link. 2010. Coherence in population trends of major ecological and commercial fish species in the Northwest Atlantic. ICES J. Mar. Sci.67:26-40.

Odum, E.P. 1964. The strategy of ecosystem development. Science 164:262-270.

Overholtz, W.J. and J.S. Link. 2007. Consumption impacts by marine mammals, fish, and seabirds on the Gulf of Maine-Georges Bank Atlantic Herring (Clupea harengus) complex during 1977-2002. ICES J. Mar. Sci. 64:83-96.

Overholtz, W.J. and J.S. Link. 2009. A simulation model to explore the response of the Gulf of Maine food web to large scale environmental and ecological changes. Ecol. Model.220:2491-2502.

Overholtz, W.J., L.D. Jacobson, and J.S. Link. 2008a. Developing an ecosystem approach for assessment advice and biological reference points for the Gulf of Maine-Georges Bank herring complex: adding the impact of predation mortality. N. Amer. J. Fish. Manag. 28:247-257.

Overholtz, W.J., M.F. Fogarty, J.S. Link, C. Legault, and L. Col. 2008b. Estimates of aggregate surplus production for the GARM and other stock groups for the US Northeast Shelf LME. GARM WP 3.3 GARM-III-BRP Meeting

Patrick, W. S., P. Spencer, O. Ormseth, J. Cope, J. Field, D. Kobayashi, T. Gedamke, E. Cortés, K. Bigelow, W. Overholtz, J. Link, and P. Lawson. 2009. Use of productivity and susceptibly indices to determine the vulnerability of a stock: with example applications to six U.S. fisheries. Final Report of the National Marine Fisheries Service Vulnerability Evaluation Work Group. Silver Spring, MD. 117 pp.

Patrick, W.S., P. Spencer, J. Link, O. Ormseth, J. Cope, J. Field, D. Kobayashi, T. Gedamke, E. Cortés, K. Bigelow, W. Overholtz, & P. Lawson. 2010. Assessing the vulnerability of U.S. fisheries to becoming overfished or undergoing overfishing through the use of productivity and susceptibility indices. Fish. Bull. 108:305-322.

Patten, B.C. and E.P. Odum. 1981. The cybernetic nature of ecosystems. Amer. Nat. 118:886-895.

Pauly, D., V. Christensen 1995. Primary production required to sustain global fisheries. Nature, 374:255-257.

Pauly, D., V. Christensen, J. Dalsgaard, R. Froese, F. T. Jr. 1998. Fishing down marine food webs. Science, 279:860-863.

Pauly D, Christensen V, Walters C. 2000. Ecopath, Ecosim and Ecospace as tools for evaluating ecosystem impact of fisheries. ICES Journal of Marine Science, 57: 697-706.

Pauly, D., V. Christensen, S. Guénette, et al. 2002. Towards Sustainability in World Fisheries. Nature, 418:689-695.

Pikitch, E.K., Santora, C., Babcock, E. A., Bakun, A., Bonfil, R., Conover, D. O., Dayton, P., Doukakis, P., Fluharty, D., Heneman, B., Houde, E.D., Link, J., Livingston, P., Mangel, M., McAllister, M., Pope, J. & Sainsbury, K.J. 2004. Ecosystem-based fishery management. Science 305 (5682):346-347.

Pitcher T.J., Kalikoski, D., Short, K. Varkey, D. and Pramoda, G. 2009. An evaluation of progress in implementing ecosystem-based management of fisheries in 33 countries. Marine Policy 33, 223-232.

Plagányi, É. E. 2007. Models for an Ecosystem Approach to Fisheries. FAO Fisheries Technical Paper. No. 477. Rome, Italy: FAO, pp 108.Platt, T.C. and S. Sathyendrath 2008. Ecological indicators for the pelagic zone of the ocean from remote sensing. Remote Sensing of Environment 112 (8), pp. 3426-3436

Polovina, J.J. 1984. Model of a coral reef ecosystem. The ECOPATH model and its application to French Frigate Shoals. Coral Reefs 3(1):1-11.

Pope, J.G. 1975. The application of mixed fisheries theory to the cod and redfish stocks of subarea 2 and division 3K. ICNAF Research Document 75/IX 126 pp.

Pope, J. 1979. Stock assessment in multistock fisheries, with special reference to the trawl in the Gulf of Thailand. South China Sea Fisheries Development Programme. SCS/DEV/79/19 FAO. Manila, Philippines. 106 pp.

Prager, M. H. 1994. A suite of extensions to a nonequilibrium surplus-production model. U.S. National Marine Fisheries Service Fishery Bulletin 92:374–389.

Roberts, C. M. and J. P. Hawkins. 1999. Extinction risk in the sea. Trends Ecol. Evol. 14: 241-248.

Rose, K. A. 2000. Why are quantitative relationships between environmental quality and fish populations so elusive? Ecological Applications, 10:367-385.

Ryther, J.H. 1969. Photosynthesis and fish production from the sea. Science 166:72-76.

Sainsbury, K.J., 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.

Samhouri, J.F., P.S. Levin, C.H. Ainsworth 2010. Identifying thresholds for ecosystem-based management. Public Library of Science (PLOS) ONE 2010;5:e8907.

Samhouri, J.F., P.S. Levin, C.A. James, J. Kershner, G. Williams 2011. Using existing scientific capacity to set targets for ecosystem-based management: A Puget Sound case study. Marine Policy, 35:508-518.

Shin, Y.-J., A. Bundy, L.J. Shannon, M. Simier, M. Coll, E.A. Fulton, J.S. Link, D. Jouffre, H. Ojaveer, S. Mackinson, J.J. Heymans, T. Raid. 2010. Can simple be useful and reliable? Using ecological indicators for representing and comparing the states of marine ecosystems. ICES Journal of Marine Science, 67: 717-731.

Smith, A.D.M., Sainsbury, K.J. and Stevens, R.A. 1999. Implementing effective fisheries-management systems—management strategy evaluation and the Australian partnership approach. ICES Journal of Marine Science 56, 967–979.

Smith, A.D.M., Fulton, E.J., Hobday, A..J, Smith, D.C., Shoulder, P. 2007. Scientific tools to support the practical implementation of ecosystem-based fisheries management. ICES Journal of Marine Science 64 (4): 633-639.

Smith, S.J., J. Black, B.J. Todd, V.E. Kostylev, and M.J. Lundy. 2009. The impact of commercial fishing on the determination of habitat associations for sea scallops (*Placopecten magellanicus*, Gmelin). ICES J. mar. Sci. 2009 66: 2043-2051.

Steele, J.H., Collie, J.S., Bisagni, J.J., Gifford, D.J., Fogarty, M.J., Link, J.S., Sullivan, B.K., Sieracki, M.K., Beet, A.R., Mountain, D.G., Durbin, E.G., Palka, D. & Stockhausen, W.T. 2007. Balancing end-to-end budgets of the Georges Bank ecosystem. Prog. Oceanogr. 74:423-448.

Stobutzki, I. C., M. J. Miller, P. Jones, and J. P. Salini. 2001a. Bycatch diversity and variation in a tropical Australian penaeid fishery: the implications for monitoring. Fish. Res. 53: 283-301.

Stobutzki, I., M. Miller, and D. Brewer. 2001b. Sustainability of fishery bycatch: a process for assessing highly diverse and numerous bycatch. Environ. Cons. 28: 167-181.

Sugihara G. 1994. Nonlinear forecasting for the classification of natural time-series. Philos T R Soc A 348(1688): 477–495

Sugihara G, May RM. 1990. Nonlinear forecasting as a way of distinguishing chaos from measurement error in time series. Nature 344(6268): 734–741

Tebaldi, C. and R. Knutti. 2007. The use of the multi-model ensemble in probabilistic climate projections. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365(1857): 2053.

Townsend, D. W., A. C. Thomas, L. M. Mayer, and M. A. Thomas. 2006. Oceanography of the Northwest Atlantic Continental Shelf (1,W). p 119-168. In A. R. Robinson and K. H. Brink [Eds.]. The Sea: The Global Coastal Ocean: Interdisciplinary Regional Studies and Syntheses. vol 14. Harvard Univ. Press.

Townsend, H. M., J. S. Link, K. E. Osgood, T. Gedamke, G. M. Watters, J. J. Polovina, P. S. Levin, N. Cyr, and K. Y. Aydin (editors). 2008. Report of the NEMoW (National Ecosystem Modeling Workshop). NOAA Technical Memorandum NMFS-F/SPO-87. 93 pp.

Tsou, T.-S., and Collie, J.S. 2001. Estimating predation mortality in the Georges Bank fish community. Canadian Journal of Fisheries and Aquatic Sciences, 58: 908-922.

Tudela, S., M. Coll, I. Palomera. 2005. Developing an operational reference framework for fisheries management on the basis of a two-dimensional index of ecosystem impact. ICES Journal of Marine Science, 62:585-591.

Tyrrell, M.C., Link J.S., Moustahfid, H. and Smith, B.E. 2007. The dynamic role of pollock (*Pollachius virens*) as a predator in the Northeast US Atlantic ecosystem: a multi-decadal perspective. J. Northwest Atl. Fish. Sci. 38:53-65.

Tyrrell, M.C., Link, J.S., Moustahfid, H. and Overholtz, W.J. 2008. Evaluating the effect of predation mortality on forage species population dynamics in the Northwest Atlantic continental shelf ecosystem: an application using multispecies virtual population analysis. ICES J. Mar. Sci. 65:1689-1700.

Tyrrell, M.C., Link, J.S. & Moustahfid, H. 2011. The importance of including predation in some fish population models: implications for biological reference points. Fisheries Research 108:1-8.

Ulanowicz, R.E. 2004. Quantitative methods for ecological network analysis. Computational Biology and Chemistry. 28/5-6:321-339.

Walters, C. J., J. S. Collie. 1988. Is research on environmental factors useful to fisheries management? Canadian Journal of Fisheries and Aquatic Science 45:1848-1854.

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

Ware, D.M. 2000. Aquatic ecosystems: properties and models. In P.J.Harrison and T.R. Parsons (Eds). Fisheries Oceanography: An Integrative Approach to Fisherues and Ecology and Management. Blackwell Sci., Oxford.

Whipple S., Link JS, LP Garrison, Fogarty, MJ. 2000. Models of predation and fishing mortality in aquatic ecosystems. Fish. and Fisheries. 1:22-40.

Table 1. Summary of the NEFSC ecosystem models with notations of salient features.

		Main Purpose of Model	Major Strengths	Major Weaknesses	Stochastic or deterministic outputs	Analytical or Statistical	Primary model intent- simulation, estimation, scenario testing, pattern detection, etc.	Static or Dynamic	Predictions or Forecasts (Y or N)	(Tactical, Strategic, Both, Heuristic, N/A) output use wrt Mgt Advice	Major Assumptions	Reference/s	Empahsized in this Review (Y or N)
Model Class	ESAM MRMs- Ecology												
Model	S-R	Augment SS Assessment Models with Ecological Interactions	Enhanced ecological realism; common outputs as SS models	Precision vs Accuracy Uncertainty Debate in SS Assessment Context; misses other processes and dynamics	Both	Both	Estimation	Both	Y	Tactical	A stock-recruitment relationship exists and can be fitted; predation or cannibalism is distinct from depensation/compensation	Tyrrell et al. 2011, Lucey & Alade unpubl. data	N
Model	SS Prod	Augment SS Assessment Models with Ecological Interactions	Enhanced ecological realism; common outputs as SS models	Precision vs Accuracy Uncertainty Debate in SS Assessment Context; misses other processes and dynamics	Both	Both	Estimation	Both	Y	Tactical	Usual for production models, esp. some equilibrium assumptions; consumption is equal to or greater than fisheries removals, has a distinct pattern/trend than fisheries removals, helps scale magnitude of pop estimates	Tyrrell et al. 2011, Link & Idoine 2009, Moustahfid et al. 2009a, NEFSC 2007a, Overholtz and Link 2007, Overholtz et al. 1999	N
Model	Age Structured	Augment SS Assessment Models with Ecological Interactions	Enhanced ecological realism; common outputs as SS models	Precision vs Accuracy Uncertainty Debate in SS Assessment Context; misses other processes and dynamics	Both	Both	Estimation	Both	Y	Tactical	Usual for age/stage structured models; consumption-at-age is estimable; consumption is equal to or greater than fisheries removals, has a distinct pattern/trend than fisheries removals, helps scale magnitude of pop estimates	Tyrrell et al. 2011, Overholtz et al. 2008, Moustahfid et al. 2009b, NEFSC 2011, NEFSC 2010	N
Model	Ecological Footprints	Context for SS Assessment Models with Ecological Interactions- Usually consumption	Enhanced ecological realism, based on copious FH data	Mainly just contextual	Deterministic	Statistical	Estimation	Both	N	Heuristic	Consumption estimates are representative of the population; parameters are reasonable, esp. Beta about 0.11 based on experiments and sensitivity analyses	Tyrrell et al. 2007, NEFSC 20007b, Overholtz and Link 2007, NEFSC 2010b, DFO 2010	N

Table 1, continued. Summary of the NEFSC ecosystem models with notations of salient features.

		Main Purpose of Model	Major Strengths	Major Weaknesses	Stochastic or deterministic outputs	Analytical or Statistical	Primary model intent- simulation, estimation, scenario testing, pattern detection, etc.	Static or Dynamic	Predictions or Forecasts (Y or N)	(Tactical, Strategic, Both, Heuristic, N/A) output use wrt Mgt Advice	Major Assumptions	Reference/s	Empahsized in this Review (Y or N)
Model Class	ESAM MRMs- Environmental												
Model	S-R	Augment SS Assessment Models with Environmental Considerations	Enhanced environmental realism; common outputs as SS models	Env-Fish relationships tend to decouple; Precision vs Accuracy Uncertainty Debate in SS Assessment Context; misses other processes and dynamics	Both	Both	Estimation	Both	Y	Tactical	A stock-recruitment relationship exists and can be fitted; environmental drivers are distinct from depensation/compensation; environmental covariates imply an understood mechanism	Hare et al. 2010, Keyl & Wolff 2008	N
Model	SS Prod	Augment SS Assessment Models with Environmental Considerations	Enhanced environmental realism; common outputs as SS models	Env-Fish relationships tend to decouple; Precision vs Accuracy Uncertainty Debate in SS Assessment Context; misses other processes and dynamics	Both	Both	Estimation	Both	Y	Tactical	Usual for production models, esp. some equilibrium assumptions; environmental covariates imply an understood mechanism; environmental covaraties provide distinct pattern/trend in addition to fisheries	Keyl & Wolff 2008	N
Model	Age Structured	Augment SS Assessment Models with Environmental Considerations	Enhanced environmental realism; common outputs as SS models	Env-Fish relationships tend to decouple; Precision vs Accuracy Uncertainty Debate in SS Assessment Context; misses other processes and dynamics	Both	Both	Estimation	Both	Y	Tactical	Usual for age/stage structured models; environmental covariates imply an understood mechanism; environmental covaraties provide distinct pattern/trend in addition to fisheries	Keyl & Wolff 2008	N

Table 1, continued. Summary of the NEFSC ecosystem models with notations of salient features.

			Main Purpose of Model	Major Strengths	Major Weaknesses	Stochastic or deterministic outputs	Analytical or Statistical	Primary model intent- simulation, estimation, scenario testing, pattern detection, etc.	Static or Dynamic	Predictions or Forecasts (Y or N)	(Tactical, Strategic, Both, Heuristic, N/A) output use wrt Mgt Advice	Major Assumptions	Reference/s	Empahsized in this Review (Y or N)
Model Class	Mutlispecies MRMs													
	Model	MS PROD	Simulate BRPs for multiple SS that include various interactions-Ecological	Enhanced ecological realism; common outputs as SS models	Precision vs Accuracy Uncertainty Debate in SS Assessment Context	Both	Analytical	Simulation	Dynamic	Y	Both	Prey switching is always possible: no feedback on predator abundance by prey; group and system carrying capacities can be exceeded given unrealistic parameterization; functional form of spp interactions is loosely Lotka-volterra and fishing is linear	Gamble and Link 2009	Y
	Model	MSYPR	Estimate BRPs for multiple SS that include various interactions-Technical	Enhanced ecological realism; common outputs as SS models	Precision vs Accuracy Uncertainty Debate in SS Assessment Context; can miss other processes and dynamics	Deterministic	Analytical	Estimation	Dynamic	N	Both	Stock-recruitment relationships exist and can be estimated; technical interactions are consistent across gears	Murawski 1984	N
	Model	MVTS-Gompertz	Nonlinear, Non parameteric estimate BRPs for multiple SS that include various interactions-Ecological	Enhanced ecological realism; minimal statistical assumptions; common outputs as SS models	Precision vs Accuracy Uncertainty Debate in SS Assessment Context; can miss other processes and dynamics	Stochastic	Statistical	Estimation	Dynamic	Y	Tactical	Intrinsically linear dynamics	Fogarty and Liu in prep.	Y
	Model	MS SPMW	Estimate BRPs for multiple SS that include various interactions-Ecological	Enhanced ecological realism; common outputs as SS models	Precision vs Accuracy Uncertainty Debate in SS Assessment Context; can miss other processes and dynamics	Both	Analytical	Estimation	Dynamic	Y	Tactical	Usual for production models, esp. some equilibrium assumptions; ecological interactions have a distinct pattern/trend than fisheries removals, helps scale magnitude of pop estimates	Link et al. 2010, Mueter & Bohyaboy & Bundy et al. unpubl. data	Y
	Model	MSVPA-X	Estimate BRPs for multiple SS that include various interactions-Ecological	Enhanced ecological realism; common outputs as SS models	Precision vs Accuracy Uncertainty Debate in SS Assessment Context; can miss other processes and dynamics	Both	Statistical	Estimation	Dynamic	Y	Both	Usual for age/stage structured models; feeding sub-model assumes functional form of Type II or III functional response; selectivity of prey is primarily size-based, but with some type preferance; mortalities are separable across fleets and predators; consumption helps scale magnitude of pop estimates	Tyrrell et al. 2008, Garrison et al. 2010, NEFSC 2006, Garrison and Link 2004, White et al. 2003	N

Table 1, continued. Summary of the NEFSC ecosystem models with notations of salient features.

		Main Purpose of Model	Major Strengths	Major Weaknesses	Stochastic or deterministic outputs	Analytical or Statistical	Primary model intent- simulation, estimation, scenario testing, pattern detection,	Static or Dynamic	Predictions or Forecasts (Y or N)	(Tactical, Strategic, Both, Heuristic, N/A) output use wrt Mgt Advice	Major Assumptions	Reference/s	Empahsized in this Review (Y or N)
Model Class	Aggregate Production												
Model	AggPROD v of MS PROD	Simulate BRPs for Aggregate Groupings	Aggregate Properties Conserved, Simple Data Needs, Scenario Testing; common outputs as SS models	Amalgamating across spp may obfuscate life history factors	Both	Analytical	Simulation	Dynamic	Y	Tactical	Prey switching is always possible: no feedback on predator abundance by prey; aggregate properties of groups do not overly amalgamate spp information	Gamble and Link 2009, Link 2003	Y
Model	ASP-SPMW	Estimate BRPs for Aggregate Groupings	Aggregate Properties Conserved, Simple Data Needs, Scenario Testing; common outputs as SS models	Amalgamating across spp may obfuscate life history factors	Both	Statistical	Estimation	Static	N	Tactical	Usual for production models, esp. some equilibrium assumptions; covariates help scale magnitude of pop estimates; aggregate properties of groups do not overly amalgamate spp information	Mueter and Megrey 2006, Link et al. 2010	Y
Model	ASP-SPMW-Dynamic	Estimate BRPs for Aggregate Groupings	Aggregate Properties Conserved, Simple Data Needs, Scenario Testing; common outputs as SS models	Amalgamating across spp may obfuscate life history factors	Both	Analytical	Estimation	Dynamic	Y	Tactical	Covariates help scale magnitude of pop estimates; aggregate properties of groups do not overly amalgamate spp information; no equilibrium assumptions	Bohaboy et al. unpubl. data, Link et al. 2010	Y
Model	Agg v of ASPIC	Estimate BRPs for Aggregate Groupings	Aggregate Properties Conserved, Simple Data Needs, Scenario Testing; common outputs as SS models	Amalgamating across spp may obfuscate life history factors	Both	Analytical	Estimation	Dynamic	Y	Tactical	Usual for production models, esp. some equilibrium assumptions; covariates help scale magnitude of pop estimates; aggregate properties of groups do not overly amalgamate spp information	Overholtz et al. 2008	Y
Model	Agg Mod - Overholtz/SAS	Estimate BRPs for Aggregate Groupings	Aggregate Properties Conserved, Simple Data Needs, Scenario Testing; common outputs as SS models	Amalgamating across spp may obfuscate life history factors	Both	Statistical	Estimation	Dynamic	N	Tactical	Usual for production models, esp. some equilibrium assumptions; covariates help scale magnitude of pop estimates; aggregate properties of groups do not overly amalgamate spp information	Overholtz et al. unpubl. Data	Y
Model	Agg Testing of MS PROD	Simulate BRPs for Aggregate Groupings	Aggregate Properties Conserved, Scenario Testing; common outputs as SS models	Amalgamating across spp may obfuscate life history factors	Stochastic	Analytical	Simulation	Dynamic	Y	Heuristic	Underlying dynamics of MS-PROD are able to be amalgamated into different groups; some equilibrium assumptions; mainly minimal as a similulator	Gaichas, Fogarty et al. unpubl. data	N

Table 1, continued. Summary of the NEFSC ecosystem models with notations of salient features.

		Main Purpose of Model	Major Strengths	Major Weaknesses	Stochastic or deterministic outputs	Analytical or Statistical	Primary model intent- simulation, estimation, scenario testing, pattern detection, etc.	Static or Dynamic	Predictions or Forecasts (Y or N)	(Tactical, Strategic, Both, Heuristic, N/A) output use wrt Mgt Advice	Major Assumptions	Reference/s	Empahsized in this Review (Y or N)
Model Class	Energy Transfers (TL transfer, food web, network, etc.)												
Model	Linear Production Potential	Estimate Fishery Production Potential	Aggregate Properties Conserved	Amalgamating across spp may obfuscate life history factors	Deterministic	Statistical	Pattern Detection	Static	N/A	Heuristic	Static transfer efficiencies across TLs; amalgamated properties within TL; catches distributed precisely across TL; PP estimable and partionable among new and recycled	Fogarty et al. 2008, NEFSC 2008	Y
Model	Stochastic Production Potential	Estimate Fishery Production Potential	Aggregate Properties Conserved	Amalgamating across spp may obfuscate life history factors	Stochastic	Statistical	Estimation	Static	Y	Tactical	Variable transfer efficiencies across TLs; amalgamated properties within TL; catches distributed precisely across TL; PP estimable and partionable among new and recycled	Fogarty et al. unpubl. data, Fogarty et al. 2008	Y
Model	Ecopath	Estimate Fishery Production Potential; Network Structure	User Friendly, good balancing tools	Too user friendly, hard to tell when balancing complete	Deterministic	Analytical	Estimation	Static	N/A	Strategic	Mass balance constraint; equilibrium assumption; vital rates germane as amalgamated across groups; transfers among groups reasonable estimatable/verifiable; balancing based off of multiple criteria here, not just EE	Link et al. 2006, 2008a, 2008b, 2009, Gaichas et al. 2009, Link 2010, Byron et al. in press; Walters et al. 1997; Christensen and Pauly 1992	Y
Model	Econetwrk	Estimate Fishery Production Potential; Network Structure	User Friendly, good balancing tools	Too user friendly, hard to tell when balancing complete	Deterministic	Analytical	Estimation	Static	N/A	Strategic	Mass balance constraint; equilibrium assumption; vital rates germane as amalgamated across groups; transfers among groups reasonable estimatable/verifiable; balancing based off of multiple criteria here, not just R/B	Link et al. 2006, 2008a, 2008b, 2009; Ulanowicz 2004	Y
Model	GOMAGG	Estimate Fishery Production Potential; Network Structure	Flexible/adaptable to myriad scenarios; based upon tuned networks	Not user friendly, assumptions on donor control not widely used in fisheries	Deterministic	Analytical	Simulation	Dynamic	Y	Strategic	Mass balance constraint; donor-controlled dynamics; vital rates germane as amalgamated across groups; transfers among groups reasonable estimatable/verifiable	Overholtz & Link 2009	N
Model	Topological Webs	Explore food web structure	Presence or absence needed; based on FH copious data	Not widely used nor applicable as DSS in fisheries	Deterministic	Statistical	Pattern Detection	Static	N/A	N/A	Linkages among groups detectable; network structure representative	Link et al. 2005, Link 2002, Link 1999	N

Table 1, continued. Summary of the NEFSC ecosystem models with notations of salient features.

			Main Purpose of Model	Major Strengths	Major Weaknesses	Stochastic or deterministic outputs	Analytical or Statistical	Primary model intent-simulation, estimation, scenario testing, pattern detection, etc.	Static or Dynamic	Predictions or Forecasts (Y or N)	(Tactical, Strategic, Both, Heuristic, N/A) output use wrt Mgt Advice	Major Assumptions	Reference/s	Empahsized in this Review (Y or N)
Model Class	Full System													
	Model	Atlantis	Simulate E2E full marine ecosystem	Flexible/adaptable to myriad scenarios; able to handle multiple processes, factors, and functional forms; highly modular; very inclusive	Not user friendly; very onerous to parameterize, initialize, and calibrate	Both	Analytical	Simulation, Scenario Testing	Dynamic	Y	Strategic	An entire ecosystem can modeled concurrently; myriad processes have multiple functional forms and these can be aptly chosen; many for each specific process being modeled	Link et al. 2010, Fulton et al. in press, Link et al. in press, Fulton et al. 2004	Y
Model Class	Misc													
	Model	AAC	Estimate alpha ijs (spp interaction terms)	Addresses a commonly needed but hard to estimate parameter	Requires inputs that may not be extant	N/A	N/A	Calculate Parameters	Static	N/A	N/A	Growth rate, clearance rate/handling time, assimilation efficiency & consumption rate all have requisite info avaible and are estimable; assumes a Type II functional response of feeding, with variable forms available but harder to calculate	Gamble & Link unpubl. data	N
	Model	Donut Selectivity Model	Estimate diet composition	Estimates DC based on 1st principles; surprisingly accurate; simple to use	Only gives selectivity if no prey field relative abunance available	N/A	N/A	Calculate Parameters	Static	N/A	N/A	Just provides preference in absence of ambient prey field (relative proportion); underlying framework based off of Hollings components of predation	Link 2004, Link & Keen 1999	N
	Model	PSA	Determine susceptibility of biota; DSS	Straightforward ranking	Overly simplistic rankings or categories can lead towards scores tending towards central estimates	Deterministic	N/A	Estimation	Static	N/A	Strategic	Risk, susceptability, and productivity can be deconstructed into salient, component features; there is enough contrast among spp to delinate levels of risk; the ranking categories are sufficient to detect risk	Patrick et al. 2010, 2009	N
	Model	LeMans	Simulate size (length) structure of food web	Explores dynamics based on size structure	Missing other dynamics	Deterministic	Analytical	Simulation	Dynamic	Y	Heuristic	Dynamics of a fish community are driven largely by size of spp; else minimal as a simulating tool	Hall et al. 2006	N
	Model	Size Spectra	Estimate size structure of food web	Based on copious data; Explores size structure	Missing other dynamics	Deterministic	Statistical	Pattern Detection	Static	N/A	Heuristic	Decay of abunance with size is due to known mechanisms; change in rate/slope represents perturbations; slope is robust in aquatic ecosystems	Methratta & Link 2006, Link 2005	N

Table 1, continued. Summary of the NEFSC ecosystem models with notations of salient features.

		Main Purpose of Model	Major Strengths	Major Weaknesses	Stochastic or deterministic outputs	Analytical or Statistical	Primary model intent-simulation, estimation, scenario testing, pattern detection, etc.	Static or Dynamic	Predictions or Forecasts (Y or N)	(Tactical, Strategic, Both, Heuristic, N/A) output use wrt Mgt Advice	Major Assumptions	Reference/s	Empahsized in this Review (Y or N)
Model Class	Misc												
Model	CCA/CanCorr	MV Statistics to explore relationships among response & explantory variables	Based on copious data	Usual MV statistical assumptions	Deterministic	Statistical	Pattern Detection	Static	Y	N/A	MV normality and linearity; minimal collinearity and redundancy; statistically significant canonical relationships not necessarily causal	Link et al. 2002, Link et al. 2009a	N
Model	DFA/MAFA	MV TS Statistics to explore relationships among response & explantory variables	Based on copious data	Usual MV statistical assumptions	Deterministic	Statistical	Pattern Detection	Static	Y	N/A	MV normality; minimal collinearity and redundancy; signicant canonical time series combined represent common responses, but not necessarily causal from covariates	Nye et al. 2009, Shackell et al. unpubl. data, Link et al. 2009b	N
Model	PCA/MDS	MV Statistics to explore relationships among variables	Based on copious data	Usual MV statistical assumptions	Deterministic	Statistical	Pattern Detection	Static	N	N/A	MV normality and linearity for PCA, more robust for non-parametric MDS; minimal collinearity and redundancy; fairly robutst methods to detect patterns	Link et al. 2002, Methratta & Link 2006	N

Table 2. NEFSC ecosystem models as typically applied to common objectives for use.

		Production Potential				*Delineate Ecosystem Overfishing*				*Enhance SS Advice*				*Evaluate Tradeoffs Among*			*MSE*		*Multisector Use*				*Other*
		Simulation	Estimation of MS MSY & other BRPs	Estimation of Agg MSY & other BRPs	Estimation of Systemic MSY & other BRPs	Simulation	Testing Thresholds and Limits	Estimate BRPs	Scenario Testing	M2	Env	Adjust ACLs	Context/Informative	Species	Fleets	Management Options	Operating Model	Scenario Testing	Evaluate Tradeoffs across sectors	MSP	Thresholds	Risk Analysis	Other
Model Class	ESAM MRMs- Ecology																						
Model	S-R									x		x	x										
Model	SS Prod									x		x	x										
Model	Age Structured									x		x	x										
Model	Ecological Footprints											x	x										
Model Class	ESAM MRMs- Environmental																						
Model	S-R										x	x	x										
Model	SS Prod										x	x	x										
Model	Age Structured										x	x	x										
Model Class	Mutlispecies MRMs																						
Model	MS PROD	x	x	x	x	x			x	x	x	x		x			x	x					
Model	MSYPR		x						x				x		x		x	x					
Model	MVTS-Gompertz		x							x		x	x	x			x						
Model	MS SPMW		x							x	x	x	x	x			x						
Model	MSVPA-X								x	x		x	x	x			x						
Model Class	Aggregate Production																						
Model	AggPROD v of MS PROD	x		x	x	x	x		x								x	x					
Model	ASP-SPMW			x	x		x	x					x				x						
Model	ASP-SPMW-Dynamic			x	x		x	x	x				x				x						
Model	Agg v of ASPIC			x	x		x	x	x				x				x						
Model	Agg Mod - Overholtz/SAS			x	x		x	x					x				x						
Model	Agg Testing of MS PROD	x		x	x	x	x		x								x	x					

Table 2, continued. NEFSC ecosystem models as typically applied to common objectives for use.

			Production Potential				*Delineate Ecosystem Overfishing*				*Enhance SS Advice*				*Evaluate Tradeoffs Among*			*MSE*		*Multisector Use*				*Other*
			Simulation	Estimation of MS MSY & other BRPs	Estimation of Agg MSY & other BRPs	Estimation of Systemic MSY & other BRPs	Simulation	Testing Thresholds and Limits	Estimate BRPs	Scenario Testing	M2	Env	Adjust ACLs	Context/Informative	Species	Fleets	Management Options	Operating Model	Scenario Testing	Evaluate Tradeoffs across sectors	MSP	Thresholds	Risk Analysis	Other
Model Class	Energy Transfers (TL transfer, food web, network, etc.)																							
	Model	Linear Production Potential			x	x								x										
	Model	Stochastic Production Potential			x	x				x				x	x			x	x					
	Model	Ecopath		x	x	x				x				x	x			x	x					
	Model	Econetwrk		x	x	x				x				x	x			x	x					
	Model	GOMAGG	x	x	x		x			x				x	x			x	x					
	Model	Topological Webs																						
Model Class	Full System																							
	Model	Atlantis	x		x	x	x	x		x				x	x	x	x	x	x	x	x	x	x	
Model Class	Misc																							
	Model	AAC																						x
	Model	Donut Selectivity Model																						x
	Model	PSA												x						x		x	x	
	Model	LeMans								x														
	Model	Size Spectra						x		x														
	Model	CCA/CanCorr																		x		x		x
	Model	DFA/MAFA																		x		x		x
	Model	PCA/MDS																		x		x		x

Table 3. The major parameters and input required to initialize and execute the ecological class Extended Stock Assessment Models (ESAM), with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	ESAM MRMs-Ecology								
	Model	S-R							
		Required Inputs			N				In NEUS, usually 40+ yrs (1963-present)
		R	Vector of Recruits	D		biomass or #	Survey data, age data	Y	
		SSB	Vector of Spawning Stock Biomass	D		biomass or #	Survey data, Age data, Landings data	Y	
		various	any covariates	D		variable	food habits data, NEUS FW Models	variable	
		Required Parameters	depending upon funcitonal form:						
		α_{ij}	scalar	S		unitless	dervied	N	
		β_{ij}	Exponential modifier	S		unitless	dervied	N	
		γ_{ij}	Exponential modifier for covariates	S		unitless	dervied	N	
		$F_{xx\%}$	Fishing Mortality	S		rate, B per yr	dervied	Y	
		optional βs	covariates	S		unitless	various	N	

Table 3, continued. The major parameters and input required to initialize and execute the ecological class Extended Stock Assessment Models (ESAM), with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	ESAM MRMs-Ecology								
	Model	SS Prod							
		Required Inputs			N				In NEUS, usually 40+ yrs (1963-present)
		B	Vector of biomass	D		Biomass (e.g. mt)	Survey data	Y	
		L	Vector of landings (or catch)	D		Biomass (e.g. mt)	Landings data	Y	
		various	covariates	D		variable	food habits data, NEUS FW Models	Y	
		Required Parameters							
		r (derives Fmsy)	exponential rate of growth	S		rate, B per yr	derived	Y	
		K (derives Bmsy)	carrying capacity	S		biomass	derived	Y	
		optional βs	other tuning measures, associated with covariates	S		unitless	food habits data, NEUS FW Models, derived	Y	

Table 3, continued. The major parameters and input required to initialize and execute the ecological class Extended Stock Assessment Models (ESAM), with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	ESAM MRMs-Ecology								
	Model	Age Structured			N				In NEUS, usually 40+ yrs (1963-present)
		Required Inputs							
		$\mathbf{N}_{i,a}$	Matrix of N	D		#	Survey data, age data	Y	
		$\mathbf{B}_{i,a}$	Matrix of B	D		biomass	Survey data, age data	Y	
		$\mathbf{W}_{i,a}$	Wt-at-age	S		biomass	Survey data, age data	Y	
		$\mathbf{O}_{i,a}$	Age-at-matruity	S		year	Survey data, age data	Y	
		$\mathbf{C}_{i,a}$	Catch-at-age	D		biomass	Landings data, age data	Y	
		various	covariates, usually in matrices at age	D		various	food habits data, NEUS FW Models	variable	
		Required Parameters							
		q, λ	Selectivity & Catchability	S		unitless	Survey data, model dervied	N	
		g	Growth between ages; in some forms	S		unitless	Age data	Y	
		F	Total Fishing Mortality	S		unitless	derived	Y	
		M2	Total Predation Mortality	S		unitless	derived	Y	
		M1	Total other Natural Mortality	S		unitless	derived	N	
		optional βs	covariates	S		unitless	derived	varies	

Table 3, continued. The major parameters and input required to initialize and execute the ecological class Extended Stock Assessment Models (ESAM), with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	ESAM MRMs-Ecology								
	Model	Ecological Footprints			N				In NEUS, usually ~40 yrs (1973-present)
		Required Inputs							
		B_i	biomass or abundance of predator	D		biomass	Survey data	Y	
		C_i	consumption of predator	D		biomass per yr	food habits data, NEUS FW Models	Y	
		L_i	landings or catch of predator	D		biomass per yr	Landings data	Y	
		length	size structure of predator	both		cm	Age data, survey data	Y	
		S_i	mean stomach contents	D		biomass	food habits data	Y	
		Required Parameters							
		α_{ij}	scalar	S		unitless	derived, Literature	N	
		β_{ij}	Exponential modifier	S		unitless	derived, Literature	N	

Table 3, continued. The major parameters and input required to initialize and execute the ecological class Extended Stock Assessment Models (ESAM), with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	ESAM MRMs-Ecology								
	Model	Ecological Footprints			N				In NEUS, usually ~40 yrs (1973-present)
		Required Inputs							
		B_i	biomass or abundance of predator	D		biomass	Survey data	Y	
		C_i	consumption of predator	D		biomass per yr	food habits data, NEUS FW Models	Y	
		L_i	landings or catch of predator	D		biomass per yr	Landings data	Y	
		length	size structure of predator	both		cm	Age data, survey data	Y	
		S_i	mean stomach contents	D		biomass	food habits data	Y	
		Required Parameters							
		α_{ij}	scalar	S		unitless	derived, Literature	N	
		β_{ij}	Exponential modifier	S		unitless	derived, Literature	N	

Table 4. The major parameters and input required to initialize and execute the environmental class Extended Stock Assessment Models (ESAM), with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	ESAM MRMs-Environmental								
	Model	S-R							
		Required Inputs			N				In NEUS, usually 40+ yrs (1963-present)
		R	Vector of Recruits	D		biomass or #	Survey data, age data	Y	
		SSB	Vector of Spawning Stock Biomass	D		biomass or #	Survey data, age data	Y	
		various	any covariates	D		variable	Oceanographic data, Climatological data	variable	
		Required Parameters	depending upon funcitonal form:						
		α_{ij}	scalar	S		unitless	derived	N	
		β_{ij}	Exponential modifier	S		unitless	derived	N	
		γ_{ij}	Exponential modifier for covariates	S		unitless	derived	N	
		$F_{xx\%}$	Fishing Mortality	S		rate, B per yr	derived	Y	
		optional βs	covariates	S		unitless	derived	N	

Table 4, continued. The major parameters and input required to initialize and execute the environmental class Extended Stock Assessment Models (ESAM), with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	ESAM MRMs-Environmental								
	Model	SS Prod							
		Required Inputs		usually time series	N				In NEUS, usually 40+ yrs (1963-present)
		B	Vector of biomass	D		Biomass (e.g. mt)	Survey data	Y	
		L	Vector of landings (or catch)	D		Biomass (e.g. mt)	Landings data	Y	
		various	covariates	D		variable	Oceanographic data, Climatological data	varies	
		Required Parameters							
		r (derives Fmsy)	exponential rate of growth	S		rate, B per yr	derived	Y	
		K (derives Bmsy)	carrying capacity	S		biomass	derived	Y	
		optional βs	other tuning measures, associated with covariates	S		unitless	derived	varies	

Table 4, continued. The major parameters and input required to initialize and execute the environmental class Extended Stock Assessment Models (ESAM), with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	ESAM MRMs-Environmental								
	Model	Age Structured			N				In NEUS, usually 40+ yrs (1963-present)
		Required Inputs							
		$\mathbf{N_{i,a}}$	Matrix of N	D		#	Survey data, age data	Y	
		$\mathbf{B_{i,a}}$	Matrix of B	D		biomass	Survey data, age data	Y	
		$\mathbf{W_{i,a}}$	Wt-at-age	S		biomass	Survey data, age data	Y	
		$\mathbf{O_{i,a}}$	Age-at-matruity	S		year	Survey data, age data	Y	
		$\mathbf{C_{i,a}}$	Catch-at-age	D		biomass	Landings data, age data	Y	
		various	covariates, usually in matrices at age	D		various	Oceanographic data, Climatological data	varies	
		Required Parameters							
		q, λ	Selectivity & Catchability	S		unitless	Survey data, model dervied	N	
		g	Growth between ages; in some forms	S		unitless	Age data	Y	
		F	Total Fishing Mortality	S		unitless	derived	Y	
		M2	Total Predation Mortality	S		unitless	derived	Y	
		M1	Total other Natural Mortality	S		unitless	derived	N	
		optional βs	covariates	S		unitless	derived	varies	

Table 5. The major parameters and input required to initialize and execute the multispecies class of Minimal Realistic Models (MRM), with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Multispecies MRMs								
	Model	MS PROD			N				Variable, is a simulator, but typically 1963-2010; 30-50 yr runs
		Required Inputs							
		N_i	Biomass or abundance of each stock, i.	D		biomass or #	Survey data	N	
		S_{ij}	Spatial overlap between each pair of stocks, i and j.	S		unitless	Survey data	N	
		PelDem	Pelagic or demersal designation	S		unitless	Survey data	N	
		Required Parameters							
		r_i	Growth rate for each stock, i.	S		unitless	Survey data, age data, Assessment models	Y (if stochasticity used)	
		K_g	Carrying capacities for each guild, g.	S		biomass or #, usually mt	Survey data, Assessment models	N	
		K_s	System carrying capacity	S		biomass or #, usually mt	Survey data, Assessment models	N	
		α_{ij}	Predation interaction strength between each predator, j, and prey, i.	S		unitless	food habits data, Literature	N	
		β_{ig}	Between guild competition coefficients of each guild g on each individual stock i within a specific guild.	S		unitless	Food habits data, Literature	N	
		β_{ij}	Within guild competition coefficients between each pair of stocks I and j	S		unitless	Food habits data, Literature	N	

Table 5, continued. The major parameters and input required to initialize and execute the multispecies class of Minimal Realistic Models (MRM), with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Multispecies MRMs								
	Model	MSYPR			N				In NEUS, usually 40+ yrs (1963-present)
		Required Inputs							
		R	Vector of Recruits	D		biomass or #	Survey data, age data	Y	
		SSB	Vector of Spawning Stock Biomass	D		biomass or #	Survey data, age data	Y	
		various	gear types	S		variable	Landings data, economic data	varies	
		Required Parameters							
		α_{ij}	scalar	S		unitless	derived	N	
		β_{ij}	Exponential modifier	S		unitless	derived	N	
		γ_{ij}	Exponential modifier for covariates	S		unitless	derived	N	
		various	interaction coefficient	S		rate, B per yr	derived	N	
		q, λ	Selectivity & Catchability	S		unitless	derived, survey data, landings data	N	
		$F_{xx\%}$	Fishing Mortality	S		unitless	derived	Y	

Table 5, continued. The major parameters and input required to initialize and execute the multispecies class of Minimal Realistic Models (MRM), with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Multispecies MRMs								
	Model	MVTS-Gompertz			N				In NEUS, usually 40+ yrs (1963-present)
		Required Inputs							
		Abundance Estimates				Biomass	survey data	Y	
		Catch or Fishing Effort				Biomass or DAS	landings data	Y	
		Environmental Data				various	various	Y	
		Required Parameters							
		β_{ij}	elements of intercept vector			unitless	derived	N	
		α_{ij}	elements of transition matrix			unitless	derived	N	
		γ_{ij}	elements of covariate vector			unitless	derived	N	

Table 5, continued. The major parameters and input required to initialize and execute the multispecies class of Minimal Realistic Models (MRM), with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Multispecies MRMs								
	Model	MS SPMW							
		Required Inputs			N				In NEUS, usually 40+ yrs (1963-present)
		B_i	Vector of biomass	D		Biomass (e.g. mt)	Survey data	Y	
		L_i	Vector of landings (or catch)	D		Biomass (e.g. mt)	Landings data	Y	
		various	covariates	D		variable	various	varies	
		Required Parameters							
		r (derives Fmsy)	exponential rate of growth	S		rate, B per yr	derived	Y	
		K (derives Bmsy)	carrying capacity	S		biomass	derived	Y	
		α_{ij}	Ecological interaction coefficient between each predator, j, and prey, i.	S		unitless	food habits data	N	
		optional βs	other tuning measures, associated with covariates	S		unitless	derived	varies	

Table 5, continued. The major parameters and input required to initialize and execute the EMs, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Multispecies MRMs								
	Model	MSVPA-X							
		Required Inputs			N				In NEUS, usually 40+ yrs (1963-present); 1973-2002 typical/latest
		$\mathbf{N_{i,a}}$	Matrix of N	D		#	Survey data, age data	Y	
		$\mathbf{B_{i,a}}$	Matrix of B	D		biomass	Survey data, age data	Y	
		$\mathbf{W_{i,a}}$	Wt-at-age	S		biomass	Survey data, age data	Y	
		$\mathbf{O_{i,a}}$	Age-at-matruity	S		year	Survey data, age data	Y	
		$\mathbf{L_{i,a}}$	Catch-at-age	D		biomass	Landings data, age data	Y	
		$C_{i,j,a}$	Consumption	D		biomass per yr	food habits data	Y	
		$\nu_{i,j,a}$	vulnerability/suitability	S		unitless	food habits data	N	
		S_i	Stomach contents	D		biomass	food habits data	Y	
		SO_{ij}	Spatial overlap between each pair of stocks, i and j.	S		unitless	Survey overlap matrix	N	
		AB	altnerate prey biomass	S		biomass	Survey data, process studies, NEUS FW Models	N	
		w_{ij}	pred/prey wt ratio	S		unitless	food habits data	N	
		various	covariates, usually in matrices at age	D		various	Oceanographic data, Climatological data	varies	

Table 5, continued. The major parameters and input required to initialize and execute the multispecies class of Minimal Realistic Models (MRM), with notations of the major structural features.

	Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Required Parameters							
q, λ	Selectivity & Catchability	S		unitless	Survey data, model dervied	N	
g	Growth between ages; in some forms	S		unitless	Age data	Y	
F	Total Fishing Mortality	S		unitless	derived	Y	
M2	Total Predation Mortality	S		unitless	derived	Y	
M1	Total other Natural Mortality	S		unitless	derived/set	N	
$A_{i,j,a}$	Preference/prey selectivity	S		unitless	food habits data, Literature	N	
α_{ij}	consumption scalar	S		unitless	food habits data	N	
β_{ij}	Consumption Exponential modifier	S		unitless	food habits data	N	
$\eta_{ia,jb}$	size selectivity	S		unitless	food habits data	N	

note, there are other possible parameters depending upon the functional forms of the various submodels used, but these represent the major, consistently used ones across various applications of MSVPA and particularly MSVPA-X

Table 6. The major parameters and input required to initialize and execute the Aggregate Production class of models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Aggregate Production								
	Model	AggPROD v of MS PROD			N				Variable, is a simulator, but typically based on data from 1963-2010; 30-50 yr runs
		Required Inputs							
		N_i	Biomass or abundance of each group, i.	D		biomass (mt) or numbers per year	Survey data	N	
		S_{ij}	Spatial overlap between each pair of stocks, i and j.	S		unitless	Survey data	N	
		PelDem	Pelagic or demersal designation	S		unitless proportion (usually 1 or 0)	Survey data	N	
		Required Parameters							
		r_i	Growth rate for each stock, i.	S		unitless	Survey data, age data, Assessment models	Y (if stochasticity used)	
		K_g	Carrying capacities for each guild, g.	S		biomass (mt) or numbers	Survey data, Assessment models	N	
		K_s	System carrying capacity	S		biomass (mt) or numbers	Survey data, Assessment models	N	
		α_{ij}	Aggregate predation interaction strength between each predator guild, j, and prey guild, i.	S		unitless	Food habits data, Literature	N	
		β_{ij}	Between guild competition coefficients of each guild j on each guild i.	S		unitless	Food habits data, Literature	N	

Table 6, continued. The major parameters and input required to initialize and execute the Aggregate Production class of models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Aggregate Production								
	Model	ASP-SPMW							
		Required Inputs			N				In NEUS, usually 40+ yrs (1963-present)
		B_i	Aggregated Biomass Indices/Time Series; Needs to be combined across spp, usually in absolute but can be in relative terms of an index	D		Biomass	Survey data	Usually Not, but can be	
		L_i	Aggregated Landings Time Series; Needs to be combined across spp	D		Biomass per year	Landings data	Usually Not, but can be	
		various	Optional Environmental or Ecological Covariates; e.g., AMO, NAO, SST, Predator Biomass	D		Various, may be as anomalies	variable; Oceanographic data, Climatological data, food habits data	Usually Not, but can be	
		Required Parameters							
		r	growth rate	S		Biomass per year	derived	N	
		K	carrying capacity	S		Biomass	derived	N	
		optional βs	covariates	S		variable	derived	N	

Table 6, continued. The major parameters and input required to initialize and execute the Aggregate Production class of models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Aggregate Production								
	Model	ASP-SPMW-Dynamic							
		Required Inputs			N				In NEUS, usually 40+ yrs (1963-present)
		B_i	Aggregated Biomass Indices/Time Series; Needs to be combined across spp, usually in absolute but can be in relative terms of an index	D		Biomass	Survey data	Y	
		L_i	Aggregated Landings Time Series; Needs to be combined across spp	D		Biomass per year	Landings data	Y	
		various	Optional Environmental or Ecological Covariates; e.g., AMO, NAO, SST, Predator Biomass	D		may be as anomalies	variable; Oceanographic data, Climatological data, food habits data	varies	
		Required Parameters							
		r	growth rate	D		Biomass per year	derived	Y	
		K	carrying capacity	D		Biomass	derived	Y	
		optional βs	covariates	D		variable	derived	Y	

Table 6, continued. The major parameters and input required to initialize and execute the Aggregate Production class of models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Aggregate Production								
	Model	Agg v of ASPIC							
		Required Inputs			N				In NEUS, usually 40+ yrs (1963-present)
		B_i	Aggregated Biomass Indices/Time Series; Needs to be combined across spp, usually in absolute but can be in relative terms of an index	D		Biomass	Survey data	Usually Not, but can be	
		L_i	Aggregated Landings Time Series; Needs to be combined across spp	D		Biomass per year	Landings data	Usually Not, but can be	
		various	Optional Environmental or Ecological Covariates; e.g., AMO, NAO, SST, Predator Biomass	D		Various, may be as anomalies	variable; Oceanographic data, Climatological data, food habits data	Usually Not, but can be	
		Required Parameters							
		r	growth rate	S		Biomass per year	derived	Y	
		K	carrying capacity	S		Biomass	derived	Y	
		optional βs	covariates	S		variable	derived	N	

Table 6, continued. The major parameters and input required to initialize and execute the Aggregate Production class of models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Aggregate Production								
	Model	Agg Mod - Overholtz/SAS							
		Required Inputs			N				In NEUS, usually 40+ yrs (1963-present)
		B_i	Aggregated Biomass Indices/Time Series; Needs to be combined across spp, usually in absolute but can be in relative terms of an index	D		Biomass	Survey data	Usually Not, but can be	
		L_i	Aggregated Landings Time Series; Needs to be combined across spp	D		Biomass per year	Landings data	Usually Not, but can be	
		various	Optional Environmental or Ecological Covariates; e.g., AMO, NAO, SST, Predator Biomass	D		varies, may be as anomalies	variable; Oceanographic data, Climatological data, food habits data	Usually Not, but can be	
		Required Parameters							
		r	growth rate	S		Biomass per year	derived	N	
		K	carrying capacity	S		Biomass	derived	N	
		optional βs	covariates	S		variable	derived	N	

Table 6, continued. The major parameters and input required to initialize and execute the Aggregate Production class of models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Aggregate Production								
	Model	Agg Testing of MS PROD			N				Variable, is a simulator, but typically based on data from 1963-2010; 30 yr runs
		Required Inputs							
		N_i	Biomass or abundance of each group, i.	D		biomass (mt) or numbers per year	Survey data	N	
		S_{ij}	Spatial overlap between each pair of stocks, i and j.	S		unitless	Survey data	N	
		PelDem	Pelagic or demersal designation	S		unitless proportion (usually 1 or 0)	Survey data	N	
		Required Parameters							
		r_i	Growth rate for each stock, i.	S		unitless	Survey data, age data, Assessment models	Y (if stochasticity used)	
		K_i	Carrying capacities for each stock, i.	S		biomass (mt) or numbers	Survey data, Assessment models	N	
		K_s	System carrying capacity	S		biomass (mt) or numbers	Survey data, Assessment models	N	
		α_{ij}	Predation interaction strength between each predator, j, and prey, i.	S		unitless	Food habits data, Literature	N	
		β_{ij}	Between stock competition coefficients of each stock i on each individual stock j.	S		unitless	Food habits data, Literature	N	

Table 7. The major parameters and input required to initialize and execute the energy transfer class of models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Energy Transfers (TL transfer, food web, network, etc.)								
	Model	Linear Production Potential			N				1997-2002
		Required Inputs							
		PP	Primary Production	S		biomass per unit area per year	Satellite Imagery, VGPM2 model	Y	1997-2002
		TL_i	Mean trophic level of the catch	S		unitless	food habits data	N	Based on data from 1973-2008
		Required Parameters							
		R	Retention Rate; Fraction of photosynthetic products retained within the system	S		unitless (proportion)	Literature	N	
		f	Fraction of new production	S		unitless	Literature, process studies, satellite imagery	N	
		TE_i	Transfer efficiencies between successive trophic levels	S		unitless (proportion)	NEUS FW Models; Literature	N	

Table 7, continued. The major parameters and input required to initialize and execute the energy transfer class of models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Energy Transfers								
	Model	Stochastic Production Potential			N				1997-2002
		Required Inputs							
		PP	Primary Production	D		biomass per unit area per year	Satellite Imagery, VGPM2 model (w/ normal distribution instead of one value)	Y	1997-2002
		TL_i	Mean trophic level of the catch	S		unitless	food habits data	Y	Based on data from 1973-2008
		Required Parameters							
		R	Retention Rate; Fraction of photosynthetic products retained within the system	S		unitless (proportion)	Literature	N	
		f	Fraction of new production	S		unitless	Literature, process studies, satellite imagery	N	
		TE_i	Transfer efficiencies between successive trophic levels	D		unitless (proportion)	NEUS FW Models; Literature (w/ Beta distribution instead of one value)	Y	

Table 7, continued. The major parameters and input required to initialize and execute the energy transfer class of models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Energy Transfers								
	Model	Ecopath			Possible, but not in NEUS				
		Required Inputs							1996-2000
		B_i	Biomass	S		biomass	Survey data, process studies	Y	
		C_i/B_i	Consumption to biomass	S		unitless	food habits data, Literature	Y	
		P_i/B_i	Production to biomass	S		unitless	Survey data, age data, Literature	Y	
		DC_{ij}	Diet composition	S		unitless	food habits data	Y	
		L_i	Landings	S		biomass per yr	Landings data	Y	
		AE_i	Assimilation efficiency	S		unitless	Literature	N	
		Required Parameters							
		EE_i	Ecotrophic effiecieny	S		unitless	derived	Y	
		Det_i	flow to detritus	S		biomass per yr	Survey data, process studies, Literature	N	
			Data pedigree	S		unitless	User Sets	Y	
		TL_i	trophic level	S		unitless	derived; food habits data	N	
		R_i/B_i	Respiration to biomass	S		unitless	Survey data, process studies, Literature	N	
		UAC_i	Unassimilated consumption	S		unitless	derived	N	
		Z_i	Total mortality	S		biomass per year; partionable	derived	N	

Table 7, continued. The major parameters and input required to initialize and execute the energy transfer class of models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Energy Transfers								
	Model	Econetwrk			N				1996-2000
		Required Inputs							
		B_i	Biomass	S		biomass	Survey data, process studies	Y	
		C_i/B_i	Consumption to biomass	S		unitless	food habits data, Literature	Y	
		P_i/B_i	Production to biomass	S		unitless	Survey data, age data, Literature	Y	
		R_i/B_i	Respiration to biomass	S		unitless	Survey data, process studies, Literature	N	
		DC_{ij}	Diet composition	S		unitless	food habits data	Y	
		L_i	Landings	S		biomass per yr	Landings data	Y	
		AE_i	Assimilation efficiency	S		unitless	Literature	N	
		Required Parameters							
		EE_i	Ecotrophic effiecieny	S		unitless	derived	Y	
		Det_i	flow to detritus	S		biomass per yr	Survey data, process studies, Literature	N	
			Data pedigree	S		unitless	User Sets	Y	
		TL_i	trophic level	S		unitless	derived; food habits data	N	
		UAC_i	Unassimilated consumption	S		unitless	derived	N	
		Z_i	Total mortality	S		biomass per year; partionable	derived	N	

Table 7, continued. The major parameters and input required to initialize and execute the energy transfer class of models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Energy Transfers								
	Model	GOMAGG			N				Variable, is a simulator, but typically based on data from 1963-2008; 20 yr runs
		Required Inputs							
		DC_{ij}	Diet composition	S		unitless	food habits data	N	
		B_i	Biomass	S		biomass	Survey data	N	
		G_{ij}	Flow of biomass	D		biomass per yr	Survey data, Landings data, food habits data, NEUS FW Models	N	
		Required Parameters							
		P_i/C_i	production to consumption rate	S		unitless	Age data, food habits data	N	
		b_k	transfer rate	S		biomass per yr	food habits data, NEUS FW models	N	
		M_i	other mortality	S		unitless	food habits data, NEUS FW models, Landings data	N	
Model Class	Energy Transfers								
	Model	Topological Webs			N				1973-1999
		Required Inputs							
		S	Number of spp	S		unitless	food habits data	N	
		L	Identifed linkages per spp (i.e., species interactions)	S		unitless	food habits data	N	
		Required Parameters							
		C	Connectivity	S		unitless	derived	N	

Table 8. The major parameters and input required to initialize and execute the full system class of models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Full System			Both, mainly dynamic	Y			Y	In NEUS, usually 40+ yrs (1964-2004 for calibration); with 10 year projections; extended runs planned
	Model	Atlantis	space prohibits all from being listed here; see Link et al. in press for a much fuller description of these input and parameter details and Link et al. 2011 for a briefer synopsis;						
			There are 45 biological groups, 18 fleets, 30 spatial boxes, 5 depth layers, 12 hr time steps, 40 yrs of time series to tune to, and 50 yr model runs; all of which has been calibrated at 4 different levels				Survey data, Age data, Landings data, food habits data, Oceanographic Data, Climatological Data, Economic Data	Y	
			Most can be loosely classed into hydrodynamic variables, physical forcing variables, biotic state variables and vital rate estimates, fleet dynamics, market drivers, and management measures						

Table 8, continued. The major parameters and input required to initialize and execute the full system class of models, with notations of the major structural features.

		Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Required Inputs								
	>1000 with age structure & w/out spatio-temporal replication							
	>200 w/out age structure w/out spatio-temporal replication							
Required Parameters								
	>8000 w/out spatio-temporal replication							

Table 9. The major parameters and input required to initialize and execute the miscellaneous models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions but	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Misc								
	Model	AAC			N				N/A; for NEUS derived from data in 1973-2004
		Required Inputs							
		DC_{ij}	Percentage of each prey as proportion of a predator's diet composition	S		Unitless (proportion)	food habits data	N	
		r_i	Growth rate	S		Unitless	Survey data, age data	N	
		N (or B)	Abundance or biomass	S		biomass (metric tons) or #	Survey data	N	
		Required Parameters							
		E_i	Assimilation Efficiency; Proportion of what predator eats that is used for growth.	S		Unitless (proportion)	Literature	N	
		C_i	Clearance rate; maximum ingestion rate by a predator, more commonly understood as handling time	S		biomass per day	food habits data	N	
		S_i	Consumption rate; derived from mean stomach contents	S		biomass per day (per unit predator biomass)	food habits data	N	

Table 9, continued. The major parameters and input required to initialize and execute the miscellaneous models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Misc								
	Model	Donut Selectivity Model			N				N/A, for NEUS based on data from 1973-1999
		Required Inputs							
		P_{ij}	relative prey abundance	S		unitless	Survey data, process studies	N	
		O_{ij}	Overlap	S		unitless	Survey data	N	
		Required Parameters							
		Rd_{ij}	Detection rank	S		rankings	1st principles, food habits data	N	
		Rr_{ij}	Reaction rank	S		rankings	1st principles, food habits data	N	
		Rc_{ij}	Capture rank	S		rankings	1st principles, food habits data	N	
		Ri_{ij}	Ingestion rank	S		rankings	1st principles, food habits data	N	
		$R1_{ij}$	"Icing" rank	S		rankings	1st principles, food habits data	N	

Table 9, continued. The major parameters and input required to initialize and execute the miscellaneous models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Misc								
	Model	PSA							
		Required Inputs-Productivity			N			Can be in form of rank certainties, but usually not	N/A; for NEUS derived from data in 1973-2006
			r, intrinsic rate of growth	S		rankings	Survey data, age data	N	
			Maximum Age	S		rankings	Survey data, age data	N	
			Maximum Size	S		rankings	Survey data, age data	N	
			von Bertalanffy Growth Coefficient (k)	S		rankings	Survey data, age data	N	
			Estimated Natural Mortality	S		rankings	food habits data	N	
			Measured Fecundity	S		rankings	Age data	N	
			Breeding Strategy	S		rankings	Age data	N	
			Recruitment Pattern	S		rankings	Survey data, age data	N	
			Age at Maturity	S		rankings	Age data	N	
			Mean Trophic Level	S		rankings	food habits data	N	

Table 9, continued. The major parameters and input required to initialize and execute the miscellaneous models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Misc								
	Model	PSA							
		Required Inputs-Susceptibility							
			Management Strategy	S		rankings	Mgt Plans, Socioeconomic data	N	
			Areal Overlap	S		rankings	Survey data, Landings data	N	
			Geographic Concentration	S		rankings	Survey data, Landings data	N	
			Vertical Overlap	S		rankings	Survey data, Landings data	N	
			Fishing rate relative to M	S		rankings	derived	N	
			Biomass of Spawners (SSB) or other proxies	S		rankings	Survey data	N	
			Seasonal Migrations	S		rankings	Survey data	N	
			Schooling/Aggregation and Other Behavioral Responses	S		rankings	Survey data	N	
			Morphology Affecting Capture	S		rankings	Survey data	N	
			Survival After Capture and Release	S		rankings	process studies, Literature	N	
			Desirability/Value of the Fishery	S		rankings	Economic data	N	
			Fishery Impact to EFH or Habitat in General for Non-targets	S		rankings	process studies, Literature	N	

Table 9, continued. The major parameters and input required to initialize and execute the miscellaneous models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Misc								
	Model	LeMans							
		Required Inputs			N				Variable, is a simulator, but set up for GB based on data from 1963-2000; ran for 25 years
		$L_{i,t}$	length	S		cm	Survey data, age data	N	
		k_i	growth rate	S		rate	Survey data, age data	N	
		S_i	Spawning stock biomass	D		biomass	Survey data, age data	N	
		R_i	recruits	D		#	Survey data, age data	N	
		$N_{i,j}$	Abundance at size	D		#	Survey data, age data	N	
		DC_{ij}	Diet composition	S		unitless	food habits data	N	
		Required Parameters							
		a_i	The intercept parameter of the length–weight relationship for species i	S		unitless	derived	N	
		b_i	The slope parameter of the length–weight relationship for species i	S		unitless	derived	N	
		$L_{\infty,i}$	Asymptotic length parameter of the von Bertalanffy growth equation	S		cm	derived	N	
		k_i	Growth parameter of the von Bertalanffy growth equation	S		rate	derived	N	

Table 9, continued. The major parameters and input required to initialize and execute the miscellaneous models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Misc								
	Model	LeMans							
		Required Parameters							
		$\phi_{i,j}$	The proportion of species i in size class j that move to the next size class in a single time step	S		unitless	Survey data, age data	N	
		α_i	Productivity parameter of the Ricker stock–recruitment equation for species i	S		unitless	derived	N	
		β_i	Density dependence parameter of the Ricker stock-recruitment equation for species i	S		biomass	derived	N	
		$S_{max,i}$	The maximum observed spawning stock biomass of species i	S		biomass	Survey data, age data	N	
		κ_i	Curvature parameter for the maturity ogive of species i	S		unitless	derived	N	
		L_{M50}	The length at which 0.5 of species i are mature	S		cm	Survey data, age data	N	
		$\omega_{i,j}$	The proportion of species i in size class j that are mature	S		unitless	Survey data, age data	N	
		$F_{i,j}$	Instantaneous rate of fishing mortality on species i in size classj	S		rate	derived	N	

Table 9, continued. The major parameters and input required to initialize and execute the miscellaneous models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Misc								
	Model	LeMans							
		φ_i	A binary variable indicating whether species i is fished	S		unitless	Landings data	N	
		F_{max}	The maximum annual fishing mortality rate for a fully recruited fish	S		unitless	derived	N	
		η	Steepness parameter for the fishing selectivity ogive	S		unitless	Survey data, age data, Landings data	N	
		L_{F50}	The length at which 0.5 selection by the fishery occurs	S		cm	Survey data, age data, Landings data	N	
		$M1_{i,j}$	Natural (nonmodelled) mortality for species i in size classj	S		rate	derived	N	
		Ψ,υ	Parameters of the beta distribution for M1	S		unitless	derived	N	
		$M2_{i,j}$	Predation mortality for species i in size classj	S		rate	derived	N	
		$\tau_{m,i}$	The preference for prey species m by predator species i	S		unitless	food habits data	N	
		$\zeta_{n,j}$	Size preference for prey of size n by predator of size j	S		unitless	food habits data	N	

Table 9, continued. The major parameters and input required to initialize and execute the miscellaneous models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Misc								
	Model	LeMans							
		$v_{i,j,m,n}$	The relative preference (suitability) for predator i of size j of prey m of size n	S		unitless	food habits data	N	
		$I_{i,j}$	The ration (ingestion rate) that must be consumed by species i in size class j to account for modeled growth in a given time step	S		biomass	food habits data	N	
		Ge_j	The growth efficiency (proportion of food consumed that is converted to body mass) of fish in size class j	S		unitless	Literature	N	

Table 9, continued. The major parameters and input required to initialize and execute the miscellaneous models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Misc								
	Model	Size Spectra			N				Variable, in NEUS usually 40+ yrs (1963-present)
		Required Inputs							
		B per size unit	biomass (or sometimes abundance)	can be both		mass or mass per unit area	Survey data, Age data, Landings data, food habits data	N	
		log of size	size bins	can be both		length, often cm or derivatives thereof	Survey data	N	
		Required Parameters							
		β	slope	S		unitless	derived	Y	
		α	intercept	S		unitless	derived	Y	
Model Class	Misc								
	Model	CCA/CanCorr/RDA			Can be, usually not				Variable, in NEUS, usually 40+ yrs (1963-present)
		Required Inputs							
		Y	Matrix of times series of various response -- usually biotic (e.g. fish abunances)-- variables	D		various	Survey data, Age data, Landings data, food habits data, Oceanographic Data, Climatological Data, Economic Data	Y	
		X	Matrix of times series of various explanatory- usually human (e.g. landings), and environmental (e.g. SST)-- variables	D		various	Survey data, Age data, Landings data, food habits data, Oceanographic Data, Climatological Data, Economic Data	Y	
		Required Parameters							
		U	Eigenvectors to establish canonical "regression"	S		unitless	derived	Y	
		Y^U	fitted canonical response	S		unitless	derived	Y	

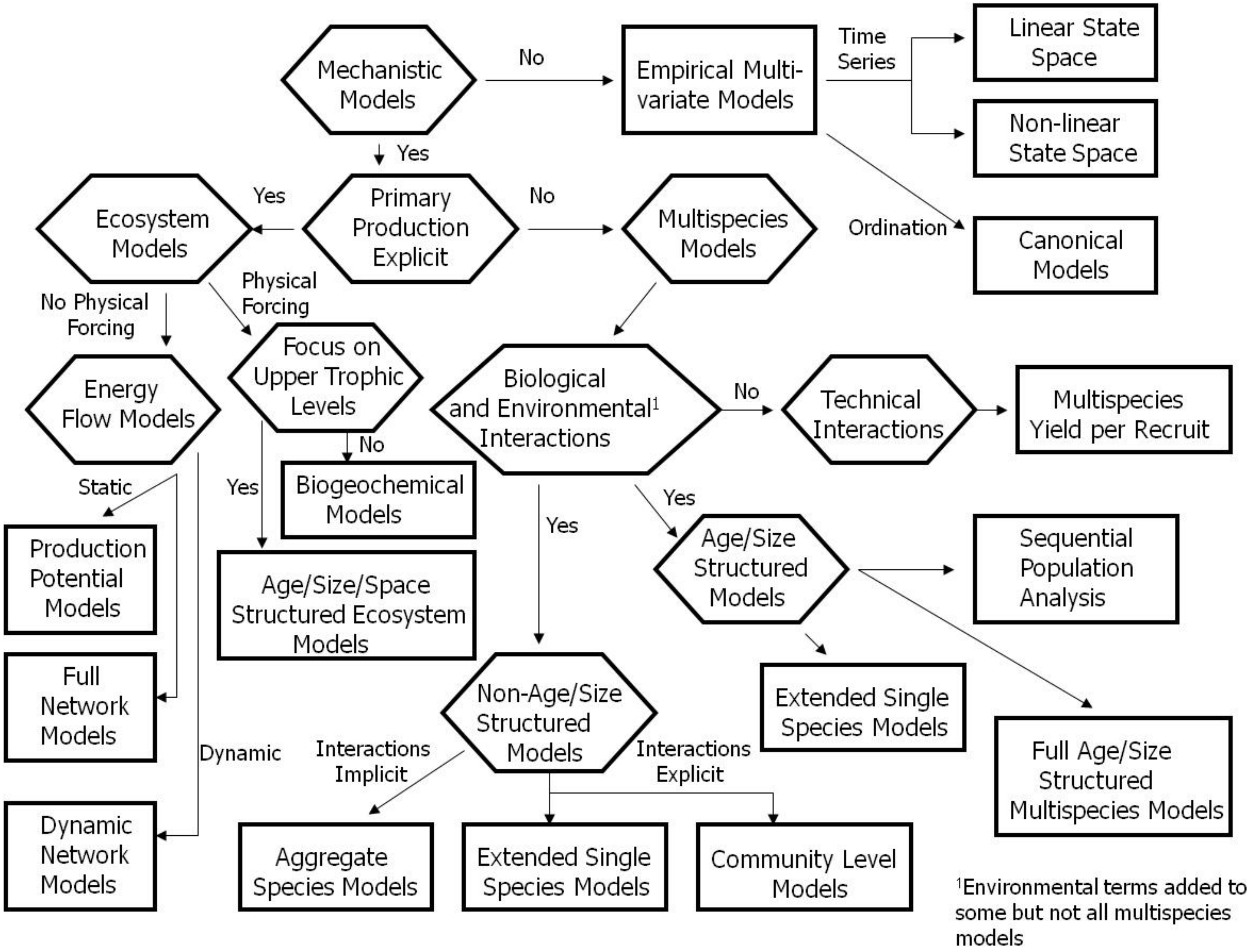
Table 9, continued. The major parameters and input required to initialize and execute the miscellaneous models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Misc								
	Model	DFA/MAFA			Can be, usually not				Variable, in NEUS, usually 40+ yrs (1963-present)
		Required Inputs							
		Y	Matrix of times series of various response -- usually biotic (e.g. fish abunances)--variables	D		various	Survey data, Age data, Landings data, food habits data, Oceanographic Data, Climatological Data, Economic Data	Y	
		X	Matrix of times series of various explanatory-usually human (e.g. landings), and environmental (e.g. SST)--variables	D		various	Survey data, Age data, Landings data, food habits data, Oceanographic Data, Climatological Data, Economic Data	Y	
		Required Parameters							
		Z_t	trend/s relating across MV time series canonical relationships	S		unitless	derived	Y	

Table 9, continued. The major parameters and input required to initialize and execute the miscellaneous models, with notations of the major structural features.

			Data description	Inputs Static (S) or Dynamic (D)	Spatially resolved (Y or N) [does not mean it is not done for different regions, but directly in the model]	units	Origin, source, or method for derivation of value	Variance incorporated (Y or N)	Timeframe for derivation of value
Model Class	Misc								
	Model	PCA/MDS			Can be, usually not				Variable, in NEUS, usually 40+ yrs (1963-present)
		Required Inputs							
		$\mathbf{A_i}$	Matrix of times series of various biotic (e.g. fish abunances), human (e.g. landings), and environmental (e.g. SST) variables	D		various	Survey data, Age data, Landings data, food habits data, Oceanographic Data, Climatological Data, Economic Data	Y	
		Required Parameters							
		λ	Eigenvalues to derive component scores & weighting	S		unitless	derived	Y	
		$\boldsymbol{\mu}$	Eigenvectors to derive principal canonical axes	S		unitless	derived	Y	

Figure 1. Taxonomy of NEFSC ecosystem models.



[1] Environmental terms added to some but not all multispecies models

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