

LETTER

Where are Ecology and Biodiversity in Social–Ecological Systems Research? A Review of Research Methods and Applied Recommendations

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Applied research; interdisciplinary; social–ecological systems; sustainability science; systematic literature review.

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Abstract

Understanding social–ecological systems (SES) is critical for effective sustainability and biodiversity conservation initiatives. We systematically reviewed SES research to examine whether and how it integrates ecological and social domains and generates decision-relevant recommendations. We aim to inform SES research methods and improve the relevance of SES research. Of 120 SES articles, two-thirds included an ecological variable while all but one included a social variable. Biodiversity was a less common ecological variable than resource productivity, land cover, and abiotic measures. We found six diverse social–ecological linking methods: modeling (9%), causal loop diagrams (18%), quantitative correlations (8%), separate quantitative measures (13%), indicators (14%), and rich description (37%). Policy recommendations addressing social–ecological dynamics were more likely in articles including both ecological and social variables, suggesting the importance of research approach for policy and practice application. Further integration of ecology and biodiversity is needed to support governance, policy, and management for SES sustainability.

Introduction

Understanding the dynamic connections between ecological and social systems is critical for the design of effective sustainability and biodiversity conservation initiatives (Liu *et al.* 2007; McClanahan *et al.* 2008). Research on social–ecological systems (SES) is rapidly advancing to understand relationships between social and ecological conditions, interactions, and outcomes (Ostrom 2009). In response to calls for interdisciplinary and solutions-oriented research (Metzger & Zare 1999; Palmer *et al.* 2005), governments and foundations have increased their investments in SES research (MA 2005). To make strong recommendations for SES sustainability, researchers must know how ecological and social dynamics relate. We conducted a systematic review to examine whether and how SES research is achieving interdisciplinarity across ecological and social domains to generate decision-relevant recommendations, with a focus on the roles of ecology and biodiversity.

SES research focus and methodologies are just beginning to be assessed (Binder *et al.* 2013), leading to an emerging concern about whether the “E” is sufficiently represented in SES research (Vogt *et al.* 2015). Following SES terminology, we understand ecological to mean ecological or environmental variables. Folke *et al.* (2005) indicate the importance of integrating social and ecological analyses, suggesting that social-only research “will not be sufficient to guide society toward sustainable outcomes,” while ecological-only research “as a basis for decision making for sustainability may lead to too narrow conclusions.” The SES field represents an important effort to develop innovative research methodologies to operationalize transdisciplinary research (Ostrom 2009) and provide more comprehensive analyses and implications than research focused on social or ecological dynamics alone (Folke *et al.* 2005). Researchers face numerous choices in framing, design, and analysis that influence their recommendations and the visibility of

certain topics. We focus on four key issues in SES research: the choice of social and ecological variables, methods for linking social and ecological measures, recommendations for policy and management, and framing of human–environment relations.

The first two key issues – the choice of social and ecological variables and methods for linking them – reflect diverse disciplines, epistemologies, and applications (Binder *et al.* 2013). Many of the first SES researchers were modelers, but a wide range of methodologies are now used to understand relationships between diverse quantitative and qualitative variables (Miller *et al.* 2008). Evolving disciplinary and epistemological communities influence researcher choice of variables. For example, the SES framework, developed through the Ostrom Workshop, originated with social scientists conducting institutional analyses of the commons (Anderies *et al.* 2004; McGinnis & Ostrom 2014). Other SES research emerged from natural scientific inquiry, such as resilience analysis (Berkes *et al.* 2003). Each approach suggests different variables and methods for analysis, influencing findings and applications.

A third key area of methodological interest lies in how SES researchers translate findings into relevant recommendations. SES research promises to enhance outcomes by providing guidance for policy on improving SES sustainability or resilience (Berkes *et al.* 2003; Folke 2006). Less is known, however, about how frequently policy recommendations are made or which SES aspects they address. Although some SES frameworks are designed to diagnose opportunities and obstacles for increasing sustainability (Ostrom 2007), it is not clear whether SES articles with both ecological and social variables are more likely to make recommendations. Diverse SES research approaches are likely to differ in how they inform policy and management, and how policymakers might draw on SES research to improve outcomes.

Finally, the framing of human–environment relationships is another important methodological issue (Binder *et al.* 2013). Ecosystems both provision and present risk for humans (Turner *et al.* 2003; Ostrom 2009). Common pool resources research has historically focused on services or benefits to humans from fisheries, forests, and water. Vulnerability research often focuses on people's exposure and sensitivity to environmental harms. We engage these different conceptualizations of human–environment relations as an opportunity to reflect on SES research's historical legacies, trajectories, and applications for policy and management.

The aim of this research is to better understand emerging SES research and help researchers anticipate how their methodological choices may impact research

relevance for policy and management. We reviewed 120 SES research articles and posed four questions:

- (1) How are ecological variables incorporated in SES research?
- (2) How do researchers analyze connections between social and ecological variables?
- (3) Does SES literature make applied recommendations for SES sustainability, and do these recommendations differ for articles with ecological variables compared to those without?
- (4) How does SES literature frame human–environment relationships?

Review Methodology

We retrieved 425 articles with a title, abstract, or keyword phrase of “socio-ecological” or “social-ecological” in Web of Science before August 2012, excluding health sciences fields, in the 10 English-language journals with the most SES publications (see Supplement 1). We restricted this sample to 290 articles reporting empirical results and then randomly selected 120 articles due to researcher capacity.

We coded articles for variables, connections between independent variables (IVs) and dependent variables (DVs), methods, recommendations, and framing of human–environment relationships (Table S2). We identified articles as social–ecological if they included both a social variable (socioeconomics OR governance OR resource management) and an ecological variable (resource productivity OR land cover OR biodiversity OR abiotic). We then categorized the primary methods for linking social and ecological variables. Most articles had identifiable IV–DV connections (101 of 120); we categorized 985 IV–DV connections in these 101 articles. We asked if articles with social and ecological variables were more likely than social-only articles to have different methods, recommendations, and human–environment framings. Differences between social–ecological and social-only articles were examined with two-tailed chi-squared tests. Among the social–ecological articles, we also analyzed whether articles with different social–ecological linking methods were more or less likely to make SES recommendations. Five tests of intercoder reliability were conducted during the coding period in which researchers read and coded the same article and compared results in order to identify and norm variations in coder interpretation.

Results

Ecology and biodiversity in SES research

The SES literature is diverse and emphasizes social variables. Two-thirds of articles (66%, 80 of 120) included

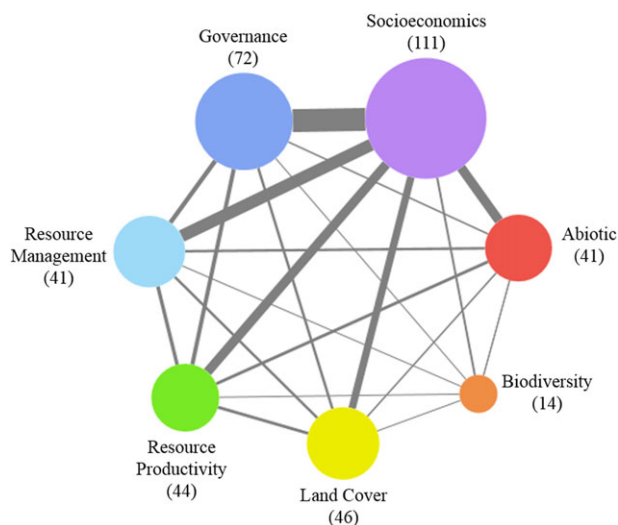


Figure 1 Bubble size and number in parentheses indicate the number of articles that include each type of variable ($n = 120$). Line width indicates the number of articles with each type of IV–DV connection ($n = 101$). Line lengths do not signify meaning.

both social and ecological variables. One-third (33%, 39 of 120) had social variables but no ecological variables, and one article had ecological but no social variables. Socioeconomic variables were most likely to be examined, and were commonly associated with governance, followed by resource management and then resource productivity (Figure 1). Connections between biodiversity and other variables were least commonly researched.

Of the 101 articles with identifiable IV–DV connections, 86 examined if a social IV influenced (\rightarrow) a social DV, 42 ecological IV \rightarrow social DV, 36 social IV \rightarrow ecological DV, and 27 ecological IV \rightarrow ecological DV. This illustrates that the SES literature is most focused on interactions among social variables, followed by the influence of ecological variables on society. When considering all seven variable categories across the 985 IV–DV connections, we found that abiotic, governance, and socioeconomic variables were more often IVs than DVs, while land cover, resource productivity, resource management, and biodiversity were more often DVs (Table 1).

Linking social and ecological variables in analysis

In response to our methods question about how researchers make connections among social and ecological variables, we found that SES literature includes both qualitative and quantitative methods, with somewhat more emphasis on qualitative methods. Half the arti-

Table 1 Percent of the 985 independent variable–dependent variable (IV–DV) connections in which each variable was an IV or a DV

		IVs (percent of IVs)	DVs (percent of DVs)
Social	Socioeconomics	53.8%	47.5%
Social	Resource management	8.5%	14.5%
Social	Governance	14.9%	12.5%
Ecological	Resource productivity	4.2%	9.3%
Ecological	Land cover	6.2%	8.0%
Ecological	Abiotic	11.5%	4.5%
Ecological	Biodiversity	0.9%	3.7%

cles (51%) were qualitative-only, one-third (32%) were quantitative-only, and 17% included both qualitative and quantitative methods. Most (62%) of the social-only articles were qualitative, while only 41% of social–ecological articles were qualitative, a statistically significant difference ($\chi^2 = 3.910$, $P = 0.048$). The majority (55%) involved a single case study, 41% had multiple case studies, and 21% were large- n studies ($n > 30$). The time span of phenomena analyzed varied widely from under 1 year to 2,500 years, with a median of 7 years. Nearly half (44%) examined a span of 10 or more years.

We identified six primary methods for linking social and ecological variables: modeling, causal loop diagrams, quantitative correlations, separate quantitative measures, indicators, and rich description (Figure 2 illustrates five of these approaches). We provide a definition, one strong example from our sample, and strengths and weaknesses for each linking method.

Social–ecological modeling

Mechanistic modeling was deployed in 9% of articles (11 of 120) to explain or predict causal relationships among social and ecological system components. In one article, a multiagent model of lobster fisher behavior is linked to a biophysical model of a patchy natural environment, which reveals when individual incentives are aligned with collective action (Wilson *et al.* 2007). SES modeling is “maturing as a discipline in its own right” drawing on natural resource modeling and complex systems research to tackle nonlinear behavior, cross-scale and interdependent dynamics, and uncertainty (Schlüter *et al.* 2012). Models allow for the comparison of scenarios and policy options. Disadvantages include extensive and expensive data requirements, difficulty of modeling all system components, lack of transparency, and difficulty of communicating methods and results to nonexperts.

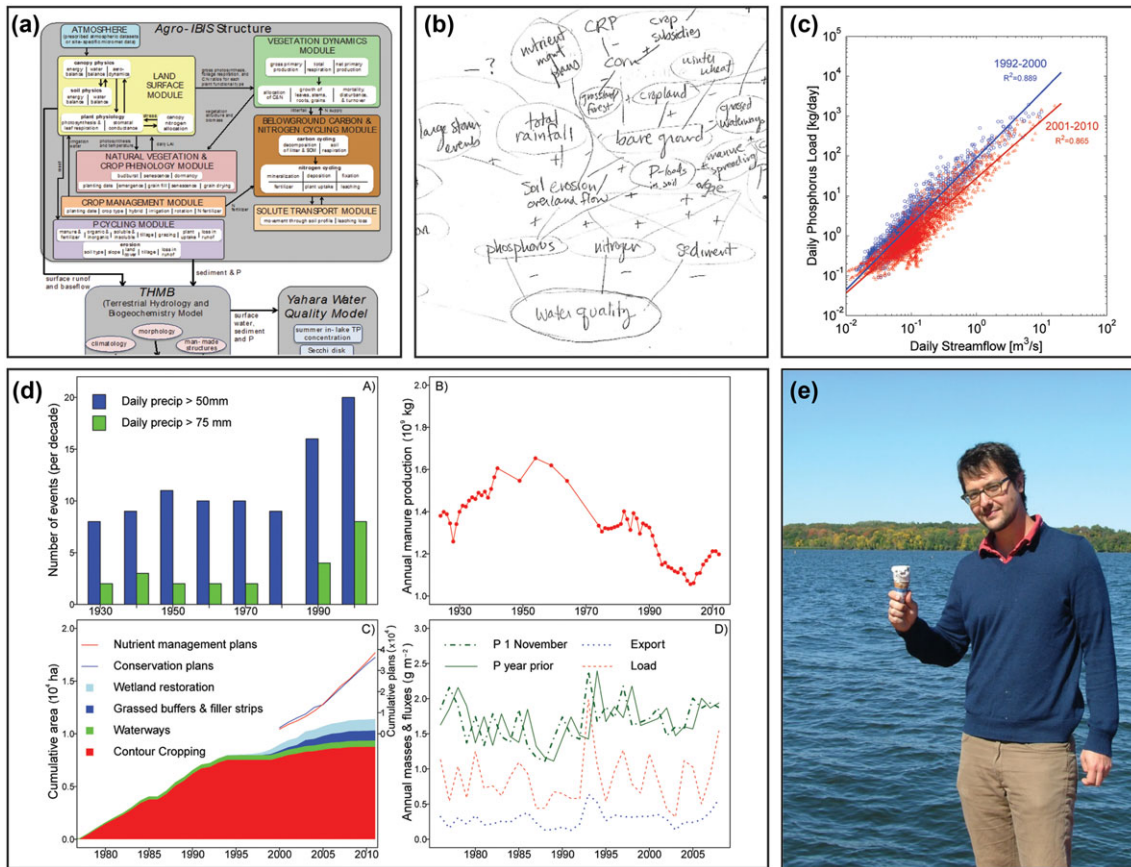


Figure 2 Methods for linking social and ecological research with examples from the Yahara Watershed, Wisconsin including (a) **models** of land use, plant and soil dynamics, and water, (b) **causal loop diagrams** such as this drawing from a participatory workshop, (c) **quantitative correlations** such as this phosphorus load-streamflow correlation showing improvement after new practice implementation, (d) **separate quantitative measures** presented together of precipitation, manure, conservation practices, and phosphorus loads, and (e) **rich description** that probes underlying causation – can we have ice cream from cows upstream and clean lakes too? (Carpenter *et al.* 2015; Gillon *et al.* 2015).

Causal loop diagrams

One-fifth (18%) of articles presented system dynamics through causal loop diagrams (called influence diagrams, cognitive mapping, or mental maps). Causal loop diagrams typically translate qualitative information into simple quantitative relationships with negative and positive feedback loops. For instance, Fazey *et al.* (2011) developed a conceptual model of SES change in the Solomon Islands based on 76 focus groups, which revealed that population growth and a desire for monetary prosperity “act synergistically to generate stress in communities” and result in “maladaptive trajectories of change” including declining provision of ecosystem services from fisheries, forests, and subsistence gardens. An advantage of causal loop diagrams is their relatively accessible communication of complex feedback dynamics involving many variables; a disadvantage is that the simple positive or negative polarity of loops may inad-

equately describe complex and variable relationships and obscure threshold effects (Richardson 1986).

Quantitative correlations

Only 8% of articles relied on statistical analysis to correlate social and ecological variables, with or without causal inferences. For example, in a study of over 50 marine reserves, multiple linear regression identified relationships between fish biomass (from visual census) and indices of socioeconomic development, compliance with reserve rules, human population, and democratic participation (largely from surveys) (Pollnac *et al.* 2010). Statistical correlations provide a quantifiable measure of association among variables but often exclude difficult-to-measure system components, ignore cross-scale dynamics and threshold effects, and may not allow for causal inference.

Separate quantitative measures

In 13% of articles, quantitative data on different social and ecological variables were linked through narrative or graphic visualization. For example, an interdisciplinary project in the Siberian Arctic narratively tied together three types of results that together told a nuanced story of social and environmental change: anthropological observation of migratory herders; remote sensing of land cover change; and field sampling of vegetation biomass (Forbes *et al.* 2009). Separate quantitative measures can accommodate differences in measurement, timing, and scale among disciplines but do not provide estimates of the mean, variance, or causal relationships among system components.

Indicators of the link

In 14% of articles, an index or composite indicator linked social and ecological variables through a mathematical calculation. Vulnerability indices, sustainability indices, resource metabolism rates, and per capita resource abundance levels quantify the link between humans and environments. For example, human appropriation of net primary production indicates the extent to which humans have appropriated natural resources (Krausmann *et al.* 2012). Indicators summarize complex information, attract public attention, and communicate a simple “big picture” to policymakers. However, they can encourage simplistic policy conclusions, obscure complex dynamics and subindicator variability, and ignore local context (European Commission Composite Indicators Research Group 2015).

Social–ecological rich description

One-third (37%) of articles provided a rich narrative, or what could be termed a social–ecological thick description, of the complex intertwining of social and environmental phenomena with little to no quantitative data. Rich or thick description involves detailed information that ascribes intentionality to behavior with specific information about the context of a situation (Creswell & Miller 2000). For example, through ethno-biological interviews and analysis of historical documents and maps, researchers traced a century of decline and renewal of managed forests of chestnuts and holm-oak-associated truffles, shaped by cross-scale socio-political legacies, values, knowledge, technology, economies, and institutions (Aumeeruddy-Thomas *et al.* 2012). Rich description allows for causal analysis and the interplay of complex system components, but does not quantify the importance of factors and may not systematically define system components to facilitate comparisons.

Making recommendations

Most articles (71%) included recommendations for policymakers, managers, or community members. Articles with social and ecological variables were significantly more likely than social-only articles to make recommendations that addressed interlinked social and ecological systems (Table 2). Articles tended to recommend big-picture shifts in governance, calling for institutional change or capacity increases rather than specific changes in policy or practice. Biodiversity conservation was uncommon as a focus of recommendations. We found only one statistically significant association between the six linking method and type of recommendation: quantitative indicator articles were more likely than SES articles with other linking methods to make recommendations for integrative social–ecological change ($n = 80$, $P = 0.018$), although small sample sizes suggest caution in interpretation (see Table S3 for additional information).

Framing human–environment relationships

Social–ecological articles were more likely than social-only articles to consider environmental benefits to humans and how humans negatively impact the environment (Table 3). Social–ecological and social-only articles were equally likely to consider environmental risks to humans. In contrast, social-only articles were more likely to consider how humans affect other humans, suggesting a trade-off between examining social equity and social–ecological dynamics.

Discussion: insights, challenges, and opportunities for ecology in SES

Research methodologies matter for the relevance of research findings. Articles with ecological and social variables were over twice as likely to make recommendations addressing integrated SESs, compared to social-only articles. One-third of articles did not link social and ecological variables, and only 12% included biodiversity measures. This confirms the concern that many SES publications do not couple social and ecological aspects of systems (Epstein *et al.* 2013). By focusing on SES research, we likely included more social science than in “coupled human and natural systems” or natural resource management literatures, which could be compared in the future. In order to make strong recommendations about improving SES sustainability, we need to understand how ecological dynamics relate to social conditions.

Approaches for linking social and ecological variables are widely divergent. We identified six primary linking methods that could help interdisciplinary teams

Table 2 Articles with social and ecological variables were more likely to have recommendations for social–ecological systems; statistical tests compare social–ecological with social-only articles (record numbers refer to articles in Supplement 2)

	Overall (<i>n</i> = 120)	Percent of social–ecological articles (<i>n</i> = 80)	Percent of social-only articles (<i>n</i> = 39)	χ^2	<i>P</i> -value
Any recommendation	71%	73%	69%	0.137	0.711
Social–ecological system recommendation	29%	38%	13%	7.692	0.006
Social system recommendation	55%	54%	59%	0.290	0.590

Social–ecological system recommendation examples:

“Long-term solutions to **scale mismatch problems** will depend on **social learning** and the development of **flexible institutions** that can **adjust and reorganize in response to changes in ecosystems**” (Record 24).

“Unless one **ensures the livelihoods** of those living around or within a forest, a major **investment in monitoring** alone is **not a sufficient, long-run management strategy** and may even be counterproductive” (Record 76).

“While we do not expect farmers or agricultural communities to ‘turn back the clock’ on time and technology, **initiatives that foster diversification** within and among agricultural landscapes, rather than their further homogenization, may be more likely to achieve the common goal of enhancing agricultural sustainability” (Record 13).

Social system recommendation examples:

“Addressing issues such as **corruption, transparency, and stability** of national governments will be key to building **effective social organization and adaptive capacity** at all scales” (Record 21).

“The results suggest **development policy** . . . needs to . . . increase **emphasis on well-being** aspects of development rather than **income generation per se**” (Record 109).

“We urge other researchers and practitioners to focus more strongly on **human relationships** and **capacity** and the **flexibility** they can create in other conservation initiatives in which local governance may be an option” (Record 9).

Table 3 Framing human–environment relationships; statistical tests compare social–ecological with social-only articles

	Percent of all articles (<i>n</i> = 120)	Percent of social–ecological articles (<i>n</i> = 80)	Percent of social-only articles (<i>n</i> = 39)	χ^2	<i>P</i> -value
How humans manage the environment	82%	86%	72%	3.635	0.057
Benefits or services the environment provides to humans	57%	65%	41%	6.153	0.013
How humans negatively impact the environment	54%	63%	36%	7.465	0.006
How humans affect other humans	48%	43%	62%	3.804	0.051
Environmental or ecosystem change and its consequences for ecosystem service provision to humans	45%	56%	23%	11.640	0.001
Environmental harms, threats, or risks to humans	43%	44%	41%	0.079	0.778
The authors conceptualize human and environmental systems as separate	42%	36%	54%	3.332	0.068
The authors suggest that humans and environment cannot be analyzed independently	32%	39%	18%	5.219	0.022

conceptualize their collaborative articles and help policymakers decide what research to prioritize. Further research on these linking methodologies could examine the trade-offs that individuals and research teams face when selecting methodologies and the contributions of analyses for diverse decision contexts.

Elements of ecosystems such as land cover, resource production, and abiotic conditions were most commonly measured, followed distantly by biodiversity. When biodiversity is measured directly, studies can reveal promising social pathways for biodiversity protection (López-

Angarita *et al.* 2014). The spatial and temporal scale of variables measured is also important for coupling social and ecological data (Gillon *et al.* 2015). Few analyses address the feedbacks among social dynamics, conservation initiatives, and linked social–ecological outcomes, although such analyses may effectively inform future policy (Miller *et al.* 2012).

Methodological pluralism is likely an advantage to the field since different methods answer questions in different situations better than others. Narrative, visual, and mathematical links between social and ecological

can produce fascinating insights, and research scope influences the resulting recommendations. Quantitative studies rely on modeling and statistics to link social and ecological variables, indicating the necessary or likely characteristics that predict sustainable resource or livelihood outcomes. For instance, models have substantial utility for testing the effects of policy options (e.g., Guzy *et al.* 2008) and often underpin environmental policies (Rissman & Carpenter 2015). Beyond direct utility as perceived by decision makers, SES research often critiques existing environmental or economic policies as overly simplified, unsustainable, insufficiently protective of people or environments, and oblivious to local context and culture (e.g., Zimmerer 2011). Rich descriptions, for example, may explore policy outcomes and explain how and why change occurs. Our findings might provide better understanding of the implications of diverse research approaches for generating information and recommendations. Clear analytical pathways would provide structure for researchers and science funders seeking best practices, comparative analysis, and usable research.

The framing of human–environment relationships varied widely in the SES literature. Humans were equally likely to be framed as threats to ecosystems or as beneficiaries of ecosystem services, while fewer articles examined environmental threats to humans. Social–ecological articles were less likely to consider relations among humans. This finding illustrates a potential trade-off in focusing on social–ecological linkages or on complex dynamics among social groups including issues of equity and power.

Social–ecological research faces obstacles, including disciplinary incentives, cultures, epistemologies, funding, and transaction costs (Metzger & Zare 1999; Pooley *et al.* 2014). Analysis that connects changes in environments, technology, knowledge, organization, and values faces an internal tension between mind-opening integration and the analytical categorization that supports empirical scholarship (Kallis & Norgaard 2010). We experienced this tension in categorizing articles, some of which aimed to break down the very categories of social and ecological.

Many opportunities exist for social scientists and ecologists to increasingly engage in cross-domain research. Ecologists are undertaking innovative SES research, and the sophistication and growth of SES research is increasing (Binder *et al.* 2013; McGinnis & Ostrom 2014). Greater systemization of methodologies is allowing for comparative work (Cox 2014), and new syntheses of research approaches are being developed to train scholars (Wiek *et al.* 2011). Transdisciplinary teams would benefit from increased resources and from reflection on how methodological routes impact knowledge destinations (Mattor *et al.* 2014).

In conclusion, better integration of ecology is needed in SES research. We have demonstrated that variable selection and methodology influence SES recommendations. Further development of quantitative and qualitative linking methodologies is needed, as is increased effort in research coordination and training. Biodiversity measures remain uncommon in the SES literature, which suggests a potential challenge and opportunity for integration. Clear links between ecological and social dynamics, feedbacks, and outcomes are needed to effectively inform policy and management and improve the social–ecological fit of conservation strategies (Bodin *et al.* 2014). Achieving this will require continued attention to methodological choices, shifts in incentives and training, and engagement with policymakers and practitioners.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

- Supplement 1.** Sampling Methodology, Variables, Definitions, and Additional Analysis
- Supplement 2.** Articles Reviewed

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