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NEW HORIZONS FOR MANAGING THE ENVIRONMENT: A REVIEW OF COUPLED SOCIAL-ECOLOGICAL SYSTEMS MODELING

M. SCHLÜTER*
Department of Biology and Ecology of Fishes, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, 12587 Berlin, Germany
E-mail: schlueter@igb-berlin.de

R. R. J. MCALLISTER
CSIRO Ecosystem Sciences, PO Box 2583 Brisbane Q 4001 Australia
E-mail: Ryan.Mcallister@csiro.au

R. ARLINGHAUS
Department of Biology and Ecology of Fishes, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, 12587 Berlin, Germany; Inland Fisheries Management Laboratory, Faculty of Agriculture and Horticulture, Humboldt-Universität zu Berlin, 10115 Berlin, Germany
E-mail: arlinghaus@igb-berlin.de

N. BUNNEFELD
Department of Life Sciences, Imperial College London, Buckhurst Road, Ascot, Berkshire SL5 7PY, UK
E-mail: n.bunnefeld06@imperial.ac.uk

K. EISENACK
Environment & Development Economics, Department of Economics, Carl von Ossietzky University Oldenburg, 26111 Oldenburg, Germany
E-mail: klaus.eisenack@uni-oldenburg.de

F. HÖLKER
Department Ecohydrology, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, 12587 Berlin, Germany
E-mail: hölker@igb-berlin.de

E.J. MILNER-GULLAND
Department of Life Sciences, Imperial College London, Buckhurst Road, Ascot, Berkshire SL5 7PY, UK
E-mail: e.j.milner-gulland@imperial.ac.uk

B. MÜLLER
Department of Ecological Modelling, UFZ—Helmholtz Centre for Environmental Research Leipzig-Halle, Germany
E-mail: birgit.mueller@ufz.de

*Corresponding author. M. Schlüter, Department of Biology and Ecology of Fishes, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, 12587 Berlin, Germany.
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E. NICHOLSON
Department of Life Sciences, Imperial College London, Buckhurst Road, Ascot, Berkshire SL5 7PY, UK
E-mail: e.nicholson@imperial.ac.uk

M. QUAAS
Department of Economics, University of Kiel, Germany
E-mail: quaas@economics.uni-kiel.de

M. STÖVEN
Department of Economics, University of Kiel, Germany
E-mail: stoeven@economics.uni-kiel.de

Abstract. Conventional approaches to natural resource management are increasingly challenged by environmental problems that are embedded in highly complex systems with profound uncertainties. These so-called social-ecological systems (SESs) are characterized by strong links between the social and the ecological system and multiple interactions across spatial and temporal scales. New approaches are needed to manage those tightly coupled systems; however, basic understanding of their nonlinear behavior is still missing. Modeling is a traditional tool in natural resource management to study complex, dynamic systems. There is a long tradition of SES modeling, but the approach is now being more widely recognized in other fields, such as ecological and economic modeling, where issues such as nonlinear ecological dynamics and complex human decision making are receiving more attention. SES modeling is maturing as a discipline in its own right, incorporating ideas from other interdisciplinary fields such as resilience or complex systems research. In this paper, we provide an overview of the emergence and state of the art of this cross-cutting field. Our analysis reveals the substantial potential of SES models to address issues that are of utmost importance for managing complex human-environment relationships, such as: (i) the implications of ecological and social structure for resource management, (ii) uncertainty in natural and social systems and ways to address it, (iii) the role of coevolutionary processes in the dynamics of SESs, and (iv) the implications of microscale human decision making for sustainable resource management and conservation. The complexity of SESs and the lack of a common analytical framework, however, also pose significant challenges for this emerging field. There are clear research needs with respect to: (i) approaches that go beyond rather simple specifications of human decision making, (ii) development of coping strategies to deal with (irreducible) uncertainties, (iii) more explicit modeling of feedbacks between the social and ecological systems, and (iv) a conceptual and methodological framework for analyzing and modeling SESs. We provide ideas for tackling some of these challenges and indicate potential key focal areas for SES modeling in the future.

KEY WORDS: Social-ecological modeling, complex systems, uncertainty, ecological structure, social structure, human-decision making.

1. Introduction. Conventional approaches to natural resource management are increasingly challenged by environmental problems that are embedded in highly complex systems with profound uncertainties (Underdal [2010], Fulton et al. [2011]). These systems are characterized by a strong interdependence between ecological systems and the social systems that use and depend on them (Fouke et al. [2010]). The dynamics and complexity of these so-called social-ecological systems (SESs) are driven by feedback between resources, actors, and institutions at and across multiple scales. SESs are complex adaptive systems characterized by nonlinear dynamics, the potential for regime shifts, self-organization, cross-scale interactions, and surprise (Levin [1998], Folks [2006]). In order to tackle today's environmental problems and adapt to global change, approaches are needed that take the interdependence between ecological and social dynamics into account (Carpenter et al. [2009], Horan et al. [2011]) and can cope with the inherent complexity and uncertainty of SESs.

Conceptualizing natural resource systems as SESs challenges some of the basic assumptions on which traditional approaches are based, such as that it is possible to fully predict and control system dynamics by addressing single system elements in isolation (Pahl-Wostl et al. [2011]; Table 1). This traditional view of natural resource systems often ignores uncertainties and neglects important feedbacks generated by, e.g., the reflexive response of humans to forecasts and interventions (Walker et al. [2002]). Moreover, while the importance of the human dimension and social dynamics for sustainable resource management is well recognized, the uncertainty generated by human responses to institutional or environmental change has only received limited attention so far (e.g., Berkes [2007], Fulton et al. [2011]).

SES models constitute a tool to improve our understanding of the factors and processes that shape sustainable outcomes in SESs of contemporary interest, such as fisheries, agriculture, and water use. They address one or several issues that are characteristic of human-environment systems, such as their often nonlinear ecological dynamics and feedbacks within or between the ecological and social systems. By

TABLE 1. Different views of and approaches to the management of human-environment systems (based on Walker et al. [2002], Chapin et al. [2010]).

Traditional view of natural resource systems	Natural resource systems as SESs
System dynamics are linear and monotonic	System dynamics exhibit thresholds, hysteresis
Uncertainty is largely ignored: probability distributions for key drivers and decision variables are treated as known	Complexity and uncertainty of SESs are explicitly considered: probability distributions for key drivers and decision variables are highly uncertain, as are outcomes; some uncertainties are irreducible
Individual elements can be treated in isolation	Complex systems of interacting entities at microscale from which macroscale patterns emerge
Focus on impact of human behavior on resource	Incorporate reflexive response of humans to forecasts and interventions
Actors are rational and have full information and computational capacity	Actors have imperfect knowledge, are boundedly rational or follow more complex decision patterns
Management objectives are based on simple reference points	Management involves complex tradeoffs
Managed by a command-and-control approach, management of resource stocks and condition, not wider ecosystem	Managed for resilience and adaptive capacity, management of stabilizing and amplifying feedbacks within a broader context

analyzing and simulating possible development pathways and outcomes of these coupled systems, SES models contribute to enhancing our understanding of SESs as complex adaptive systems and so to our ability to manage them effectively. The aims of SES models are therefore in general to: (i) enhance our understanding of how structural

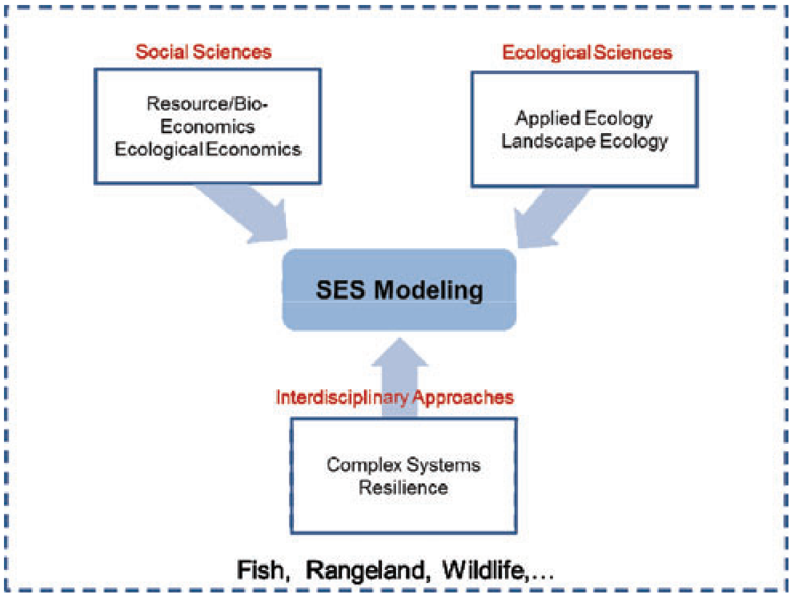

FIGURE 1. Different disciplinary and interdisciplinary fields contributing to SES modeling and the main resource types considered in our overview. Landscape ecology also develops SES models but is beyond the scope of our review. See Matthews et al. [2007] for a review of agent-based models in land use science.

characteristics of the ecological and social system and dynamic feedbacks within and between the two determine overall system behavior and (ii) provide management advice that takes the coevolving nature of SESs into account and supports strategies to cope with uncertainty.

Developing SES models poses a range of conceptual and methodological challenges associated with the complexity of SESs and the need to integrate natural and social science methods to adequately address the coupling between the ecological and social domains. The traditional fields of ecological and economic modeling are beginning to tackle those challenges by moving toward more integrated models that take the complexity and uncertainty of SESs into account. These developments are complemented by modeling approaches in some new interdisciplinary fields that have set out to tackle the issue of interlinked

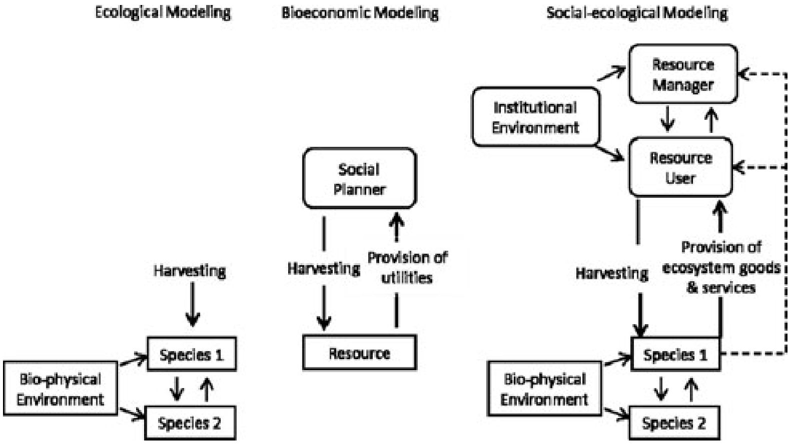

FIGURE 2. Feedbacks considered in different modeling approaches. Traditional ecological modeling focuses on complex ecological dynamics under anthropogenic pressure. Here, only feedbacks within the ecological system are considered. Traditional bioeconomic modeling focuses on determining socially or individually optimal harvest levels that maximize profit under the constraints of the resource. Here, feedbacks between the social and ecological are considered, however, diverse actors of the social system are not considered and resource dynamics are generally very simple. Note that the representation of ecological and bioeconomic modeling is simplified to highlight major aspects of the traditional approaches. There are approaches in both fields that go significantly beyond the simple models shown here including elements of SESs as we show in our overview. SES modeling includes complex ecological dynamics as well as heterogeneous resource users that receive multiple ecosystem services from the ecological system. Hence, ecological, social, and social-ecological feedbacks are considered (the dotted arrows indicate information flows). Note, however, that no SES model includes all of the elements shown here simultaneously, but rather focuses on selected feedbacks considered relevant for a given research question.

SESs (e.g., in resilience thinking) or the nonlinear dynamics of complex adaptive systems (complex systems science). Together these developments contribute to an emerging field of SES modeling (Figure 1).

The aim of this paper is to provide an overview of the emergence and state-of-the art conceptual and methodological development of SES modeling across various fields. The overview is not intended to be complete but rather to focus on those aspects we consider to be particularly topical and important. We highlight major cross-cutting issues that result from a synthesis across those diverse fields. We conclude by highlighting relevant conceptual and methodological issues that need to be tackled in order to move the field of SES modeling forward and suggest potential research issues that will be a focus of SES modeling in the near future.

2. The emergence of social-ecological modeling. SES modeling does not yet exist as a distinct field with a unifying analytical and methodological framework and well-defined questions, theories, and approaches. It is rather a cross-cutting field that is developing as a multidisciplinary and multiperspective endeavor where each field and discipline contributes different aspects to the study of these complex adaptive systems. SES models build on the different traditions in modeling natural resources in ecology, economics, and conservation but go a step further by explicitly considering two-way interactions within and between the social and ecological systems (Figure 2). We begin our overview of the different contributions by: (i) highlighting some recent developments in modeling natural resources in selected sectors, demonstrating the increased recognition of natural resources as SESs, followed by (ii) a review of work in economics that addresses selected characteristics of SES such as nonlinear ecological dynamics and uncertainty. We complete the overview with (iii) a presentation of new interdisciplinary approaches that, in recognition of the limitations of traditional approaches, are seeking to achieve a more integrated, mechanistic, and dynamic view of SESs. The contributions of each field and discipline to the development of the field of SES modeling are summarized in Table 2.

2.1. Social-ecological modeling in fisheries, rangelands, and wildlife management. Mathematical modeling has long been a tool to support natural resource management. Models of the efficient and optimal exploitation of natural resources have been at the core of resource economics since its emergence in the 1970s (Clark [1976], Dasgupta and Heal [1979]). Based in neoclassical economics, these models are used to maximize individual or social welfare under the assumptions of deterministic resource dynamics, full information about the effects of extraction, and rational utility-maximizing agents. In these studies, ecological dynamics have typically been described by simple models of resource populations (e.g., fish stocks, vegetation, etc.) but recent ecosystem models have addressed the complexity observed in marine and terrestrial systems (Fulton et al. [2004], Smith et al. [2007], Holdo et al. [2009]). In applied ecology, models have been used

TABLE 2. The relationship between different fields and SES modeling. The list of selected fields is not exhaustive and rather meant to illustrate the development of the cross-cutting field of SES modeling as a multidisciplinary and multiperspective endeavor.

Modeling field	Key issues with relation to SESs	Methods to tackle these issues	Key references/examples
Fisheries	• Effects of spatially and temporally variable fishing effort • Integration of more complex and heterogeneous human decision making and implementation uncertainty	• Bioeconomic models with complex utility functions and heterogeneous actors • Agent-based models • Management strategy evaluation.	Allen and McGlade [1986], Hunt et al. [2011], Little et al. [2004], Dichmont et al. [2006], Johnston et al. [2010]
Rangeland	• Strategies to deal with resource variability and manage risk; detecting thresholds and memory effects	• State and transition models	Sandford and Scoones [2006], Campbell et al. [2006], Müller et al. [2011], Janssen et al. [2000], Rouchier et al. [2001]

(Continued)

TABLE 2. *(Continued)*

Modeling field	Key issues with relation to SESs	Methods to tackle these issues	Key references/examples
	• Dealing with changing institutional conditions and social change	• Disequilibrium models • Numerical simulations of bioeconomic models, game-theoretic approaches • Agent-based models	
Wildlife	• Implications of mismatch between manager and user objectives leading to noncompliance with regulations • Implications of complex decision making of actors	• Bioeconomic approaches that model individual decision making • Management Strategy Evaluation	Barrett and Arcese [1998], Keane et al. [2008], Bunnefeld et al. [2011]
Bioeconomics ecological economics	• Optimal harvesting and behavior in markets under risk/uncertainty	• Discrete or continuous time bioeconomic models with stochastic biomass growth function	Reed [1979], Pindyck [1984], Tahvonen [2009], Mäler et al. [2003], Baumgärtner and Quaas [2010a]

(Continued)

TABLE 2. *(Continued)*

Modeling field	Key issues with relation to SESs	Methods to tackle these issues	Key references/examples
	• Implications of including more ecological realism • Sustainability as inter- and intragenerational justice	• Numerical optimization • Game theory	
Resilience thinking	• Regime shifts and their implication for management, regime shift indicators • Robust management strategies for resilience • Impact of structural characteristics of an SES for resilience	• Bioeconomic models that include resilience in the objective function • Agent-based models • Numerical simulations of systems of differential equations of complex ecosystem dynamics	Fletcher and Hilbert [2007], Janssen et al. [2004], Carpenter and; Brock [2004], Horan et al. [2011]

(Continued)

TABLE 2. *(Continued)*

Modeling field	Key issues with relation to SESs	Methods to tackle these issues	Key references/examples
Complex systems	• Implications of biophysical networks for natural resources management • Role of social networks for facilitating collective management; to moderate institutional and ecological scale mismatches	• Agent-based modeling • Network approaches (empirical, incorporated in agent-based model (ABM) or as exogenous structures in optimization models, evolved in ABMs)	Lansing et al. [2009], Becu et al. [2003], Bodin and Norberg [2005], Chadés et al. [2011]

extensively to study the conservation of populations and ecosystems under anthropogenic pressure (e.g., Coulson et al. [2001]). Given their focus on ecological dynamics, these models typically represent the human dimension simply as an external and static pressure on the resource, neglecting human decision making and behavior (Milner-Gulland [2011]).

Recent years have seen developments in both fields that more explicitly account for realistic ecological dynamics and human decision making. These new models in fisheries, wildlife, or rangeland management are motivated by the goal of better understanding the consequences for conservation of nonlinear resource dynamics and heterogeneous user behavior in the light of particular management interventions or policy choices (Table 2). In the following section, we highlight some of these recent developments in modeling natural resources in selected sectors, demonstrating the increased recognition of natural resources as SESs.

2.1.1. *Fisheries.* The main objective of fisheries science has always been the development of robust management advice and strategies that minimize the risk of fish population collapse and maximize fish yield and other tangible metrics of interest to humans (e.g., catch of large fish, maximum economic yield). Modeling has constituted a key tool to achieve this objective, particularly in the marine environment, since the emergence of quantitative, model-based fisheries biology in the mid 20th century (Beverton and Holt [1957]). Early models were biomass-based (e.g., the surplus production model, Schaefer [1957]) and generally were single-species (e.g., yield-per-recruit and other age-structured dynamic pool models, Beverton and Holt [1957]). Neoclassical bioeconomic approaches that optimize discounted net economic returns have the longest tradition with respect to addressing management questions (Clark [1976], Smith [2002], Tahvonen [2010]). These models have focused largely on providing explanations for collapse and biological overfishing (e.g., Gordon [1954]), or to derive management reference points such as maximum economic yield (Christensen [2010]).

In recent years, the single-species-oriented management philosophy has been increasingly replaced by an ecosystem approach to fisheries (Pikitch et al. [2004]). This demands the development of multispecies (May et al. [1979]) and ecosystems models that account for trophic interactions and energy flow among a network of species and functional groups (e.g., Ecopath with Ecosim, Walters et al. [1997], Pauly et al. [2000]). These developments have been made possible by improved computing power, enabling more complex biological models to be developed that include differentiated age structure and complex ecological interactions (e.g., Tahvonen [2008, 2009, 2010], Voss et al. [2011]). The findings from these models challenge results from the traditional biomass models, indicating that they may lead to incorrect harvesting recommendations.

However, these models have still mainly focused on the ecological dynamics of a fishery largely omitting dynamics of harvesters and rule-making agents (Garcia and Charles [2008]). The incorporation of the human component into fisheries models has only slowly evolved (Larkin [1978], Fulton et al. [2011]), partially due to the belief that the uncertainty in the biological submodels of fish stock dynamics needed to be reduced first before introducing human decision making, which was largely thought to be controllable through management. In the 1980s, the classical bioeconomic approach was widened by considering complex, sometimes spatially explicit fleet dynamics (Allen and McGlade [1986], Hilborn and Walters [1987]), in which fleet and fisher-specific utility functions drive decisions such as choice of fishing grounds or capital investments. Such approaches have also been extended over a fisheries landscape, in which mobile fishers interact with a spatially structured stock complex (Hunt et al. [2011]). In addition to accounting for more complex user behavior in single-species models, economic aspects have also been added to fisheries ecosystem models. Christensen and Walters [2004] and Christensen et al. [2011], for example, extended a trophic mass balance analysis (Ecopath) with a dynamic modeling capability (Ecosim) by adding a value chain module to describe economic and social aspects of fish product flows.

A more recent line of inquiry investigates more fine scale and often individually variable human behavior where fisher decision making is assumed to be boundedly rational. Such assumptions of imperfect knowledge and limited cognitive capacities as well as the influence of information exchange, learning, and social networks have usually been included in more flexible, agent-based fisheries models (e.g., Dreyfus-León [1999], Little et al. [2004], McDonald et al. [2006]). These approaches integrate a range of empirical social data with the underlying biological dynamics of the exploited ecosystem to produce a more "systemic" view of fisheries (Garcia and Charles [2008]).

Despite these developments, contemporary fisheries scientists continue to raise concerns that the human behavioral dynamics tend to be underappreciated in fisheries models, potentially resulting in misguided management advice and unsustainable exploitation (Fulton et al. [2011]).

2.1.2. *Rangelands.* Coping with and managing resource variability is a major issue in rangeland science because of the highly variable arid and semiarid environments that most grazing systems are located in. In the last 30 years, ecological models of different types have contributed to an improved understanding of the complex ecological dynamics of rangelands. Threshold effects and irreversible vegetation changes, which occur, for example, when a system changes from a self-perpetuating grassland to a shrub-dominated state have been studied using state-and-transition models (Westoby et al. [1989], Walker [1993], Perrings and Walker [1997], Bestelmeyer et al. [2004]). The underlying ecological processes and structures such as memory effects, thresholds and spatial configurations have been addressed using difference- and differential-equation models (cf. Noy-Meir [1982], van de Koppel et al. [2002]) and structurally realistic rule-based models (cf. Coughenour [1992], Jeltsch et al. [1997], Weber et al. [1998], see also reviews in Tietjen and Jeltsch [2007] and Wiegand et al. [2008]). These studies revealed, for example, that feedbacks between surface water distribution, plant cover, and grazing on a patch scale may explain irreversible vegetation shifts on larger spatial scales (Van de Koppel et al. [2002]). Others have highlighted a mismatch between management and ecological timescales with respect to shrub encroachment (Jeltsch et al. [1997], Weber et al. [1998]). These models focus on the ecological dynamics and model the human dimension in a very rudimentary way, similarly to the fisheries models discussed above.

Early modeling studies that include the human dimension focused on identifying the optimal constant grazing level that maximizes livestock off-take in the tradition of natural resource economics (e.g., Whitson [1975]). This approach is based on an equilibrium view that is embedded with the concept of fixed carrying capacities, steady-state resource dynamics, and maximum sustainable yields. It disregards important grazing system characteristics, such as the irreversibility of some ecological changes, the high variability and unpredictability of rainfall in space and time, and the spatial heterogeneity of vegetation (see Illius and O'Connor [1999]).

Alternatives to the equilibrium model were proposed and debated from the mid 1990s. Nonequilibrium refers to the decoupling of plant and herbivore relations due to resource variability. The disequilibrium approach describes rangelands on a continuum between equilibrium and nonequilibrium (see Derry and Boone [2010]). Models taking this view incorporate opportunistic stocking strategies that track rainfall variability (Behnke et al. [1993], Pickup [1996]). Debate continues, however, as to when constant stocking is more appropriate compared to opportunistic stocking regimes (see Campbell et al. [2006], Sandford and Scoones [2006], Gillson and Hoffman [2007], Higgins et al. [2007]). Analytical models (solved numerically) have captured highly uncertain fodder production (see Anderies et al. [2002], Walker and Janssen [2002], Börner et al. [2007], Weikard and Hein [2011]). Economic equation-based and game-theoretical models have been used to investigate cooperation in common-property regimes (McCarthy et al. [2001], Brekke et al. [2007], Crépin and Lindahl [2009], Johannesen and Skonhoft [2009]) or to compare different land tenure regimes (cf. Goodhue and McCarthy [2009]).

More recently, modeling studies in rangeland science have focused on the impacts of institutional or social change, in response to growing empirical evidence that the lack, or erosion, of institutions managing for variability leads to land degradation or desertification. For example, ecological-economic or game-theoretic models have been used to analyze the consequences of changing policy instruments (Janssen et al. [2000], Müller et al. [2011]), access regimes (cf. Goodhue and McCarthy [2009]) and the role of cooperation in common-property regimes (Brekke et al. [2007], Crépin and Lindahl [2009], Johannesen and Skonhoft [2009]). However, to adequately represent heterogeneous responses of resource users on the microlevel to changing institutional settings, models need to go beyond the rather abstract representation of single resource users common in economic models by incorporating more realistic social dynamics. Examples are models investigating the role of different rationalities for herdsmen-peasant relationships (Rouchier et al. [2001]), learning by decision makers (Gross et al. [2006]), and livestock mobility networks ("agistment"; McAllister et al. [2006]). Multiagent models have been used to analyze household-level livelihoods and vulnerability to changing social-ecological conditions, particularly in case studies in Africa (Galvin et al. [2006], Dougill et al. [2010]) and Central Asia (Milner-Gulland et al. [2006]).

2.1.3. *Wildlife.* Traditional wildlife management modeling is built on the assumption of wildlife populations that show density-dependent growth and the aim of exploiting the system at maximum sustainable yield (Sinclair et al. 2005). While the science behind the biology and optimal management of hunting is well understood, mostly through advances in fisheries (Clark [1976]), humans are only starting to be acknowledged and researched as active participants in the process of exploitation (Bunnefeld et al. [2011]). Humans make decisions based on the incentives and the tradeoffs they face. In developing countries, for example, resource use is often for subsistence, which is better described as maximizing individual household welfare or utility (happiness, satisfaction) instead of maximum sustainable yield. Management plans aimed at wildlife conservation are thus often contrary to the motivations of local resource users (McAllister et al. [2009a]). This can lead to noncompliance of resource users with management rules (e.g., illegal offtake), which undermines management goals (Keane et al. [2008]). Using a bioeconomic model based on household utility, Barrett and Arcese [1998] showed that people's decision making regarding the relative effort devoted to hunting depends on broader economic incentives and the availability of alternative livelihood, such as agriculture. There are an increasing number of studies on integrated conservation and development projects, which model the interactions between management of protected areas and agricultural activity at the household level (Barrett and Arcese [1995], Bulte and Horan [2003], Johannesen [2006], Winkler [2011]).

Differences in objectives between those that manage and those that exploit natural resources is not only important in the context of subsistence hunting (Rondeau and Bulte [2007]), but also for recreational hunting in the developed world, where hunting is mainly a leisure activity (Sharp and Wollscheid [2009]). Studies on hunter attitudes show that hunter satisfaction is a complex process not only related to the density of the harvested species but to a combination of experiences (Hendee [1974]). These include recreation, companionship, environmental conditions, and time of the hunting season (e.g., deer hunting, Gigliotti [2000], Heberlein and Kuentzel [2002]). Recreational hunting models that include these more complex human decision-making processes have so far not been developed, but suggestions have been made as to how these models could be useful to improve the sustainability of wildlife management in the developed world (Bunnefeld et al. [2011]). Thus, hunting both for subsistence and recreation is driven by individual decision making aiming for utility maximization, which goes beyond simple maximization of harvest. Unified frameworks that incorporate human decision making and the biological dynamics of wildlife are needed if we are to manage wildlife sustainably (Milner-Gulland et al. [2010], Bunnefeld et al. [2011]).

2.2. Social-ecological modeling in bioeconomics and ecological economics. Acknowledging the fact that the abundance of natural resources varies in space and time, recent work in bioeconomics has investigated questions of optimal decision making under risk generated by temporally variable resource dynamics. Much of this research has taken fisheries as the resource in question, hence this more conceptual approach to modeling complements the more biological and management-focused approach to fisheries modeling discussed above. In economics, a situation of risk is characterized by knowledge of both the set of possible outcomes and the probability distribution over this set (Knight [1921], Faber et al. [1996]). This distinguishes it from uncertainty or ignorance where probability distributions or the outcome set itself are not known. An important example of decision making under risk is the optimal harvesting of a natural resource with a stochastic biomass growth function in discrete time. In this context, a long-standing result is that it is optimal for a risk-neutral decision maker to leave a constant amount of the resource in the stock after harvesting (Reed [1979]). Several articles refine Reed's model by adding multiple uncertainties (Sethi et al. [2005]), costly capital adjustments (Singh et al. [2006]), the choice of the regulatory instrument (Weitzman [2002]), the spatial structure of the resource (Costello and Polasky [2008]), and management of a stochastic resource with environmental prediction (Costello et al. [2001], Eisenack et al. [2006]). In continuous time models, Pindyck [1984] shows that the effect of risk on optimal harvesting is ambiguous and depends on the specific model under consideration. More sustainable use of ecosystems by risk-averse decision makers may be promoted if the natural insurance function of ecosystems and biodiversity is explicitly considered (Quaas and Baumärtner [2008]).

Ecological Economics has been defined as the "science and management of sustainability" (Costanza [1991]). Sustainability is understood in this context as justice between humans of current and future generations as well as justice toward nature (Baumgärtner and Quaas [2010a,b]). It is thus a broad societal objective, which goes beyond considering single resources (e.g., fish stocks) in isolation and beyond traditional economic objectives such as maximizing the present value of welfare derived from resource use. In practical terms, ecological economics differs from resource economics by including a more realistic representation of ecological dynamics and by explicit consideration of ethical questions related to sustainable management of resources. The need to realistically represent ecological dynamics in bioeconomic models of natural resource use has for a long time been overshadowed by the desire to come up with clear-cut analytical results. Only step by step have relevant ecosystem effects been taken into account, producing less simplistic management recommendations. For example, the inclusion of nonlinearities and nonconvexities in ecological dynamics leads to multiple equilibriums and limited ecosystem resilience. Such effects have been incorporated into relatively simple models of shallow lakes (e.g., Mäler et al. [2003]) as well as more complex models of rangeland use (e.g., Janssen et al. [2004]) and coral reef fisheries (Crépin [2007]). The unique perspective of ecological economics on these issues is bringing the societal objective of sustainability to center stage along with a consideration of resilience (Derissen et al. [2011]).

2.3. Social-ecological modeling in resilience and complex systems research

2.3.1. *Resilience.* Resilience thinking is a perspective for the analysis of SESs that emphasizes their nonlinear dynamics, the existence of thresholds, uncertainty and surprise, and feedbacks between social and ecological systems across temporal and spatial scales (Folke et al. [2010]). Resilience is defined as both the capacity of an SES to absorb shocks, and its capacity to learn from shocks to adapt and reorganize

(Folke [2006]). When introduced in the 1970s (Holling [1973]), the concept of resilience challenged the dominant stable equilibrium view of ecology (Folke [2006]) and introduced the notion of alternative states and regime shifts. In recent years, attention in resilience research has shifted away from purely ecological resilience toward processes of adaptation and transformation in the social systems that are needed to maintain SES resilience at different scales (Folke et al. [2010]).

Modeling has been used in resilience research to study the dynamics and management of SESs that can exist in alternative states (e.g., Scheffer [2009]). Classic examples are regime shifts in lakes caused by slow changes in phosphorous concentrations in sediments and their recycling into the water column (Carpenter et al. [1999a]), or shifts between grass- and shrub-dominated states in rangelands and their implication for optimal management (Perrings and Walker [1997], Anderies et al. [2002]). In a recent work, Horan et al. [2011] used a bioeconomics framework to study how different institutional settings affect critical tipping points between alternative regimes. Models have also been used extensively to identify indicators for regime shifts such as rising variance (Brock and Carpenter [2006]) or critical slowing down (van Nes and Scheffer [2007]; Scheffer et al. [2009]) and to explore theoretically how indicators could help to prevent a shift into an undesirable regime (e.g., Biggs et al. [2009], Contamin and Ellison [2009]). However, the application of these indicators to detect regime shifts in real-world systems remains problematic (although see Carpenter et al. [2011] for an empirical example from lake ecosystems).

Early resilience models follow an ecological modeling approach based on difference or differential equations. They represent human behavior simply through changes in the rates of an environmental variable (e.g., phosphorous input or grazing rate). Despite the emphasis of resilience thinking on the role of feedbacks for system dynamics, only a few models so far truly address social-ecological feedbacks in a dynamic way, e.g., by modeling adaptive human behavior. These include early models that investigate learning and adaptation to environmental change of resource users with limited knowledge about nonlinear ecological dynamics and the effect those processes have on resilience (e.g., Carpenter et al. [1999b], Janssen et al. [2000], Janssen et al. [2004]). Other applications assess management strategies or policies for complex human-environment systems in situations where resource users respond to local changes in resource state, e.g., robust strategies for pastoralists (Janssen et al. [2004]) or policies for spatial fisheries in a landscape (Carpenter and Brock [2004]).

In recent years, however, SES modeling in resilience research has increasingly focused on human behavior, particularly the capacity of actors to adapt to variable and changing resource conditions. Examples include studies investigating the impact of the governance structure and multipurpose resource use on system dynamics (Schlüter and Pahl-Wostl [2007]), the diversity of resource uses (Schlüter et al. [2009]), and the linkages and tradeoffs between different ecosystem services (Leslie et al. [2009], Kellner et al. [2011]). Bodin and Norberg [2005] use a model to explore how the intensity of information sharing in a network of resource users in an uncertain environment affects the likelihood of collapse of a renewable resource. They show that a highly connected network can more easily lead to collapse because of the synchronization of behavior. These studies have all used agent-based models (ABMs) to represent heterogeneous user behavior in response to perceived or real environmental changes.

2.3.2. *Complex systems theory.* A complex system is "a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution" (Mitchell [2009, p. 13]). A rationale for complexity thinking is that the behaviors that emerge from the interactions of numerous system components are not a simple average of the behaviors of the individual components. In the context of natural resource management, complex systems research has addressed how decentralized local interactions of heterogeneous autonomous agents and the ecological or social structure within which they are embedded give rise to collective outcomes such as system-level population dynamics or cooperation and collective action between resource users (Macy and Willer [2002], Epstein [2006]). Those studies can help to better understand mechanisms driving the evolution of SESs and determining system-level properties, such as resilience.

Complex systems research uses bottom-up modeling approaches such as ABM to generate macroscale patterns from local, spatially explicit, interactions of organisms or resource users that vary in certain relevant attributes. The aim is to detect microscale, simple rules that can explain an observed macroscale pattern. In anthropology, for example, researchers have developed ABMs to investigate the survival or collapse of human populations resulting from their social and social-ecological interactions. A seminal work is the model of Lansing and Kremer [1993] that developed an empirically based ABM to understand the coordination of water management in the rice terraces of Bali (see also Lansing et al. [2009]). They could show how sociocultural structures such as a water temple network coevolved with and constrained environmental processes such as crop growth and pest dynamics. Dean et al. [2000] developed an ABM of the Anasazi Indians in the American Southwest to understand population movements in response to environmental crisis. Both models have inspired a whole set of models to understand collective action and local governance of common pool resources such as irrigation systems (e.g., Becu et al. [2003], Barreteau et al. [2004]).

Networks, which are maps of interconnecting parts in a complex system, are another natural tool for thinking about complexity. Networks can be conceptualized where there are transfers (e.g., knowledge, money, food, material, electricity, etc.) or connections (trust, roads, family ties, power lines, etc.) between definable nodes (people, houses, institutions, airports, countries, etc.). In natural resource contexts, networks can also be seen as the physical fabric on which socioecological systems operate. "Fabrics" include energy flows through food webs (Vasas and Jordan [2006]), animal movements between forest patches (Urban and Keitt [2001], Galpern et al. [2011]), and invasive species propagation via road systems (Drake and Mandrak [2010]). Exploration of the implication of biophysical networks can yield important insights for natural resource management. Chadès et al. [2011], for example, embed exogenous network structures into an optimization model. Their work develops robust rules of thumb for prioritizing where and when to monitor and manage across various types of ecological network structures, and can be applied to invasive and endangered species and diseases. In this case, the structure of the ecological network is used to guide recommendations for human behavior.

Social networks on the other hand have been embedded into ABMs in order to test the implications of network structure for system dynamics (e.g., Bodin and Norberg [2005], Bhattacharyya and Ohlsson [2010]), or have been simulated using ABM in order to explore how networks are shaped within SESs (e.g., McAllister et al. [2011]). Here, the link between the social and ecological systems tends to be based on how the social network facilitates collective management of resources. These studies explore natural resource outcomes against observed network characteristics (e.g., density, clustering, redundancy), which can be used as indicators of a network's ability to adapt, learn, innovate, and persist. However, social networks not only allow for collective resource management; resource distributions also shape the networks. Furthermore, for many natural resource problems an observed network is only interesting as far as it provides an observable manifestation of the underlying institutions or ecosystem. For example, observed interactions between pastoralists as they bargain to opportunistically move livestock across semiarid grazing lands partially reflects landscape variability. More insightfully, the observed interactions provide a snapshot of the underpinning social norms that emerge based on both ecological and cultural landscapes (McAllister et al. [2006]).

An emerging application of network methods in SESs is in unpacking the coordination of multiple policies or institutions for natural resource management. Lubell et al. (2010) have used a network approach to map the participation of actors across multiple water management policies. Outcomes for natural resources are not the result of a single institution, and participation in various institutions requires actors finding and implementing those that are mutually beneficial, the distribution of which is determined by bargaining. Networks involving multiple actors and institutions therefore characterize the structural nature of a collective-action problem.

3. Major cross-cutting issues and research questions. Based on our overview of recent developments in disciplinary and interdisciplinary fields dealing with natural resources as SESs, we have identified four major cross-cutting issues in SES modeling: (i) the implications of complex social and ecological structure for the management of SESs, (ii) the need to address the uncertainty of ecological and social dynamics in decision making, (iii) the role of coevolutionary processes for the management of SESs, and (iv) understanding the macroscale effects of microscale drivers of human behavior. In the following section, we discuss these four cross-cutting issues in more detail and point to some of the challenges associated with them.

3.1. Implications of complex social and ecological structure for the management of SESs. SESs outcomes are determined by many variables that interact at multiple temporal and spatial scales (Kates et al. [2001]). SES models of natural resources thus generally incorporate more complex and realistic representations of social and ecological structure than traditional modeling approaches. Taking into account complex ecological structure (including spatial structure) poses a challenge to current single-species- and often biomass-based regulations and puts the emphasis on the tradeoffs between different ecosystem services or geographic regions. For example, Carpenter and Brock [2004] show how spatial shifts of anglers following local collapse of fish populations in a heterogeneous landscape of lakes can lead to serial collapse in neighboring fisheries. Their results indicate that one size fits all policies that do not account for spatial variability can make natural resources more vulnerable.

The same applies to the social system, where modelers are beginning to include more realistic representations of social structure, such as heterogeneity of actors, interactions between actors, and social networks. As with resources, space has received more attention and is being included as a major factor in SES models that incorporate human decision making. For example, Castella and Verburg [2007] developed a spatially explicit model of individual land use decisions in a mountain area in Vietnam and showed its relevance for analyzing alternative policies and guiding decision making.

Assessing the implications of social and ecological complexity for the behavior and management of SESs poses many challenges. One main challenge is to abstract from the target system in a manner that includes just enough detail to answer a problem-oriented research question and investigate the implications of real-world complexity but not more. For example, should individual variability at the local level be included or is it sufficient to model processes at the population level? When confronted with complex SESs, there are temptations to include too much detail, particularly with ABMs where it is easy to do so, or to revert to well-known overly simplistic models. Choices of the system boundary, of relevant variables and processes, of the level of aggregation that is most appropriate for a given research question are difficult but crucial because they can potentially have major effects on model outcomes. For that purpose, model-to-model analysis comparing models on different levels of aggregation is a promising tool (see Rouchier et al. [2008] for a review on model-to-model analysis in social sciences; Eisinger & Thulke [2008] and Edwards et al. [2003] for examples from ecological and social sciences, respectively). The choices of the system boundary, relevant variables and processes are more difficult in an interdisciplinary context, where one needs to integrate the conceptual backgrounds and methodological approaches from different disciplines. The lack of a common analytical framework for the analysis of SESs is a major shortcoming in this respect, but some first suggestions for such frameworks have been made (e.g., Anderies et al. [2004], Ostrom [2007, 2009] and section "A common framework for the analysis of SESs").

3.2. Coping with uncertainty in resource and social dynamics in decision making. Taking the view of natural resources systems as SESs implies acknowledging that natural resources need to be managed in the face of variability, uncertainty, information gaps, and asymmetries. Despite uncertainty, resource users, managers, and policymakers still need to take decisions.

We discuss progress in coping with uncertainty in SESs in terms of how best to support decision making under uncertainty through the development of optimal strategies that take uncertainty into account, i.e., try to reduce uncertainty; and, accepting that many uncertainties cannot be reduced, how to develop strategies to cope with irreducible ecological and social uncertainties.

3.2.1. *Support tools for decision making under uncertainty.* The development of decision-support tools for situations of risk and uncertainty generated by variable and nonlinear resource dynamics has long been a focus in fields such as fisheries and rangelands and within bioeconomics more generally (see sections above). These tools provide for the design of incentives and regulatory instruments for resource management in variable environments such as rangelands, optimal offtake strategies for stochastic resources, or decision rules for investment and use of infrastructure to cope with variability, e.g., of water flows (Fisher and Rubio [1997], Callaway [2003]). However, currently these tools tend not to consider microlevel human decision making and its impacts on the outcomes of top-down decisions. Another research strand has addressed ecological uncertainty by analyzing the consequences of how people make decisions under uncertainty, e.g., the implication of their subjective perceptions of ecological dynamics for sustainable resource management (Janssen and Ostrom [2006]). Carpenter et al. [1999a], for example, have shown how in a situation where the aggregate behavior of many individual agents determines the state of an ecosystem, heterogeneous beliefs of the agents about ecosystem dynamics or differential access to information about the state of the ecosystem can cause irregular oscillations among ecosystem states.

Current research toward decision support under uncertainty focuses on distilling the uncertainty and making the best possible decision. However, this approach falls short when there is no unique and objectively given probability distribution for a social-ecologically relevant outcome. For example, various climate models predict different probability distributions of global mean temperature in 100 years from now. As there is no objective means to decide which model is most likely to give the correct prediction, designing climate policies is a problem that involves irreducible uncertainties. There is not yet a methodically sound and convincing way of dealing with such problems (Heal [2009]). Similarly, it is not clear how humans handle tradeoffs between different uncertainties, e.g., the uncertainty of climate change impacts on a fishery and the uncertainty of a collapse of the fishery due to overfishing. These questions may be addressed, as suggested by Carpenter et al. [1999a], by developing institutional designs or system structures that can respond flexibly to unexpected conditions. Alternatively, strategies may be developed that enable decision makers to cope with, rather than reduce, uncertainty.

3.2.2. *Decision support and policymaking for coping with ecological uncertainty.* Rather than seeking to reduce uncertainty, decision support for coping with uncertainty concerns accepting uncertainty and seeking to support physical, social, and organizational strategies, which can manage and reduce risk across a range of plausible levels and patterns of resource abundance. The research field seeks to understand how users and managers cope with variability, and then to support strategies that work and seek to redress strategies that fail. In this regard, dealing with variability is not just related to single strategies, but to portfolios of strategies that collectively manage uncertainty. SES modeling can be used to explore the portfolios of coping mechanisms, which can best manage for uncertainty (e.g., Schlüter and Pahl-Wostl [2007], McAllister et al. [2009b]). Such models take a resilience approach, where rather than trying to make any one "best" decision, the ability to persist is based upon embedding into the institutional framework for resource management the ability to deal with a range of resource abundance patterns in both time and space.

Variability coping strategies are most studied in rangelands, where they have a long history (Niamir-Fuller [1999]). Temporal strategies store resources (forage or money, for example) in good times as a buffer against deficiencies in poor times (e.g., Quaas et al. [2007], Müller et al. [2007a], Müller et al. [2011]). Spatial strategies facilitate movement of livestock from a place of low resource abundance to places of high abundance (McAllister et al. [2006]). There have also been studies that use traditional knowledge to inform the development of strategies to deal with environmental variability. Traditional pastoral cultures are characterized by mobility and flexibility, adapted to spatially and temporally heterogeneous fodder production. Recent studies in rangeland science aim to understand and test the suitability of these traditional strategies for rangeland management under new conditions of global change (e.g., on the role of local knowledge (cf. Müller et al. [2007b]), evaluate the consequences of changing access regimes (Boone et al. [2005]), the role of diversification (Berhanu et al. [2007]), and impacts of institutional change on mobility (cf. Huysentruyt et al. [2009]). Similarly, Withey and van Kooten [2011] use a participatory approach to analyze changes in hunting behavior under different climate change scenarios.

3.2.3. *Decision support and policymaking under social uncertainty.* One of the problems with many traditional decision-making tools in natural resource management is that their outcomes depend on humans behaving in a defined and predicable manner. This assumption is flawed, and hence we need to be cognizant of social uncertainty as well. Unexpected responses of humans to management interventions have been identified as one of the key sources of uncertainty in fisheries management (Fulton et al. [2011]) and wildlife conservation (Keane et al. [2008]). Due to unforeseen behavioral responses of users or consumers or their noncompliance with rules, a measure taken to enhance ecosystem services does not necessarily lead to the expected outcome or may even worsen the situation.

A well-known example of such unexpected feedbacks is the rebound effect known to economists since the mid 19th century. Technological innovations to improve the efficiency of energetically costly products or systems do not necessarily lead to lower energy consumption and hence less environmental impact. This is because of both direct "rebound" or "take-back" effects that lower the price of energy, often leading to greater consumption, and indirect effects in that consumers spend more money on other energy consuming products and services since more income is available (Herring and Roy [2007]). As a result, the impact on ecosystem goods and services might worsen (e.g., the debate on efficient light consumption versus light pollution, Hölker et al. [2010]). While the literature on the rebound effect generally focuses on energy efficiency, the theory can also be applied to other natural resources. In commercial fisheries, for example, concern about greenhouse gas emissions and the recent increases in fuel price provide incentives to reduce fuel consumption, either by developing new fuel-efficient technologies or by adapting fishing practices. By modeling the spatial allocation of fishing effort, related fuel consumption, and landings distribution on a vessel-level scale, Bastardie et al. [2010] demonstrate that minimization of fishing costs under these circumstances is likely to lead to an increase in fishing effort. Cox and Walters [2002] showed that in open-access sports fisheries there is a "basic pathology in which success breeds failure," i.e., the development of high-quality fishing results in increased fishing effort until quality is reduced to be hardly any better or even worse compared to other comparable situations. Such effects should be better incorporated within models of the adaptive responses of resource users to policy change.

Management strategy evaluation (MSE) is a recent development in fisheries that integrates various sources of uncertainty in both resource and social dynamics in order to explore the full range of likely outcomes (e.g., Dichmont et al. [2006]). MSE is a simulation-based approach that provides a framework for comparing management procedures in a virtual world and is now becoming the main framework for commercial fisheries management advice (Butterworth and Punt [1999], Sainsbury et al. [2000]). It is also being introduced in a wildlife-management context (Chee and Wintle [2010]) and in catchment management (Turner et al. [2003]). MSE tests different management procedures against a set of performance metrics and instead of finding a single solution, evaluates the outcome under, often competing, objectives (economic, recreational, or conservation). The strength of MSE is that it explicitly incorporates a range of uncertainties by integrating the stochastic dynamics of the resource, the monitoring of the resource (observation error), and the management decision (implementation error). However, MSE has so far been limited to fisheries and has only recently started to incorporate human decision making (e.g., effort responses), a development that is necessary for its successful application in terrestrial conservation and management. Milner-Gulland [2011] extended the implementation error of the manager's decision by explicitly including household utility models in a terrestrial, subsistence harvesting system and showed that yield, the performance metric commonly used in most natural resource modeling, does not correlate with performance metrics of benefit to individual resource users (i.e., utility) or to conservation goals (e.g., the probability of the stock size remaining above a threshold level). The future holds many promising developments due to extensive work in fisheries (Bunnefeld et al. [2011]) and the flexibility of the MSE framework, which enables the incorporation of ecosystem dynamics (Fulton et al. [2004], Smith et al. [2007]), more realistic economics (Dichmont et al. [2008], Hoshino et al. [2010], Maravelias et al. [2010]), and individual harvester decision making (Little et al. [2005, 2009]).

3.3. Role of coevolutionary processes in SES management. SESs evolve through the interactions of users, resources and the governance, and ecological systems they are embedded in. Hence, a recurring theme in SES modeling is studying SESs as codynamic or coevolving systems where the dynamics of the social system affect the evolution of the biophysical environment, which in turn affects the dynamics or evolution of the social system (Norgaard [1994], Jeffrey and McIntosh [2006]). These feedbacks between social and ecological processes have implications for the sustainability and management of the SES (Folke et al. [2010]).

Research in this area often models agents or agent groups as individuals that respond to environmental feedback by changing their resource extraction behavior or rules, which in turn affects resource dynamics, in a bottom-up manner. Models often originate in complex systems theory or in the natural resource management fields that use bioeconomic approaches and complex utility functions to represent human decision making. Resource users adapt their behavior to perceived or real environmental change based on either simple heuristics or their individual utilities, with system behavior then evolving as a result of these interactions (see Miller and Page [2007] for an introduction to models of complex adaptive social systems). Actors in these models tend not to optimize their strategy to maximize a specific value, but are often represented as boundedly rational. Nevertheless, those approaches can converge to optimal solutions (Epstein [2006]). A major challenge for modeling SESs as coevolving systems is how to operationalize the changing relationship between trends in ecosystem services and trends in the well-being experienced by users. This is not straightforward, because human preferences adapt as circumstances change, and the anticipated effects of a particular change may bear little relationship to the reality as it evolves over time. To take an extreme example, someone's anticipated reduction in well-being when considering the loss of a limb may be extreme, but it is less obvious how they will feel 5 years after the event after having adapted to their new circumstances. This issue is important for policy makers because often they are making decisions based on anticipated relationships between ecological change and change in utility. Models of SESs that incorporate realistic representations of the linked dynamics of well-being and ecological change would be a major advance (Nicholson et al. [2009]).

An example of modeling a codynamic process using a bioeconomic approach is Hunt et al.'s [2011] study of the dynamics of social welfare and fish populations in a fishery where anglers respond to changes in the state of the fish population. Schlüter et al. [2009] use an ABM to investigate the evolution of the tradeoff between two ecosystem services derived from water use in an arid environment: crop production through irrigated agriculture and fish production in a deltaic fishery. They show that a system that evolves multiple uses of the water resource is more robust to variability in water flow, even though using water only for irrigation gives a higher economic return. Brock and Carpenter [2007] show that in situations where ecological dynamics include the possibility for regime shifts, a process of adaptive learning by agents that adjust policies based on knowledge about ecological states without taking uncertainties and spatial heterogeneity into account can lead to one-size-fits-all policies. This happens particularly in phases when system dynamics appear relatively stable.

Modeling SESs as coevolving systems acknowledges that history matters, i.e., the system's dynamics are path-dependent, such that previous developments and states of the system constrain possible future developments. Fletcher and Hilbert [2007], for example, showed that different management strategies that all yield the same long term sustainable production in equilibrium can nevertheless have very different impacts on the resilience of the system when it is far from equilibrium. Transient, irreversible, and nonequilibrium dynamics are frequently brought about by coevolving processes on overlapping time scales. For example, the integrated assessment of climate change requires addressing long-term processes that interact with rapid processes (Stecker et al. [2010]). Slowly evolving institutional rules and infrastructure systems interact with faster resource dynamics and even faster economic decisions. Understanding these relationships requires coupled models of ecological, economic, and institutional dynamics.

3.4. Understanding macroscale effects of microscale drivers of human behavior. SES modelers are increasingly taking the decision making of resource users on the individual, household, or group level into account in order to understand how fine-scale behavioral dynamics generate the aggregate spatial, temporal, and social patterns observed in SESs (e.g., Jager et al. [2000]). This represents a move away from modeling an average representative agent as is common in standard economic approaches. By representing heterogeneous agents, that base their decisions on their own specific utility function or rule, those models can also address questions about how changes in individual values or behavior affect sustainability and adaptation to changing environmental conditions at the system level. The social embeddedness of the individuals becomes important when representing individual decision making. This is because how people behave is determined both by agency (who those individuals are) and structure (in which groups of people and organizations individuals are embedded). An important research question is therefore how social norms and their interactions with environmental and other drivers affect individual human decision making and collective societal outcomes.

The two predominant approaches to including individual decision making in SES models are: (i) agent-based modeling and (ii) bioeconomic models that include specific utility functions, which vary between individuals or groups. ABMs give emphasis to the decision-making process of the agents and to the social organization in which these individuals are embedded. Bioeconomic models focus on the impact of interventions on individual utilities and behavior, and the subsequent consequences for optimal resource management. However, the distinction between those two is not clear cut, with ABMs often based on specific utilities, but potentially also including social structure or direct interactions that are not as prominent in bioeconomic approaches. In both approaches, an agent does not necessarily have to be an individual but can represent any level of organization (a herd, a cohort, a village, etc; Bousquet and Le Page [2004]).

Johnston et al. [2010], for example, used a bioeconomic approach to model the interaction of four different angler types with a fish population in a recreational fishery. Anglers react to changes in the fish population in different ways depending on their preferences for certain attributes of the fishery. Including dynamic angler response and variable compositions of the angler community into the model changes the predictions about optimal regulations compared to a static, homogeneous model. Wilson et al. [2007] use an ABM to identify factors from the adaptive behavior of competing fishers that influence the emergence of social structure facilitating self-governance of a small-scale lobster fishery. Next to the biological and technological attributes of the fishery, information availability was an important factor enabling collective action to emerge. However, effective collective action could only emerge when fishers were allowed to interfere with the fishing of other fishers. Milner-Gulland et al. [2006] use an ABM to investigate tradeoffs in the allocation of wealth and the impact of management interventions in a pastoral system. They highlight that the effect of interventions on individual decision making can be very different from expected when the perceived value of an asset is different from its expected rational economic value, e.g., when a livelihood activity is valued for its status or cultural reasons or when actors are risk-averse. Furthermore, they identify key factors that drive the dynamics of the system, such as the limitation of winter forage availability or the ability to move to distant pastures.

Modeling individual decision making beyond the rather simple specifications currently in wide use poses many challenges. Some have already been mentioned, such as identification of decision criteria and determining the role of social norms in individual decision making. Others are rooted in the many different explanations for individual behavior offered by the social sciences. Actor decision making can be based, for example, on psychological theories, space-based theories, on theories of environmental sociology or economics (see Li [2011] for a review on modeling human decisions in coupled human and natural systems). It can be an *ad hoc* heuristic informed by empirical observations or following a rigorous theoretical approach such as the rational actor model commonly used in economics (Feola and Binder [2010]; see Schreinemachers and Berger [2006] for a comparison between optimizing and heuristic behavior in multiagent systems). Furthermore, when empirical data or simulation results are available, it is not always straightforward to determine causality because of confounding external drivers or complex human decision making. In order to represent processes in a model, however, it is necessary to define a causal relationship between variables considered relevant for the given process.

While individual decision making and social structure in the form of networks is receiving increasing attention, some aspects of societal relations have so far been less well addressed. Those include aspects of power relations (however, see Geller and Moss [2008] for an example of an empirically based ABM of Afghan power structures). In particular, when SESs have a broad spatial scope, generate high economic value to some actors, or are strongly regulated by national or even international governance, power relations can play a crucial role in system dynamics. Capturing these processes requires explicit modeling of sources and effects of power relations, and a normatively neutral approach to participatory and top-down management. Power can be an important analytical category to understand the evolution of SESs, and changes in power structures may also (in specific cases) play an important role in generating sustainable pathways. Empowerment, however, can only be discussed if power is captured by model features.

4. Toward improved modeling of SESs. We propose several important next steps that need attention in order to further develop the field of SES modeling and its application to address real-world problems of resource and environmental management. These include the need for a common analytical framework for SES, the need for protocols to document SES models, and improved analysis of different types of model uncertainties.

4.1. A common framework for the analysis of SESs. Our overview of fields that are developing and applying SES models reveals a large diversity of conceptual and methodological approaches. While this diversity is very valuable and necessary to enhance our understanding of complex SESs, it also makes the accumulation and integration of knowledge about SESs across disciplines difficult. Different disciplines involved in SES modeling focus on particular aspects of SESs and base their models on different theories about human-nature interactions and human decision making. Hence, models make different assumptions, address different levels of aggregation, and use different evaluation criteria. All of these have an impact on model outcomes and their interpretation. Different disciplines also use different terminologies and concepts or definitions thereof that complicate communication and comparison of models across disciplines. Hence, in order to facilitate interpretation and evaluation of SES models across different disciplines as well as integration of knowledge and theories a common framework for SES is needed, using concepts and variables that are commonly understood across disciplines (Jeffrey and McIntosh [2006], Ostrom [2009]).

Recently, Ostrom [2007, 2009] has proposed a multitier framework for the analysis of SESs. The framework is being further developed and tested by a growing international group of scientists. It consists of a structured collection of concepts and variables that have proven to be relevant for explaining SES outcomes. At the highest level an SES consists of the variables "resource system," "resource services and units," "actor," "governance system" and "environment." These concepts consist of many other variables, e.g., the actor has a utility and knowledge, and can be further specified into different types, e.g., an angler is a type of actor. The framework thus provides a hierarchy of variables that gives the analyst and modeler an overview of concepts and variables potentially of relevance for a given research question; and, probably even more valuable, provides SES modelers from different disciplines with a vocabulary that can be used to describe a specific conceptualization of a SES.

Additionally the framework can be used for model development, particularly to guide and structure a rigorous procedure of abstracting from the target system when developing the conceptual model that underlies a specific model implementation. The aim of the framework is to make explicit the normative and theoretical choices for the representation of major variables and interactions and the empirical evidence used in model development. This facilitates model evaluation and comparison. It can also support the development of models based on different assumptions about model structure by providing a set of different possible causal relationships.

4.2. Protocols for presenting and communicating SES. The introduction of more ecological or social realism into SES models and the use of parameter-intensive approaches such as ABM make SES models more complex and thus more difficult to communicate. Some of the newer computational approaches such as ABM still lack methodological standards that facilitate easy understanding and evaluation of models and their outcomes. Recently, Grimm et al. [2006, 2010, see also Janssen et al. [2008]] have proposed the ODD protocol (Overview, Design concepts, and Details) for describing individual-based models in ecology. ODD provides a guide for presentation of the purpose of a model, its input and state variables, temporal and spatial scales considered, the processes in the model, as well as issues related to the implementation of the model such as the scheduling of events, the design concepts used, and model initialization. ODD has been extended by Schmolke et al. [2010] who propose TRACE (transparent and comprehensive ecological modeling) as a standard format for documenting not only models but also their analysis. Others have proposed protocols for ABMs of land-use cover and change (Parker et al. [2008]) or agent-based modeling in the social sciences (Richiardi et al. [2006]).

SES modeling would greatly benefit from adapting and using these standard protocols for documenting models in a comprehensive and understandable way across disciplines. This is tightly linked to the previous point of making explicit the choices made when developing a conceptual model of a SES.

4.3. Explicit consideration of model uncertainty. Another critical issue with SES modeling is the increase in model uncertainty that accompanies the linkage of ecological and social dynamics, a the more explicit consideration of complex human decision making processes, and the interdisciplinary nature of many SES modeling projects. Sources of uncertainty can be epistemic (of knowledge and understanding), ontological (of the processes themselves), and linguistic (of communication and definition). Types of uncertainty in SES models range from uncertainties in model parameters and structure (Regan et al. [2002]), to higher level ambiguities, relating to the way a problem is perceived or framed (Brugnach et al. [2011]). Parameter uncertainty can be treated with a variety of techniques, such as sensitivity and uncertainty analysis (for epistemic uncertainty, Pannell [1997], Burgman et al. [2005]), or probability distributions or interval analysis (for ontological uncertainty, Regan et al. [2002], Brugnach et al. [2008]). The impacts of model uncertainty can be assessed though sensitivity analysis, by running the model using different model structure and parameters (Burgman et al. [2005]); in practice, however, thorough exploration of model uncertainty is very rare (Burgman et al. [2005]) and physically impossible when dealing with very high-dimensional models. In this regard, pattern-oriented modeling techniques may present powerful tools to reduce uncertainty (Grimm et al. [2005], Janssen et al. [2009]).

Ambiguity is a particular problem in interdisciplinary areas such as SES modeling and is more difficult to address. Researchers from different disciplines often have different approaches to modeling, and build models to address different types of questions, as our review has shown. The best ways of dealing with ambiguity within management tend to include group decision making, communication, and participatory management, such as developing participatory models (Biggs et al. [2011], Brugnach et al. [2011]). Similar methods should be used in research, whereby models are built with input from researchers from different disciplines (Armsworth et al. [2009]), and with feedback throughout, though in reality this is rare. Ambiguity is exacerbated by linguistic uncertainty, which arises because much of our natural and scientific language is underspecific, vague, or context-dependent (Regan et al. [2002]). This is particularly relevant when working across disciplines, where similar terms are used to mean different things or different terms are used for the same concept, and when different worldviews are present. There is a range of methods for reducing linguistic uncertainty, including being specific about context and clarifying assumptions and definitions (as would be achieved through a common SES framework), as well as mathematical and statistical treatments such as fuzzy sets (Regan et al. [2002]).

For models to enhance our understanding of SESs and become more relevant for decision making in natural resource management, there is a need for better analysis of uncertainties, in particular model structure uncertainties and those arising from ambiguity. There are many SES models that do no or only rudimentary uncertainty analysis, which makes interpretation of their results difficult. One field that has most required a systematic treatment and presentation of uncertainty is predictions of climate change and its impacts. Here, novel methods for disentangling and presenting the effects of different types of uncertainty, such as parameter, model and scenario uncertainty, have been developed that may provide a useful way forward for other fields (e.g., Hawkins and Sutton [2009]).

5. Conclusions and outlook. SES modeling is an emerging field that conceptualizes human-environment systems as dynamic and interlinked. The field of SES modeling is characterized by approaches that take relevant real-world ecological and social structure and dynamics into account by incorporating more sophisticated models of human behavior and ecological dynamics. We have identified a diversity of modeling approaches that address resource management problems from an SES perspective with different focuses and at different levels of aggregation (top-down or bottom-up). The diversity of theories and methods is very valuable in generating insights on different aspects of those complex systems and provides for a process of critical questioning and improvement. SES modeling provides a framework for cross-fertilization between the different fields. However, conceptual integration of the insights gained from individual studies remains a challenge. Common frameworks and protocols for SES analysis, modeling, and model communication are currently being developed and will, hopefully, help the field to further develop an integrated knowledge base.

Key issues addressed with SES models are connected to their nature as complex adaptive systems, with concomitant implications for management. A major cross-cutting issue in SES research is the need to cope with the uncertainty inherent in these systems. Uncertainty affects model conceptualizations of SESs as well as SESs management itself. With respect to resource and environmental management, the emphasis is shifting from trying to reduce uncertainties toward developing strategies and institutional arrangements for coping with uncertainties. Such models take a resilience approach, where rather than trying to make any one "best" decision, the ability to persist is based upon embedding the ability to deal with resource abundance patterns that vary in both time and space. With respect to model conceptualization, uncertainty is aggravated by the need to consider both ecological and social dynamics. When modeling SESs, one has to accept that there is no single correct or best model for a given problem setting. Instead, SES modelers have to rely on developing suites of models that offer different perspectives and insights into a complex problem. The multiple model approach acknowledges that there is often no single best solution that one can find through optimization, but that the whole spectrum of possible options needs exploration in order to develop strategies that are robust to changing conditions.

Another issue that is receiving much attention in the field of SES modeling is that SESs are both self-organizing and controlled by human intervention, with both processes often interacting in unintended ways. This has motivated research into the coevolution of SES based on the interactions of social and ecological dynamics, the emergence of macroscale patterns from microscale drivers of human behavior, and ways to cope with these dynamics in natural resource management.

Our overview shows the large potential of SES modeling to contribute to a better understanding of the dynamics of SESs, their sustainable management, and adaptation to global change. Current approaches, however, also show major limitations. While SES research is primarily problem-oriented, the majority of SES models so far remain largely theoretical. Modeling of SESs using agent-based approaches, for example, has mostly been applied to address theoretical issues providing a "proof of concept" rather than solutions to empirically measurable phenomena (Janssen and Ostrom [2006]). It is still an open question as to whether SES models are only useful as research tools for developing the underlying knowledge base (Matthews et al. [2007]) or also as tools for operational decision support. It might be, for example, that models seen as tools to aid the "learning-in-action" process are more likely to be used in practice than those seen as repositories of knowledge (McCown [2002]). It also remains to be shown whether SES models are able to solve problems in the real world better than traditional modeling approaches (Matthews et al. [2007]).

A better linkage between SES models and real-world problems can be achieved by: (i) parameterizing SES models with empirical data, e.g., using data from random utility models to specify human decision making (e.g., Massey et al. [2006], Hunt et al. [2011]), (ii) by comparing model results with empirical patterns observed in large data sets (e.g., Wilson et al. [2007]), and (iii) most importantly, by integrating models with empirical research and management in an adaptive manner (Walters 1986). There are too few models that follow those three suggestions. A closer connection to real-world case studies will also contribute to better validation of SES models, which is another serious limitation of current applications. A constant process of model revision based on comparing model outcomes with real-world observations can help to improve the development and application of SES models. This tight linkage of model development, analysis, application, evaluation, and model refinement within an adaptive framework represents the only suitable way forward to better understand the feedbacks between resource users and their resources and to provide management advice that is relevant and useful to decision makers.

Several issues pertinent to natural resource management under global change have not yet received much attention in SES modeling. These include the role of individual and social learning in resource management, adaptation to climate change, and models of institutional dynamics. Learning is a central issue in the (adaptive) governance of natural resources. It is an essential mechanism for dealing with changing boundary conditions caused by institutional, sociopolitical or environmental change. Learning can happen at the individual and collective level (so-called social learning; Reed 1979). Research on social learning processes and adaptive governance within SES models is only just beginning. Despite this, several studies have applied models to support actual learning in natural resource management within participatory processes (e.g., Etienne [2003], Gurung et al. [2006], see also Sandker et al. [2010] for a review of participatory modeling in landscape approaches to development and conservation). Adaptation of ecosystems, individuals, and societies to climate change has been the focus of fields such as resilience research and climate change adaptation. While it is relatively straightforward to extend existing SES models to include a climatic component, it is a further challenge to move beyond pure sensitivity studies (that assess how a system is affected by environmental change) to models of adaptation that endogenously incorporate conscious responses of human actors to change. The same applies to institutional dynamics: while the impact of exogenous institutional change on agent behavior and subsequent resource dynamics has been the focus of various SES models, there are only a few that model endogenous institutional change (e.g., Smajgl et al. [2008]).

Given the recent developments reviewed here and the challenges ahead, we expect promising developments in modeling SESs in the near future with respect to: (i) exploring dynamic social-ecological linkages and their effect on SES resilience in a more rigorous way, (ii) assessing tradeoffs between and management of multiple resources, (iii) studying the implication of interlinked time scales, (iv) accounting for the multiple roles of social networks in dealing with natural resource problems and the need to engage different networks at different stages of management, and (v) combining SES modeling with experimental and field research to enhance our understanding of those complex systems (see e.g., Janssen and Ostrom [2006], and Baumgärtner et al. [2008] for a discussion of the role of models as mediators between theory and case studies).

Our overview of approaches that conceptualize and model human-environment systems as SESs has shown how the field, in resource management at least, has emerged from somewhat separate applications. Research on fisheries, wildlife, and rangelands, and from within interdisciplinary fields such as resilience or complex systems theory, have all contributed to the emergence of SES modeling. There is a great potential for SES models to help researchers address problems that originate from and are impacted by the complex and nonlinear nature of SES.

There is also potential for SES models to support the development of management strategies and approaches that provide opportunities to cope with uncertainty and that react to changing environmental and social conditions in a flexible way. However, to advance the field of SES modeling, issues of model uncertainty, the lack of a common framework and standards for model communication, and poor integration of models with real-world problems need to be readdressed.

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