Modeling Social–Ecological Scenarios in Marine Systems

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Human activities have substantial impacts on marine ecosystems, including rapid regime shifts with large consequences for human well-being. We highlight the use of model-based scenarios as a scientific tool for adaptive stewardship in the face of such consequences. The natural sciences have a long history of developing scenarios but rarely with an in-depth understanding of factors influencing human actions. Social scientists have traditionally investigated human behavior, but scholars often argue that behavior is too complex to be represented by broad generalizations useful for models and scenarios. We address this scientific divide with a framework for integrated marine social–ecological scenarios, combining quantitative process-based models from the biogeochemical and ecological disciplines with qualitative studies on governance and social change. The aim is to develop policy-relevant scenarios based on an in-depth empirical understanding from both the natural and the social sciences, thereby contributing to adaptive stewardship of marine social–ecological systems.

Keywords: Baltic Sea, ecosystem approach, governance, human dimension, Nereus

The biosphere produces multiple ecosystem services of crucial importance for human well-being. However, the production of such services can change rapidly as a consequence of large, sometimes surprising dynamics, which may be the result of external forcing or internal systems dynamics (Folke et al. 2004). Such dynamics, often termed *regime shifts*, are here defined as large, persistent changes in the structure and function of a system, with substantive impacts on the ecosystem services provided. Regime shifts have been observed in a wide variety of systems and at multiple scales (Biggs et al. 2012), with shifts that may result in alternative states (Scheffer et al. 2001, Nyström et al. 2012). A key challenge for policymakers and resource managers is to understand how societies can develop strategies that will enable them to adapt and continue to develop in the face of such complexity and change.

Adaptive governance (Folke et al. 2005) refers to an approach for effectively dealing with complexity and change under uncertain conditions (including regime shifts). A cornerstone of this approach is the involvement of diverse knowledge systems and interest groups in learning and decisionmaking processes (Dietz et al. 2003). Adaptive governance appears to improve the ability of society to address complex problems and may also foster the prevention or resolution of conflicts resulting from differences in values, interests, and perspectives (Dietz et al. 2003, Folke et al. 2005). One way in which science can assist and facilitate the understanding and learning needed for adaptive governance is the use of *scenario studies* (Carpenter et al. 2006), in which a range of plausible future trajectories due to societal and ecological changes are investigated and through which knowledge can be integrated both in qualitative and quantitative terms from a wide set of disciplines (Nakićenović and Swart 2000).

Scenario studies were primarily developed by the military for security reasons during the Cold War but were, from the late 1960s onward, increasingly used in the corporate world (van der Heijden 1996). Scenarios formed an important part of the Millennium Ecosystem Assessment (MA), through which qualitative inputs from stakeholders were combined with quantitative analyses (Carpenter et al. 2006). These inputs and analyses generated four different global potential future scenarios with very different associated levels of human well-being and ecosystem services production (Butler and Oluoch-Kosura 2006). The scenarios were developed to stimulate a discussion about these diverse potential futures and the challenges and opportunities associated with them. These MA studies made clear that policy-relevant scenarios require information on how both ecosystems and social processes interact (Collins et al. 2011). In fact, social and ecological systems are interdependent in what we refer to as *social–ecological systems*, a term

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that emphasizes the humans-in-nature perspective (Berkes and Folke 1998).

The natural sciences have a long and well-established tradition of developing models and scenarios (Christensen and Waters 2011). However, there has been relatively limited scientific interest in making predictions and designing scenarios in the social sciences, except in economics, in part because it is commonly assumed that social processes are too complex to warrant general laws that would be useful for predicting future events (Popper 1960, George and Bennett 2005). The integration of the social and natural sciences, when natural resource management is studied, is regarded as crucial but also challenging and has been slow to develop (Costanza et al. 1993, Mooney et al. 2013).

Here, we attempt to bridge this gap by specifically building on decades of previous experiences with the development of marine ecosystem models, in combination with insights from a rapidly growing social sciences and interdisciplinary literature on marine resource management. Our ambition is to find a middle ground between the natural and social sciences with respect to marine resource use and to develop a social–ecological approach for marine models and scenarios. We introduce a framework as a road map for developing social–ecological models across scientific disciplines, with the goal of providing empirical models that can be used to develop policy-relevant future scenarios for marine social–ecological systems and their stewardship.

Our objective with scenario studies is not to predict what will happen but, rather, to formulate different possible futures for marine social–ecological systems at regional (international) and global scales, with a focus on fisheries, aquaculture, and land-use changes related to nutrient emissions. These activities represent key factors affecting marine ecosystems (Halpern et al. 2008), and our intention is also to understand the relevant social processes influencing the dynamics of these activities. Scenarios should be well grounded in data concerning both the natural and the social sciences, since inclusion of empirical information, especially on anthropogenic drivers (i.e., human action and its interrelation with social and ecological conditions, including the wider governance system in which they operate), make scenario studies more realistic and more relevant as policymaking tools. Several approaches, including both social and natural science data and models, are used for terrestrial systems (Matthews et al. 2007, Mooney et al. 2013). Marine models, in contrast, often lack many important aspects of the human dimension (Fulton 2010, Fulton et al. 2011). Important exceptions that incorporate specific parts of the human dimension include the Atlantis model, which includes, for example, the dynamics of fishing fleets (Fulton et al. 2011), and the Quantifying and Understanding the Earth System (QUEST-Fish) project, which incorporates market information related to, for example, fishmeal production (Merino et al. 2012).

In this article, we present a new, interdisciplinary framework for marine scenario building whereby quantitative process-based marine models from the biogeochemical and ecological disciplines are coupled with qualitative studies on the processes of governance and social change. The aim is to develop social–ecological scenarios that can inspire and facilitate adaptive governance through dialogues with decisionmakers and other marine stakeholders, thereby stimulating a discussion about potential futures for marine systems and possible pathways toward marine stewardship (Chapin et al. 2010). Our aim with the method proposed here is to account for multiple causes influencing outcomes rather than to rely on simple linear or cause–effect thinking. Emphasizing causal complexity facilitates adaptive governance, because it can help policymakers think through a more complete and representative set of alternative options.

The present state of affairs

Adaptive governance of marine systems requires an understanding of the relevant ecosystem (physical, chemical, and biological) processes (Folke et al. 2005). The long tradition of marine ecosystem studies has clarified important interacting internal components and natural and anthropogenic factors influencing the dynamics of marine ecosystems, including regime shifts (Folke et al. 2004, Halpern et al. 2008, Nyström et al. 2012). Since the 1970s, numerous marine models have been designed, drawing from that in-depth understanding of marine ecosystems, combined with rigorous calibration and validation processes based on historical empirical observations (Christensen and Walters 2011, Fulton et al. 2011). Although early ecosystem models could deal exclusively with the dynamics of a specific ecosystem component, later models included multiple ecosystem components and their respective driving forces (for an overview, see Fulton 2010). These models are becoming increasingly realistic and detailed, encompassing knowledge from different subdisciplines, including hydrology, biogeochemistry, climate, and food webs (Fulton 2010, Christensen and Walters 2011). Here, we illustrate these respective submodels as interacting components to illustrate relevant aspects that must be modeled in order to understand marine ecosystem dynamics from a social–ecological systems approach (see figure 1). Examples of such end-to-end models that link separate mechanistic models (describing, e.g., the dynamics of watershed catchments, marine biogeochemistry, food web dynamics, and possible management actions) are increasingly being developed and used. The ability to anticipate nonlinear dynamics, such as regime shifts, is also increasing as a consequence of recent model developments (see Fulton 2010, Rose et al. 2010).

Marine ecosystem modelers have developed a high level of detail in modeling complex ecosystem processes, but this level of detail is not mirrored in an analogous understanding of complex social processes (Fulton 2010). Several existing models are able to incorporate multiple potential management interventions (e.g., changes in fishing pressure, spatial protection measures, changes in nutrient runoff), but these models primarily employ a *what-if* approach

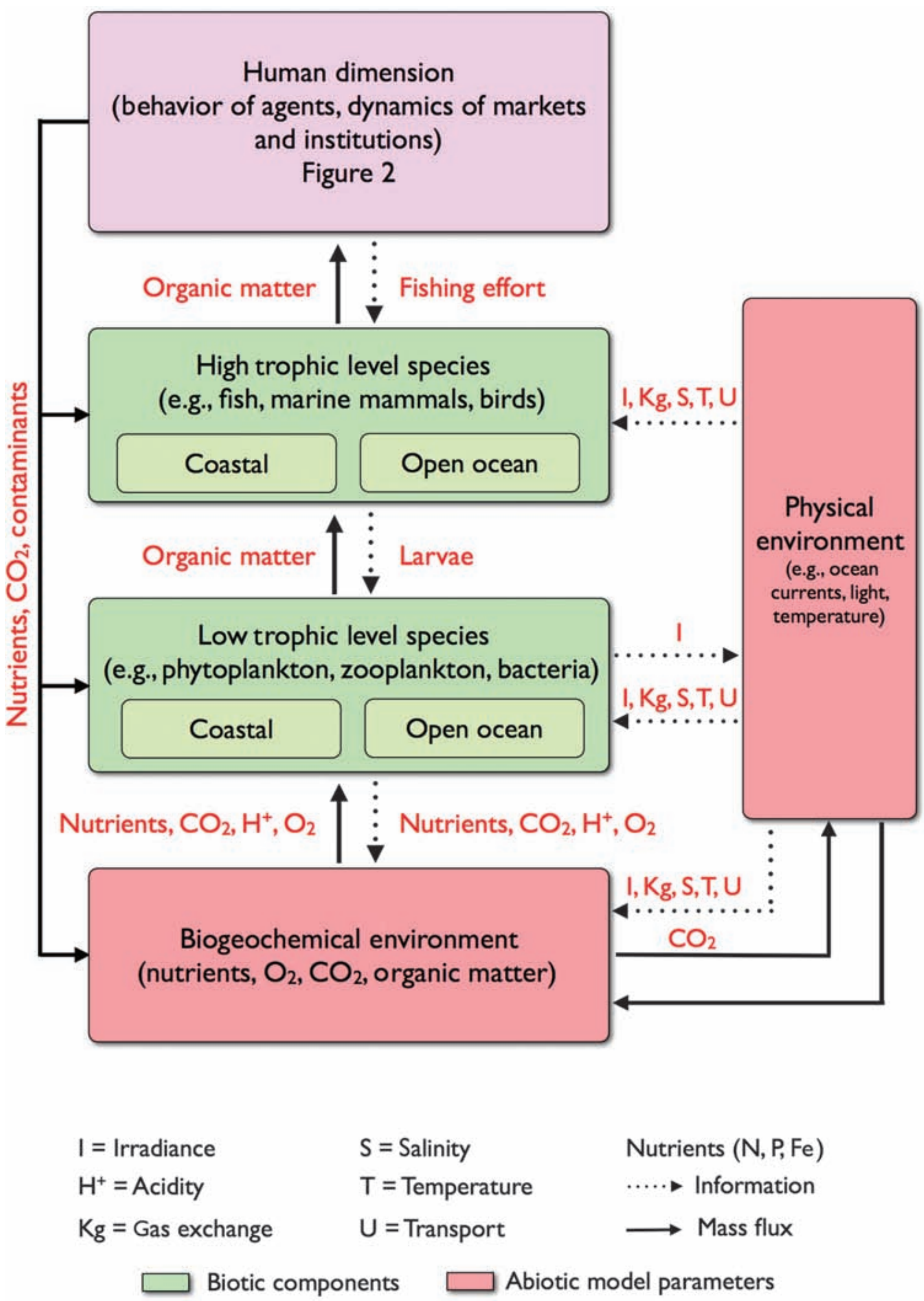

Figure 1. The ecosystem components for creating social–ecological scenarios. The diagram describes marine ecosystem dynamics, including the physical environment, the biogeochemical environment, food-web dynamics (low- and high-trophic-level species), and the human dimension (expanded on in figure 2). Abbreviations: CO_2, carbon dioxide; Fe, iron; N, nitrogen; O_2, oxygen; P, phosphorus.

(Fulton 2010). As a consequence, they are unable to address how scenarios could be realized or to describe the necessary components of the human dimension, which would be crucial for an adaptive governance system. Most models and model-based scenarios therefore have limited capacity to address the fact that environmental outcomes are shaped by interactions among science, policy, and natural resource use practices (Österblom et al. 2010).

Knowledge of crucial ecological thresholds (e.g., Cury et al. 2011, Howarth et al. 2012) can be incorporated into the design of management rules and can thereby contribute to an adaptive response to ecological change. That adaptive governance can indeed change environmental conditions for the better can be observed in the Baltic Sea, where scientific identification of critical loads of nutrients motivated changes in international nutrient discharge policy direction and agricultural practices for all nine countries that border the sea (Österblom et al. 2010). However, discharges of nutrients from agriculture are also dependent on changing markets and consumption patterns. Analogously, new rules and management tools for cod (*Gadus morhua*) fishing in the Baltic Sea, political commitment to follow scientific advice, improved environmental conditions, and increased compliance have interacted to improve the status of the depleted cod stock (Eero et al. 2012).

Adaptive governance emphasizes the interplay of science, policy, and practitioners for creating conditions that will enable governments (or other relevant authorities) to cope with uncertainty and surprise. Many governance systems are, however, operating at scales other than that of the ecosystem and are unable to adapt to complex ecosystem dynamics (Crowder et al. 2006, Folke et al. 2007). Although efforts to move toward more ecosystem-based and adaptive marine governance approaches are emerging (Olsson et al. 2008, Ruckelshaus et al. 2008), such approaches can also meet important institutional challenges (Crowder et al. 2006). People and nature are often treated as fundamentally separate, and attempts to move toward more integrated or ecosystem-based approaches are often focused on, for example, marine spatial planning or marine reserves, rather than on building adaptive capacity (Chapin et al. 2010). Investigating ways to improve the adaptive capacity of governance systems should be of high priority, because reactive responses to ecological challenges are likely to be more costly and time consuming than proactive action prior to large-scale ecological change (Biggs et al. 2009). However, creating awareness that dramatic and unwanted change could be close at hand, when all indicators suggest otherwise, represents a significant challenge.

Notwithstanding the difficulties of understanding many of the complex social–ecological interactions, the marine research community is rapidly moving in this direction. A number of recently published data sets (including global databases and in-depth empirical case studies) shed important light on the links between variables and outcomes of relevance for adaptive marine governance (supplemental material S1, available online at *http://dx.doi.org/10.1525/bio.2013.63.9.9*). These data sets and empirical case studies have uncovered important aspects of the dynamics of human actions and the governance systems in which they operate, analogous to how historical food web and ecosystem studies have contributed to what is contemporary common knowledge about the structure and function of marine ecosystems. Given the differences in natural and social systems research and understanding (Fulton 2010, Mooney et al. 2013), we will focus on describing the human dimensions in more detail. For instance, studies of governance shifts toward sustainability have identified key variables of relevance for building scenarios, including how ecological crises create windows of opportunity for political and institutional change toward marine ecosystem stewardship (Olsson et al. 2008, Österblom and Sumaila 2011). Other aspects addressed by these studies include how policy entrepreneurs conceptualize problems and solutions and how political change, technological innovation, and emerging markets influence outcomes (Berkes et al. 2006, Österblom and Sumaila 2011).

The challenge of modeling the human dimension

A crucial first step in developing realistic social–ecological scenarios is to better incorporate the human dimension by finding the right balance between insights derived from in-depth and context-dependent case studies and an understanding of general interactions between variables and outcomes, which may be identified through systematic comparison across multiple in-depth case studies (Goldstone 2008, Rihoux and Ragin 2009). Solid empirical understanding of social–ecological interactions is fundamental for a future development of models and scenarios, and we will draw extensively on existing databases and single-case studies in order to generate robust general conclusions (see supplemental material S1).

The research underpinning our scenarios has to meet two methodological requirements: It must produce an empirically valid and meaningful general understanding of the diversity and complexity of processes of social–ecological change, and it must address the dynamics of a system (i.e., its changes over time) in order to account for feedback and path-dependent causal relationships between anthropogenic and nonanthropogenic drivers and social–ecological conditions. These requirements can be best pursued through a multimethod research loop that integrates general knowledge from cross-case analysis and modeling, with in-depth insights from historical within-case analysis.

Cross-case analysis typically includes quantitative methods, large sample sizes, external validity (i.e., its conclusions apply to a broader, unstudied population), and estimations of its causes and effects. Within-case analysis, in contrast, includes qualitative methods, small sample sizes, high internal validity (i.e., its conclusions account for all the important aspects of the relevant case), and identification of its causal mechanisms (table 1; Mahoney and Goertz 2006, Gerring 2007). The research loop has three distinct steps. First, outcomes of cross-case analysis can be used to inform selection procedures for within-case studies to secure their generalizability and validity. Second, the qualitative within-case analysis of a limited number of cases can generate hypotheses on social–ecological system change; that is, it can produce hypothetical explanations for the change. Qualitative and simple models, which are fast and flexible and are often used when modeling ecosystems (Fulton 2010), can provide an important conceptual understanding of the social–ecological feedbacks contributing to diverse outcomes. For instance, Österblom and colleagues (2011) used empirical information from case studies of North American and European fisheries management systems to generate a simple and conceptual social–ecological model proposing the interacting roles of compliance, the status

Table 1. Cross-case and within-case research objectives and design.

	Within-case study	Cross-case study
Research objectives		
Hypothesis	Generating	Testing
Explanation	Causes of effects, necessary and sufficient causes, set-theoretic logic	Effects of causes, correlation, probability
Scope	Narrow	Broad
Application	Social sciences	Natural sciences
Research design		
Case selection	Positive cases on the dependent variable	Random selection on independent variables
Population of cases	Small sample size, heterogeneous	Large sample size, homogeneous
Methods	Qualitative	Quantitative

Source: Adapted from Mahoney and Goertz (2006) and Gerring (2007).

of scientific advice, political decisionmaking processes, and ecosystem function for determining outcomes in different fisheries governance systems. Third, the validity and accuracy of such proposed hypotheses from simple conceptual models can be tested with both qualitative and quantitative cross-case analysis.

It will be possible to investigate, in a manner analogous to the approach outlined above, crucial factors that in the past have been important for determining changes in human actions. For instance, this approach will involve incentives for rule compliance, conflicting interests between stakeholders, and the changing institutional setting in which actors operate. Trade-offs between, for example, conventional agricultural development and other land-use activities that do not involve high nutrient input, or between high levels of wild capture fisheries that lead to disturbed food webs and precautionary catch limits, will become increasingly apparent if ecological systems are pushed toward their thresholds.

Cross-scale dynamics in a globally interconnected world will influence the potential for addressing such trade-offs and challenges (Berkes et al. 2006, Merino et al. 2012). Investigating how actors within these interlinked systems adapt to and cope with ecological, social, political, and market dynamics will be essential, combined with an understanding of the potential to steer these dynamics in sustainable directions. The development of long-term scenarios also emphasizes the need to address how actors share the burdens associated with conservation and monitoring and how they distribute the benefits from resource harvest, across both communities and generations (Gosseries and Meyer 2009).

A marine social–ecological framework to guide modeling and scenario analysis

We reviewed a number of initiatives aimed at modeling the human-dimension aspects of global change, including the social-process diagram developed by William Kuhn and his colleagues for the Consortium for International Earth Science Information Networks (CIESIN) in the early 1990s (CIESIN 1992; see Mooney et al. 2013), more-recent modeling approaches (Collins et al. 2011, Fulton et al. 2011, Merino et al. 2012), a general framework for analyzing social–ecological systems (Ostrom 2009), and recent studies of marine governance (supplemental material S1). These combined frameworks and empirical case studies illustrate a wide set of social–ecological feedbacks and interactions among science, policy, and practice. The social-process diagram (Mooney et al. 2013) includes a wide set of dimensions, including global demographics, political systems and institutions, preferences and expectations, knowledge and experience, factors of production and technology, and economic systems, as well as their interactions with global environmental processes. The framework for analyzing social–ecological systems (Ostrom 2009) is, in turn, specifically focused on natural resource systems and describes attributes of users and institutions of relevance for governance, primarily drawing on empirical information from the local level. We combined components from these two separate approaches, with the goal of reducing complexity to a level at which it was analogous to our Bretherton diagram (see, e.g., Mooney et al. 2013) focusing on biophysical dynamics (figure 1). Existing modeling approaches that share similarities with our approach (Collins et al. 2011, Fulton et al. 2011, Merino et al. 2012) added specific details of relevance for modeling marine systems. Specifically, Collins and colleagues (2011) illustrated an approach in which the social and biophysical aspects are equally weighted. The QUEST-Fish model (Merino et al. 2012) includes both a component modeling climate impacts on marine ecosystems and an economic component modeling potential future fishmeal demand but lacks the high social-science resolution found in CIESIN (1992) and Ostrom (2009). The Atlantis model (Fulton et al. 2011) includes a wide set of social-science variables focusing specifically on fisheries management systems. We used these different approaches, in combination with existing empirical in-depth case studies (supplemental material S1) to define the human-dimensions framework (figure 2) of our marine social–ecological framework. This framework is developed to give equal attention to human and biophysical components, which has previously been lacking in marine models (Fulton 2010).

This framework suggests variables, links, and feedbacks of relevance for dynamic modeling of marine social–ecological systems. The framework includes a number of domains that influence human behavioral change, including society, knowledge systems, political and institutional setting, and the economy. It also involves different individual and collective actors, including implementing organizations and actors. Finally, the framework includes the activities of actors in the marine systems that we focus on here—namely, capture fisheries, land use, and aquaculture—and which ultimately affect the ecological system (see box 1 for

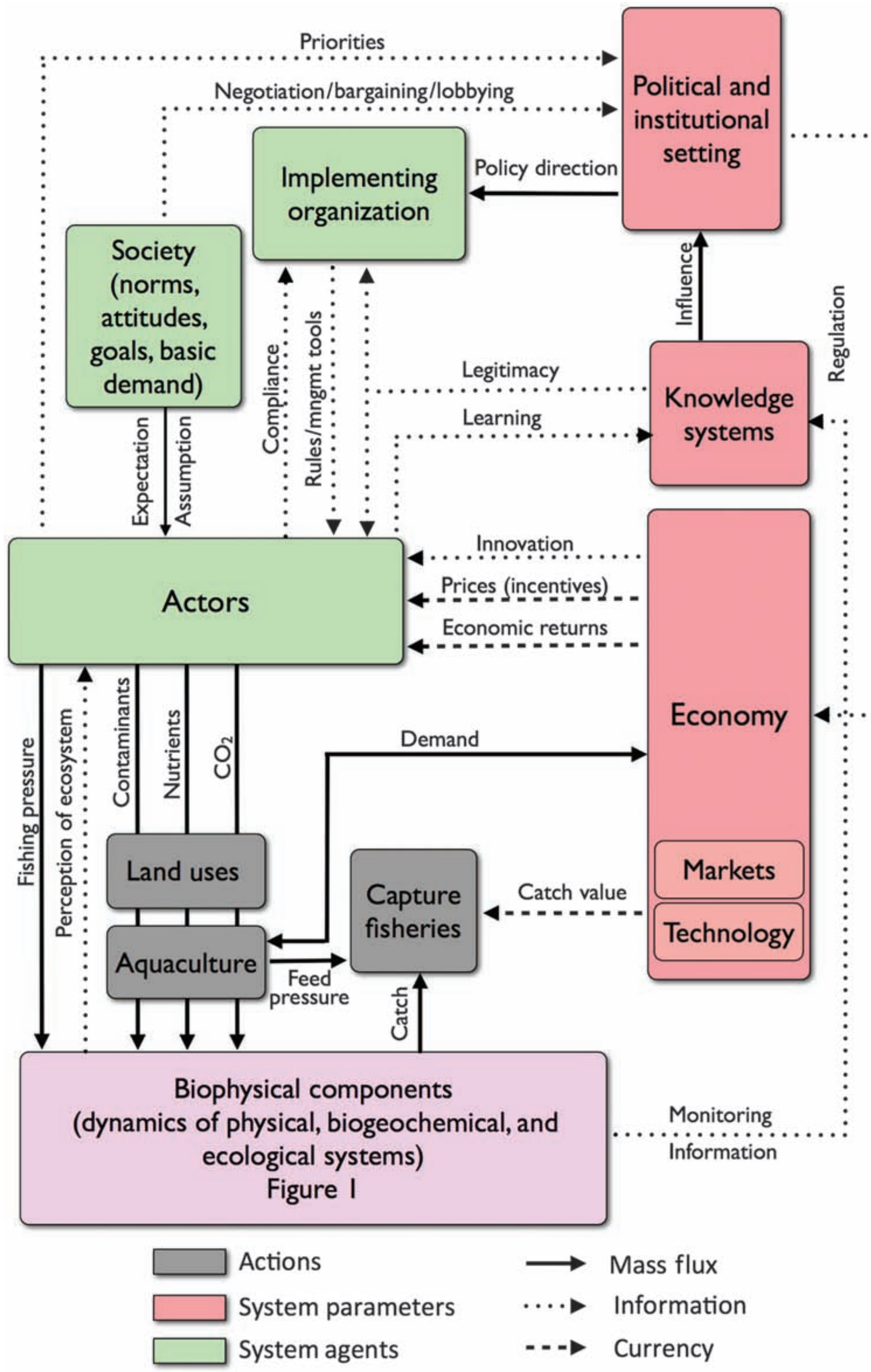

Figure 2. Human dimensions for creating social–ecological scenarios. The behavior of actors (e.g., fishermen, aquaculture industries, farmers) results in different human impacts on marine ecosystems (e.g., fishing pressure, nutrients, contaminants). Actors can be influenced through rules and management tools but also through the perceived legitimacy of science and other knowledge systems, economic incentives, norms and attitudes in society, technological innovation, and the perception of ecosystem status in their decisions to, for example, increase or decrease fishing. Implementing organizations are in turn influenced by different political and institutional settings. System parameters are depicted in pink, agents in green, and actions in gray. Abbreviations: CO_2, carbon dioxide; mngmt, management.

Box 1. Adaptive governance of illegal fisheries in the Southern Ocean.

The workings of the framework proposed in the present article can be illustrated by the origin of more effective governance of illegal fisheries in the Southern Ocean (Österblom and Sumaila 2011, Österblom and Folke 2013). Changing attitudes in Australia influenced national political priorities related to illegal fishing in the Southern Ocean. Australia, together with other nations involved in the Commission for the Conservation of Antarctic Marine Living Resources, changed the political direction of this commission, which led to the development of new rules and management tools. Scientists played a key role in these changes, because they were able to make credible projections of a likely collapse of valuable fish stocks and of endangered seabird populations. These combined actions reduced illegal fishing and therefore improved compliance. Licensed industry actors directly affected by illegal fishing were also actively engaged in lobbying for political change. Although new rules and management tools stimulated compliance by the actors, they were probably also influenced by market signals of the changing prices of illegally caught fish and the related economic returns. New technologies (e.g., deep-sea gillnets) have also been used more recently by a small number of remaining illegal fisheries. The ecological effects of a reduction of capture fisheries in this case can be further modeled in the ecosystem components of the proposed framework.

an example of how this framework can be used to describe some of these connections and supplemental material S2 for a comprehensive description of all of the included variables). This conceptual framework illustrates hypotheses of potentially important system interactions and feedbacks. In doing so, it provides a road map for the systematic exploration and evaluation of challenges and opportunities for marine governance at regional and global levels.

The conceptual framework will be used to organize the collection of empirical data that will be analyzed across case studies, which will, in turn, be used for developing models, including agent-based models, and game-theoretic analyses. We will initially select parts of the framework that can be modeled realistically. Subcomponents of this framework (e.g., models describing factors contributing to outcomes in the aquaculture sector) can be modeled separately, with increasing complexity as our empirical understanding increases. Scenarios could include, for example, the rapid or slow diffusion of harvesting or monitoring technology and high or low levels of political attention toward marine stewardship (which would lead to well-managed and precautionary governance approaches or noncompliance and unregulated markets, respectively).

Assessing multiple pathways and outcomes

Modeling potential causal pathways and outcomes in marine social–ecological systems represents a significant challenge. The framework presented here is intended to be used, for example, to evaluate how the status of high-trophic-level fish species is determined by a combination of ecosystem factors (e.g., dynamics in the physical environment, biogeochemical environment, and low trophic levels; figure 1) and the human dimension (e.g., interactions among scientists, policymakers, and managers; figure 2). Human actions will influence high-trophic-level fish not only directly, through fishing, but also indirectly, through fishing for low-trophic-level species, and through other impacts on the physical and biogeochemical environment (e.g., through the discharge of nutrients and contaminants). Different pathways of human actions (e.g., high or low fishing pressure) will be projected depending on the level of forcing of the human-dimensions model (figure 2), in which we intend to use combinations of qualitative and quantitative data, as was described above. We will test different interactions influencing human actions, including the role of prices and incentives (the economy module), the effectiveness of institutions, and the compliance of actors, as well as the efficiency of resource use (determined by the status of the environment) and how these factors shape ecosystem dynamics. An increased empirical understanding of the human dimension and social–ecological couplings will create conditions for well-grounded models and scenarios, including two-way interactions between ecosystems and the human dimension.

We will use different case studies that provide in-depth understanding of social and ecological dynamics as a basis for understanding different statuses or trajectories. Such case studies will inform the assumptions in our models by constituting starting points for scenarios. For instance, we started to develop end-to-end models for the Baltic Sea on the basis of figure 1, describing catchment nutrient loads (figure 3a), biogeochemical dynamics (figure 3b), and ecological (figure 3c) dynamics. These models can be combined with potential future levels of human impact (through changes in, e.g., climate, fishing pressure, and land use) and will describe the potential for nonlinear shifts resulting from the combinations of such human impacts, either under a *business-as-usual* scenario or a *nutrient reduction scenario* (in line with the Baltic Sea Action Plan; see supplemental material S3). The models will also include consideration of low or high potential levels of fishing pressure, combined with scenarios for climate change (figure 3d). Reconstruction of long-term historical trends in combination with future scenarios can be used, for example, to determine possible future nutrient loads and phytoplankton production (figure 3e). We are in the process of collecting and analyzing information on the long-term social dynamics of, for instance, the existing governance institutions, knowledge providers, and user groups in the region (Österblom et al. 2010), in order to understand how existing institutions and actors could adapt to such rapid change. Developing an analogous empirical in-depth understanding of additional social–ecological systems is a key priority in

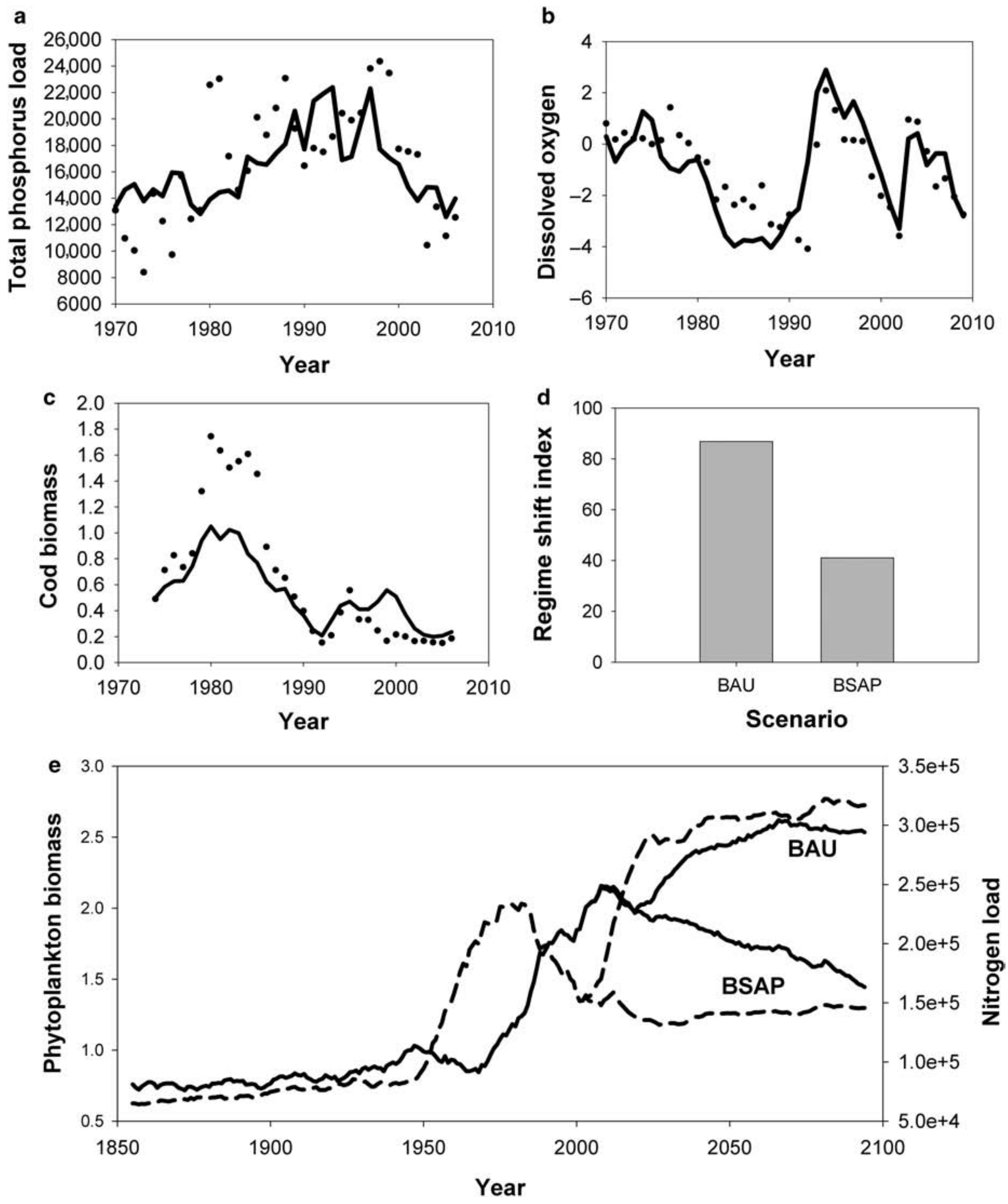

*Figure 3. End-to-end modeling using long-term monitoring data from the Baltic Sea. Illustrated are the past 30 years of observed and modeled nonlinear dynamics for (a) total phosphorus load (in metric tons per year), (b) dissolved deepwater oxygen concentration (in milliliters of oxygen per liter of water), and (c) cod (*Gadus morhua*) biomass (in metric tons per square kilometer) (see supplemental material S3, available online at* http://dx.doi.org/10.1525/bio.2013.63.9.9*). (d) Scenario exercise in which a future climate scenario with two land-use scenarios (business as usual [BAU], Baltic Sea Action Plan [BSAP]) have been used to force catchment, biogeochemical, and food-web models. (e) Long-term simulation results from 1850 to 2100 with the BAU and BSAP future land-use scenarios showing the dynamics of nitrogen load (dotted lines; in metric tons per year, as an example for nutrient load from land) and phytoplankton biomass (solid lines; in milligrams of nitrogen per cubic meter). This graph shows the long-term eutrophication development in the twentieth century with lag effects of phytoplankton and the potential future development of the two land-use scenarios in the twenty-first century.*

comparing governance systems and the factors that contribute to their respective performance and adaptive capacity. These cross-case-study analyses will be combined with the development of global end-to-end models and analogous global governance aspects within the Nereus program (*www.nereusprogram.org*). The framework presented here will serve as a template for data collection, and empirical insights from these diverse studies will be used to adjust models.

The combination of natural- and social-science approaches into one framework constitutes a foundation for novel, conceptual, and empirical models and scenarios useful for investigating potential pathways to marine stewardship. We will use these scenarios when we engage in dialogues with policymakers and practitioners, with the goal of discussing how the modeled, hypothetical futures of marine social–ecological systems could be avoided or encouraged in the real world.

It should be acknowledged that it will not be possible to develop quantitative predictive models for all variables and outcomes of integrated social–ecological systems. We also acknowledge that it will be a challenge to couple the two modeling approaches and that dealing with uncertainty in such complex models will represent an additional challenge. A complex social–ecological systems approach is, in itself, confronted with uncertainty and surprise (Levin et al. 2013).

However, the common framework presented here represents an important step toward integrating the understanding of the social and natural sciences. This integration will contribute to the development of explorative models that can improve our understanding of coupled systems dynamics under certain (empirical or theoretical) assumptions. It will probably be possible to develop a long-term, historical, empirical understanding of changing markets and technologies and to model potential future driving forces and the effects of continuous change in such factors. However, understanding governance shifts and how such shifts influence actors will have to take the form of discrete interactions (e.g., high or low compliance, a governance shift toward stewardship, science that is perceived as legitimate or science that is questioned). A crucial factor to model will be the extent of spatial and temporal matches between environmental problems and policy responses. A high degree of mismatch might lead to ineffective governance; conversely, a highly matched system of adaptive governance could enable social–ecological sustainability (Folke et al. 2005).

Conclusions

We have made a case for integrated social–ecological scenarios as a tool for exploring future possibilities that can assist in providing advice for the stewardship of marine social–ecological systems. Realistic scenarios require an interdisciplinary approach and innovative combinations of methods and data. In the approach outlined here, existing data sets and case studies of the human dimension will be used to investigate the variables contributing to relevant outcomes for sustainable fisheries and marine stewardship. With this approach, we aim to suggest potential options for the future and also to describe crucial components enabling change toward desirable trajectories for marine stewardship and human well-being that avoid undesirable development pathways.

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References cited

Berkes F, Folke C. 1998. Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press.

Berkes F, et al. 2006. Globalization, roving bandits, and marine resources. Science 311: 1557–1558.

Biggs R, Carpenter SR, Brock WA. 2009. Turning back from the brink: Detecting an impending regime shift in time to avert it. Proceedings of the National Academy of Sciences 106: 826–831.

Biggs R, Blenckner T, Folke C, Gordon L, Norström A[V], Nyström M, Peterson G. 2012. Regime shifts. Pages 609–629 in Hastings A, Gross L, eds. Encyclopedia of Theoretical Ecology. University of California Press.

Butler CD, Oluoch-Kosura W. 2006. Linking future ecosystem services and future human well-being. Ecology and Society 11 (art. 30). (13 June 2013; *www.ecologyandsociety.org/vol11/iss1/art30*)

Carpenter SR, Bennett EM, Peterson GD. 2006. Scenarios for ecosystem services: An overview. Ecology and Society 11 (art. 29). (13 June 2013; *www.ecologyandsociety.org/vol11/iss1/art29*)

Costanza R, Waigner L, Folke C, Mäler K-G. 1993. Modeling complex ecological economic systems: Toward an evolutionary dynamic understanding of people and nature. BioScience 43: 545–555.

Chapin FS III, et al. 2010. Ecosystem stewardship: Sustainability strategies for a rapidly changing planet. Trends in Ecology and Evolution 25: 241–249.

Christensen V, Walters CJ. 2011. Progress in the use of ecosystem models for fisheries management. Pages 189–205 in Christensen V, Maclean J, eds. Ecosystem Approaches to Fisheries: A Global Perspective. Cambridge University Press.

[CIESIN] Consortium for International Earth Science Information Network. 1992. Pathways of Understanding: The Interactions of Humanity and Global Environmental Change. CIESIN.

Collins SL, et al. 2011. An integrated conceptual framework for long-term social–ecological research. Frontiers in Ecology and the Environment 9: 351–357.

Crowder LB, et al. 2006. Resolving Mismatches in U.S. Ocean Governance. Science 314: 617–618.

Cury PM, et al. 2011. Global seabird response to forage fish depletion—One-third for the birds. Science 334: 1703–1706.

Dietz T, Ostrom E, Stern PC. 2003. The struggle to govern the commons. Science 302: 1907–1912.

Eero M, Köster FW, Vinther M. 2012. Why is the Eastern Baltic cod recovering? Marine Policy 36: 235–240.

Folke C, Carpenter S[R], Walker B, Scheffer M, Elmqvist T, Gunderson L, Holling CS. 2004. Regime shifts, resilience and biodiversity in ecosystem management. Annual Review of Ecology, Evolution, and Systematics 35: 557–581.

Folke C, Hahn T, Olsson P, Norberg J. 2005. Adaptive governance of social–ecological systems. Annual Review of Environment and Resources 30: 441–473.

Folke C, Pritchard L, Berkes F, Colding J, Svedin U. 2007. The problem of fit between ecosystems and institutions: Ten years later. Ecology and Society 12 (art. 30). (13 June 2013; *www.ecologyandsociety.org/vol12/iss1/art30*)

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

Fulton EA, et al. 2011. Lessons in modelling and management of marine ecosystems: The Atlantis experience. Fish and Fisheries 12: 171–188.

George AL, Bennett A. 2005. Case Studies and Theory Development in the Social Sciences. MIT Press.

Gerring J. 2007. Case Study Research: Principles and Practices. Cambridge University Press.

Goldstone JA. 2008. Comment: Bully for prediction. Sociological Methodology 38: 59–65.

Gosseries A, Meyer LH, eds. 2009. Intergenerational Justice. Oxford University Press.

Halpern BS, et al. 2008. A global map of human impact on marine ecosystems. Science 319: 948–952.

Howarth R, Swaney D, Billen G, Garnier J, Hong B, Humborg C, Johnes P, Mörth C-M, Marino R. 2012. Nitrogen fluxes from the landscape are controlled by net anthropogenic nitrogen inputs and by climate. Frontiers in Ecology and the Environment 10: 37–43.

Levin S, et al. 2013. Social–ecological systems as complex adaptive systems: Modeling and policy implications? Environment and Development Economics 18: 111–132.

Mahoney J, Goertz G. 2006. A tale of two cultures: Contrasting quantitative and qualitative research. Political Analysis 14: 227–249.

Matthews RB, Gilbert NG, Roach A, Polhill JG, Gotts NM. 2007. Agent-based land-use models: A review of applications. Landscape Ecology 22: 1447–1459.

Merino G, et al. 2012. Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? Global Environmental Change 22: 795–806.

Mooney HA, Duraiappah A, Larigauderie A. 2013. Evolution of natural and social science interactions in global change research programs. Proceedings of the National Academy of Sciences. (13 June 2013; *www.pnas.org/cgi/doi/10.1073/pnas.1107484110*)

Nakićenović N, Swart R, eds. 2000. Emissions Scenarios. Cambridge University Press.

Nyström M, Norström AV, Bleckner T, de la Torre-Castro M, Eklöf JS, Folke C, Österblom H, Steneck RS, Thyresson M, Troell M. 2012. Confronting feedbacks of degraded marine ecosystems. Ecosystems 15: 695–710.

Olsson P, Folke C, Hughes TP. 2008. Navigating the transition to ecosystem-based management of the Great Barrier Reef, Australia. Proceedings of the National Academy of Sciences 105: 9489–9494.

Österblom H, Folke C. 2013. Emergence of global adaptive governance for stewardship of regional marine resources. Ecology and Society 18: 4. (10 July 2013; *http://dx.doi.org/10.5751/ES-05373-180204*)

Österblom H, Sumaila UR. 2011. Toothfish crises, actor diversity and the emergence of compliance mechanisms in the Southern Ocean. Global Environmental Change 21: 972–982.

Österblom H, et al. 2010. Making the ecosystem approach operational—Can regime shifts in ecological- and governance systems facilitate the transition? Marine Policy 34: 1290–1299.

Österblom H, Sissenwine M, Symes D, Kadin M, Daw T, Folke C. 2011. Incentives, social–ecological feedbacks and European fisheries. Marine Policy 35: 568–574.

Ostrom E. 2009. A general framework for analyzing sustainability of social–ecological systems. Science 325: 419–422.

Popper KR. 1960. The Poverty of Historicism, 2nd ed. Routledge.

Rose KA, et al. 2010. End-to-end models for the analysis of marine ecosystems: Challenges, issues, and next steps. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 2: 115–130.

Rihoux B, Ragin CC, eds. 2009. Configurational Comparative Methods: Qualitative Comparative Analysis (QCA) and Related Techniques. Sage.

Ruckelshaus M, Klinger T, Knowlton N, DeMaster DP. 2008. Marine ecosystem-based management in practice: Scientific and governance challenges. BioScience 58: 53–63.

Scheffer M, Carpenter S[R], Foley JA, Folke C, Walker B. 2001. Catastrophic shifts in ecosystems. Nature 413: 591–596.

Van der Heijden K. 1996. Scenarios: The Art of Strategic Conversation. Wiley.

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