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End-to-End Models: Management Applications

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Preface

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1. Introduction

The need for end-to-end (E2E) models of marine ecosystem is motivated by the recognition of the close coupling between physical dynamics and ecological processes in the sea and by a desire for ecosystem-based management of marine resources. However, the complications involved in linking ocean physics to nutrient fluxes through the microbial food web, and then to the demographics of dominant fish species and top predators, including humans, contravenes the general definition of science as the art of the soluble (Medawar, 1967), as well as more specific ideas of intermediate complexity as the optimal approach (Friedrichs et al., 2007; Hannah et al., 2010).

One way to resolve these contradictions is to select some simplifying assumption about ecosystem structure and use it to determine consequent model systems. A widely used concept is the species-centric or "rhomboid" approach that emphasizes the species dynamics in one or two adjacent trophic levels with decreased attention to the levels above and below (de Young et al., 2004). The complementary trophic–centric approach includes the fullest range of trophic levels in terms of broad functional components of the food web (Vezina and Platt, 1988; Christensen and Pauly, 1993). The former approach combines complex functional relations with relatively simple food web structure; the latter has simple links between components of complicated food webs (Steele and Gifford, 2010), with a diversity of structures in between. The details of the different methods in use for E2E models have been adequately reviewed (Plaganyi, 2007; Travers et al., 2007; Fulton, 2010; Moloney et al., 2010; Rose et al., 2010).

Rather than attempting to find a general format, an alternative organizing principle is to focus on the potential applications to management problems, on the premise that the structure of each model should be determined by its intended use. Model diversity is then a function of the range of possible applications. It was this principle that defined the choice of themes for a workshop on *End-to-End Modeling of Marine Ecosystems* held at Woods Hole Oceanographic Institution 19–22 April 2010 with support from the US National Oceanic and Atmospheric Administration (NOAA) as part of the CAMEO (Comparative Analysis of Marine Ecosystem Organization) Program. These themes were to:

1. review extant end-to-end models and their underlying rationales;
2. consider application to management and decision making; and
3. develop recommendations for skill assessment of end-to-end models.

The workshop consisted of plenary talks, focused workshop presentations, and working groups, that were designed to provide inputs for each theme. The opening keynote address, given by Dr. Steve Murawski, Director of Scientific Programs and Chief Scientific Advisor for NOAA Fisheries, was entitled, "*Ecosystem-based research in the oceans: academic curiosity or operational technology?*", and provided the context for the subsequent working groups and discussions. The workshop presentations gave a good overview and representation of US contributions to the international E2E modeling activity. The one international contribution to the workshop (Mike Heath, UK) was presented by teleconference because of the disruption in air travel caused by the Icelandic volcano. Plenary talks (Kenny Rose, Eileen Hofmann) reviewed the general field of food web modeling and the issues facing development of these models. There were also two broad reviews of modeling at the global scale (Watson Gregg, Raghu Murtugudde).

The general conclusions from the discussions are given in Steele et al. (2011). The papers presented in this special section, which represent ideas and approaches presented from the Workshop, are considered primarily in the context of the second theme, applications to management and decision making. However, the diversity of applications generates a corresponding range of models (theme 1) and raise questions about assessment of performance (theme 3).

2. Review of papers

Steele et al. (2011) describe the limits to the range of models in terms of *Virtual Worlds* and *Construction Kits*, categories that are used, respectively, for very detailed pictures of particular ecosystems and simpler representations of general ecosystem patterns, such as is illustrated by the ATLANTIS model approach (Fulton et al., 2004). This approach is used by Kaplan et al. (this volume) to simulate the California Current System using circulation derived from the Regional Ocean Model System (ROMS) as a basis for an ecosystem with 62 functional groups, including 26 fish groups, three seabird groups, and six mammal groups. All vertebrate groups have 10 age classes. Twenty-year scenarios were developed to capture a range of viable options for spatial management and shifts in prevalence of particular fishing gears. Fishing was simulated on a per fleet basis, where a fleet was generally a gear (e.g. groundfish trawl, recreational hook and line). Such detailed representations can provide what Fulton et al. (2004) term Management Strategy Evaluations of specific management options for a particular region. Because of the large number of parameters required and the significant effort involved, this approach is best suited for applications restricted to individual regions and management strategies.

At the other end of the spectrum, but also applied to the California Current ecosystem, Ruzicka et al. (this volume) describe a much simpler E2E model that uses a two-dimensional (y, z)

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representation of upwelling physics and builds on the mass-balance budgets of energy flow constructed using ECOPATH (Christensen and Pauly, 1993). The focus of this study is on the effect of changes in abundance of gelatinous organisms on the rest of the ecosystem. This assessment is a contribution to the world-wide concern about the causes and consequences of apparent outbursts of these organisms in diverse ecosystems (Richardson et al., 2009). Their model analysis (ECOTRAN, Steele and Ruzicka, 2011), which is done in terms of function rather than species, can be used for comparisons of ecosystem responses across regions, such as the historical abundance of marine mammals in different ecosystems, and requirements for their revival.

In comparing highly structured models with their simpler counterparts, the level of physical complexity is as important as the degree of food web subdivision. Both aspects can be the focus for simplification depending in part on the nature of the system to be modeled, as well as the aim of the analysis. Models depicting an open ocean, purely pelagic system and one dominant fish species such as salmon (Aydin et al., 2005), or tuna (Lehodey et al., 2003) can use quite different components from those included in models used for analysis of a semi-enclosed continental shelf Heath (this volume). The former focus on horizontal advection, using circulation fields obtained from ROMS (Haidvogel et al., 2000), to relate physical structure to larval advection. The latter emphasize vertical nutrient fluxes as an overall control of fish production (Heath, this volume; Steele, this volume).

Heath (this volume) adopts a spatially aggregated description of the various habitats within the North Sea ecosystem, which is based on the assumption that the benthic components of this system are as important as the planktonic components, but not as responsive to horizontal transport. Attempting a model with detailed spatial structure may introduce more errors than what is obtained by implicit averaging. However, the model retains vertical structure as a two-layer system, because nutrient fluxes are drivers for the North Sea ecosystem. In terms of food web structure, the 15-component North Sea system might be classed as "intermediate", but with non-linear functional relations between many of these components. The scenarios presented cover a wide range of management options, but the overall conclusion is that management goals based on simultaneously achieving maximum sustainable biomass yields from all commercial fish stocks is simply unattainable. Trade-offs between, for example pelagic and demersal fishery sectors and other properties of the ecosystem have to be considered in devising an overall harvesting strategy.

Within these questions of the relative detail to be given to the physical and ecological aspects of an overall E2E model, there are further distinctions relating to the appropriate spatial scale for such studies, and the optimal division between highly aggregated components such as total trophic level biomass and detailed demographics of individual species. The focus on Large Marine Ecosystems (LMEs, Hempel and Sherman, 2003) has proven useful for delineating sectors that are relevant to management issues, although these can beg the question of their appropriateness for ecological purposes (Longhurst, 1998). Within the classification of oceanic LMEs, the Antarctic Ocean was defined as a single LME (Hempel and Sherman, 2003). This introduces the question of spatial scale discussed by Murphy et al. (this volume) in the context of the Antarctic. Historically, this region was viewed as a single system, or subdivided into 2–3 latitudinal zones, based on the Antarctic Circumpolar Current. Recent field studies have shown regional differences in the individual characteristics of populations of marine mammals, other vertebrate predators, and intermediate trophic groups in areas such as the west Antarctic Peninsula, South Georgia, and the Ross Sea. Although different in character, these regional areas are connected at the larger scale by Antarctic krill populations, which are transported by the large scale circulation. This leads Murphy et al. (this volume) to propose development of suites of scale-based models that bring together the range of issues emerging in this polar region.

There is a corresponding issue concerning the scale of aggregation into ecological categories that range from approaches based on details of the demography of individual species to those based on broad functional guilds such as piscivores, benthivores and planktivores. In part this has a practical or empirical basis in terms of available data and model complexity. But there is also the question of predictability, which focuses on the level of aggregation that will allow simulation of long term changes in terms of a small number of metrics. This issue relates to the practical matter of the usefulness to management of forecasts of, say, total fish biomass; or guilds such as "groundfish"; or of commercial species like cod or haddock. Scenarios in terms of changing patterns for functional groups or guilds may be more reliable than are estimates of abundance of individual species (Mangel and Levin, 2005; Meuter and Megrey, 2006; Auster and Link, 2009; Steele and Gifford, 2010). Steele (this volume) uses an E2E model of the Georges Bank ecosystem to relate different levels of aggregation – total biomass, feeding guilds and species composition – to prediction, scenarios, and insight, respectively.

A major point made by the Workshop participants was that management applications will likely require long-term interactions between researchers and stakeholders. These processes merit more study across research and user communities. It should not be assumed that these interactions will happen automatically after the ecological modeling is done. One potential way to enhance this interaction is to link the ecological processes to relevant economic assessments. Jin et al. (this volume) show how an E2E model of Georges Bank can be coupled to a computable general equilibrium model of the northeast US coastal community to provide an integrated economic-ecological framework designed to aid implementation of ecosystem-based fisheries management in New England.

The Workshop report acknowledges that the third objective, to develop recommendations for skill assessment, was discussed only briefly. Heath (this volume) shows how the technique of simulated annealing can be used to locate the maximum likelihood parameter set. For the North Sea ecosystem model, this approach consistently delivered improvements to the model fit compared to parameter sets obtained using other model-data fitting approaches. Heath (this volume) concluded that technical optimization schemes are rarely employed in ecosystem modeling, but need to become the norm if the conclusions reached from ecosystem simulations are to gain credibility.

The paper by Link et al. (this volume) dealt directly with the problems of uncertainty, pointing out that this encompasses diverse aspects that extend from natural variability, through model complexity to management objectives. In addition to the usual problems arising from observation errors and model structure, Link et al. (this volume) focus on inadequate communication between scientists, decision makers, and stakeholders as a major factor in generating uncertainty about the applicability of ecosystem models to management. The responsibility of addressing these aspects does not end with accounting for uncertainty in terms of model inputs, outputs, and structure. It also includes uncertainty in how the models are communicated and applied. There is more to model uncertainty than solely mathematical characterization. Addressing these other less tangible and less quantitative types of uncertainty will require greater engagement by modelers with other participants in the process, including stakeholders, managers, policy makers, and field researchers.

3. Discussion

From general reviews (Plaganyi, 2007; Travers et al., 2007; Fulton, 2010; Moloney et al., 2010; Rose et al., 2010) and the papers in this special section, it is evident that the E2E model concept can have diverse interpretations. We chose to take the range of possible applications to management as a unifying theme for the Workshop on the basis that the structure of any model should be determined primarily by its intended use. Thus, the nature of physical dynamics needed to drive the system, and the details of ecological processes required to describe the output should be determined as much by the potential applications as by each particular environment.

Link et al. (this volume) note that ecosystem models are rarely intended to provide precise predictions of future states. Rather, they are designed to offer insights regarding how a suite of characteristics in a given ecosystem might respond to a specific set of conditions and perturbations. The preferred approach in delivering results or advice appears to be through the construction of a range of scenarios (Heath, 2005; Kaplan et al., this volume; Jin et al., this volume; Steele, this volume; Ruzicka et al., this volume). Predictions with statistical limits are replaced by a discrete set of options.

As noted in the Workshop discussions and conclusions (Steele et al., 2011), the hypothetical decision makers do not want to be faced with complicated and uncertain predictions. For this reason, 1–2-year projections of species-by-species estimates of Maximum Sustainable Yield (MSY) remain the gold standard for managers. However, one conclusion from the papers in this special issue (e.g. Link et al., this volume; Heath, this volume) and from others elsewhere (see Mace, 2001) is that the sum of MSY values for all the commercial fish species in an exploited ecosystem generally exceeds the limits set by the ecosystem for the functional groups that include these species. The effects of variable stresses, from fishing to climatic change, will operate through multispecies interactions. Further, the competitive hierarchies within guilds as well as prey-predator relations between functional groups will also impose constraints on overall yields (Duplisea and Blanchard, 2005; Gifford et al., 2009). These competitive constraints are not a significant component of E2E models, yet they are a major factor in the transition from the yields of functional guilds to those for individual species. From this perspective, ecosystem-based scenarios are a complement rather than an alternative to single species assessments.

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