

Research

Methods for understanding social-ecological systems: a review of place-based studies

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ABSTRACT. In recent years, social-ecological systems (SES) have emerged as a prominent analytical framing with which to investigate pressing sustainability issues associated with the Anthropocene era. Despite the growth of SES research, the lack of a delineated set of methods commonly contributes to disorientation for those entering into a field where methodological pluralism is the norm. We conduct a review of SES research, focusing particularly on methods used in this field. Our results reflect the rapid growth in SES research relative to other publications in relevant subject areas, and suggest a maturation of the field. Whilst institutions investigating SES have been mostly based in the global north, focal SES has been more globally distributed, although key regions, especially island regions, remain poorly studied. Key problems addressed in the studies related to policy, trade, conservation, adaptation, land use change, water, forests, sustainability, urban problems, and governance and institutions. We identified 311 methods, which we grouped into 27 method categories that can serve as a guide to SES research methods for newcomers to the field. We also performed an exploratory assessment of the ability of these methods to account for key features of SES as complex adaptive systems. We found that methods do better at accounting for the relational and context-dependent nature of SES, and least well with complex causality. Our study highlights the plurality of methods used in SES research, and helps highlight key areas in need of further methodological development.

Key Words: *complex adaptive systems; global change; methodological pluralism; methods; place-based; resilience; social-ecological systems*

INTRODUCTION

Human activities are changing the ecosystems upon which humanity depends in unprecedented and profound ways (Rockström et al. 2009). In the fast-changing and ever-more-connected era of the Anthropocene (Rockström et al. 2009, Steffen et al. 2011), the environmental and social challenges we face demand better understanding of the complex and evolving links between ecosystems and human societies (Rockström et al. 2009, Fischer et al. 2015). The concept of social-ecological systems (SES) has emerged as a key conceptual and analytical framing with which to understand the connections and feedbacks between social and environmental interactions in real-world systems (Carpenter et al. 2012, Fischer et al. 2015, Colding and Barthel 2019). The concept has helped facilitate increased recognition of the dependence of humanity on ecosystems (Díaz et al. 2006, Summers et al. 2012, Wu 2013), has improved collaboration across disciplines and between science and society (Carpenter et al. 2012), has increased methodological pluralism that has led to improved systems understanding (Levin et al. 2013, Tengö et al. 2014, Lade and Niiranen 2017, Preiser et al. 2018), and has manifested in major policy frameworks and initiatives, such as Future Earth (Rockström 2016) and the Sustainable Development Goals (Díaz et al. 2015a, Fischer et al. 2015). Recent years have also seen the emergence of new research areas (Folke 2006), modeling approaches (Schlüter et al. 2012), and analytic frameworks (Turner et al. 2003, Janssen et al. 2006, Collins et al. 2011, Bodin and Tengö 2012, Schlüter et al. 2019).

Despite progress, SES research remains challenging (Fischer et al. 2015, Turner et al. 2016, Haider et al. 2018). Central to this challenge is the recognition that SES research represents an emergent “third” space that transcends the mere sum of social and ecological research practices and disciplines (Walker et al. 2006, Liu et al. 2007a, Folke et al. 2016). Many methods and

approaches used in SES research do not fall within the realms of traditional social and natural sciences, or any singular discipline, and as a result SES as a research field lacks its own coherent methodological identity, instead drawing strongly on methodological pluralism (Tengö et al. 2014, Folke et al. 2016). Fluidity of identity is also evident in the multiple terms used to describe SES (e.g., coupled human-environmental systems, man-environmental systems), varied definitions for what SES are (Herrero-Jáuregui et al. 2018, Colding and Barthel 2019), and the different ways that SES are spoken about in academic literature, ranging from a boundary object to bridge disciplines (Hertz and Schlüter 2015) to describing real epistemic systems that can be understood using empirical methods (Becker 2012).

Although a variety of conceptual and methodological ambiguities plague this emerging research area, there is sufficient coherence to enable analysis of key dimensions of this research field. All SES research has in common a nomenclature that designates the object of study as having integrated social and ecological components, as is also reflected in the names of prominent journals in the field. Indeed, several recent reviews have attempted such analyses of the SES field (Binder et al. 2013, Turner et al. 2016, Herrero-Jáuregui et al. 2018, Partelow 2018, Colding and Barthel 2019). From these reviews, it is clear that SES research, which is often approached alongside concepts such as ecosystem services, sustainability science, and transdisciplinary research (Brandt et al. 2013, Turner II et al. 2016, Haider et al. 2018, Herrero-Jáuregui et al. 2018, Partelow 2018), has grown over the past 20 years (Droste et al. 2018, Herrero-Jáuregui et al. 2018, Colding and Barthel 2019). Having its origins in place-based, local resource management studies (Colding and Barthel 2019), the field is still largely characterized by place-based studies, especially at the local scale (Norberg and Cumming 2008, Becker 2012, Angelstam et al. 2013, Hertz and Schlüter 2015, Folke et

Erratum: In the original publication Figure 1 was incorrect. The correct Figure 1 was put into place on 20 January 2020.

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al. 2016). Meta-approaches/comparative analyses and framework development are, however, also often conducted (Partelow 2018). Indeed, several large databases now exist to collect case studies for meta-analyses, e.g. SESMAD, SESGO, IFRI (Partelow 2018). SES research derive from a broad range of disciplines, including the environmental, social, agricultural, biological, Earth and planetary, and computer sciences, as well as medicine and the humanities (Colding and Barthel 2019). Although the focus of SES research has shifted slightly over time (Droste et al. 2018, Herrero-Jáuregui et al. 2018), studies on adaptive management, governance, restoration, and poverty alleviation in sectors such as fisheries, forestry, and watersheds have been popular throughout (Droste et al. 2018, Herrero-Jáuregui et al. 2018, Partelow 2018).

A picture of the SES field has thus started to emerge, but the SES concept is nevertheless still in transition (Herrero-Jáuregui et al. 2018), and there are gaps in our understanding of how the field functions and develops (Colding and Barthel 2019). Aside from lacking a broadly agreed-upon definition for SES (Herrero-Jáuregui et al. 2018, Colding and Barthel 2019), much of this gap relates to the methodological pluralism that characterizes the field (Partelow 2018). Methodological pluralism creates challenges for synthesis and data comparison, in part because it is more difficult to know what methods can and should be used in research (Partelow 2018). Lack of methodological transparency hampers attempts to generalize across case studies and frameworks (Magliocca et al. 2018, Colding and Barthel 2019), and can prove particularly challenging for postgraduate students and other early-career researchers (Haider et al. 2018). Understanding and interrogating methods used in the SES field is also important because of the nature of the systems being investigated. There is increasing agreement that SES can be conceptualized as complex adaptive systems (CAS) (Liu et al. 2007b, Levin et al. 2013, Rogers et al. 2013, Folke et al. 2016, Preiser et al. 2018, Herrero-Jáuregui et al. 2018), which place demands on the approaches and methods that SES researchers employ (Preiser et al. 2018), and necessitates an understanding and interrogation of the methods used in the field.

We thus expand on recent reviews of the development of the SES field, focusing specifically on the methods used in empirical, place-based SES research. We define methods as codified ways of producing knowledge of a focus of interest, a specific information-generating practice (Pahl-Wostl et al. 2013, Stirling 2015). By having a clearer idea of the range of methods that SES researchers are using when engaging in real-world problem-solving or solution-based research, we can improve our characterization of SES research as a field of inquiry, and also help guide researchers new to the field in identifying and selecting appropriate research methods.

We used a systematic review approach to conduct a broad analysis of the different terms being used to study coupled social and ecological systems and characterize these studies according to their type, distinguishing place-based studies from studies that outline “frameworks” and “reviews.” Focusing on a subset of place-based research, we then identified the journals, institutions, and countries in which SES have been studied, and how these have changed over time. Having broadly contextualized SES research, we identified a large set of methods used in place-based research,

and explored the topics or problems they have most commonly sought to investigate. We summarized the methods into categories, providing a typology that can serve as a guide to the range of methods used in SES research.

Our positioning in this paper centers around the conceptualizations of SES as complex adaptive systems (CAS; Liu et al. 2007b, Levin et al. 2013, Rogers et al. 2013, Folke et al. 2016, Preiser et al. 2018). In this realm, Preiser et al. (2018) have recently made some progress in moving toward a cohesive, theoretically derived definition (Schlüter et al. 2012, Cumming 2014, Bots et al. 2015) of SES research. They offer a typology of six underlying organizing principles of CAS that characterize the various features and properties of such systems. This typology (Table 1) can be used to recognize and assess the demands that CAS make on the methods that SES researchers employ. A final goal of this paper was thus to relate the list of method categories to these underlying principles of CAS through an exploratory assessment of how well different method categories account for core features of CAS.

METHODS

Systematic reviews are synthesis-based approaches that have in common the aim to build new knowledge from a rigorous analysis of existing research findings (Thorne et al. 2004). Regardless of their aim, systematic reviews follow a strict protocol to maximize transparency and repeatability while minimizing bias (Petticrew and Roberts 2006, Pullin and Stewart 2006, Pullin and Knight 2009, Gough et al. 2012). The systematic review process can be summarized as: formulating a question, generating a protocol, systematic selection, critical appraisal of results, data extraction, data synthesis, and reporting and dissemination (Gough et al. 2012).

Defining a search strategy and predocument selection

After situating our study in the conceptual framework outlined in the introduction and defining our study questions, we conducted a first exploratory search in Google Scholar and Scopus databases. We used the search terms “social-ecological,” “coupled human*,” “SES,” “CHANS,” “coupled human-environment*,” and “social relations to nature.” We found that the acronyms “CHANS” and “SES” produced a lot of noise in our results, and subsequently dropped these from our search. During this exploratory phase, we discovered several additional terms that identified studies dealing with human-nature interactions, and included them in subsequent searches. The final terms used in our systematic review were: “social-ecological,” “socio-ecological,” “human environment,” “human-environment*,” “affective ecology*,” “social-environmental,” “socio-environmental,” “human-nature relation*,” “coupled human*,” “human-earth relation*,” “environment relation*,” “human-environment*,” “man-environment relation*,” “eco-social,” and “nature-society relation” (Appendix 1).

Document selection

Document selection was based on a key word search in Scopus, limited to the title, abstract, and key words. We chose Scopus because of its extensive and interdisciplinary coverage and high recognition as a standardized database for conducting meta-analyses (Wagner et al. 2011). Our first search, using the final key words above to search all journals in the Scopus database over all

Table 1. Key complex adaptive systems features and attributes with related practical implications for understanding and governing complex adaptive systems (CAS), based on Preiser et al. (2018).

Underlying features of CAS	Key features and attributes	Related concepts and capacities that characterize CAS features	Practical implications for engaging with CAS
Constituted Relationally	Process-dependent interactions on multiple scales result in networks of interactive relations. CAS are defined more by the interactions among their constituent components than by the components themselves.	Net-like structures, hierarchies, diverse components, built-in redundancy, heterogeneity.	The nature and structure of relationships between components in a system have to be considered explicitly; Collaborative processes should be fostered to build trust and social networks; Diversity is key and allows for different kinds of interactions to take place.
Radically Open	All systems exhibit hierarchy in that every system is part of a wider system and is made up of subsystems. How we describe (or identify) systems is a function of our individual points of view. Systemic interactions generate effects that have impacts across scales and domains.	Permeable boundaries, embeddedness, nestedness, exchange of matter, information, energy, and teleconnections.	Projects are not closed and contained entities, therefore any intervention will influence and shape systems and realities that are situated outside of the scope of the project's aims and objectives; Changes at local scales from individual decisions result in cumulative changes that have impacts globally and similarly, global events have impacts on local ecosystems and communities.
Context-dependent	The identity and functions of CAS are defined by the context in which they exist.	CAS are continuously shaped by dynamic interactions with their environment.	Systems must be understood in the context of their environment; Changing a system affects both its subsystems and the environment in which it is embedded; Transformative spaces should be created for activating systemic change processes.
Adaptive	CAS have self-organizing capacities and can adjust their behavior as a response to changes in their environments.	Self-generating, self-organization, decentralized control, has memory, evolutionary, concurrent persistence and change (resilience), anticipatory capacities.	Guard against rigid planning and strategy design and implement adaptive comanagement practices that foster iterative learning and participatory collaborative processes of engagement; Foster iterative learning and participatory collaborative processes of engagement;
Dynamic	Nonlinear dynamic processes bring about the behavioral patterns of CAS. As a result of nonlinear feedback loops that can dampen or amplify perturbations, small changes can have significant, cascading effects resulting in multiple modes of system-wide reorganization or regime shifts.	Far-from-equilibrium, nonlinear interactions, attractors, thresholds; tipping points, regime-shifts, feedback loops (enabling and constraining), cross-scale interactions.	Assess resilience and anticipate possible future organizational patterns and pathways. Map systemic feedbacks across different spatial and temporal scales to identify systemic thresholds, traps, and indicators that could help detect possible leverage points; Assess which mechanisms build or inhibit systemic agency and resilience.
Complex Causality	Through the interaction of the individual components, novel qualities and phenomena emerge. Hence, the whole is more than the sum of its parts, meaning that systems cannot be understood, nor their behavior predicted based solely on information relating to the individual parts.	Emergence and novelty come about through complex underlying mechanisms.	Cause-and-effect cannot be traced in linear causal trajectories, thus manage for emergence and expect unintended consequences; CAS are inherently unpredictable and deeply uncertain; Foster responses that are flexible to redefine outcomes and responses as necessary.

years, yielded over 20,000 documents. This included results from the mental health, engineering, and information technology literature, which were not relevant to our study. We thus removed results with the key words “adolescent,” “male” and “female,”

“middle aged,” “aged,” and “child” because these were associated with social-ecological critical theory in psychology, which is different from the SES focus of this article. We also restricted the search to the subject areas of environmental science, social

science, agricultural and biological science, Earth and planetary science, economics, econometrics and finance, energy, “multidisciplinary,” and decision sciences. We excluded environmental education because the overlaps with the health and psychological literature produced a lot of nonrelevant studies. Further, we restricted our search to journals, books, and book series, and to publications in English, and items published or in press. Our final search, conducted on 22 July 2015, yielded a result of 5222 documents. In addition to the abstracts and (index and author) key words, we downloaded the year published, journals published in, number of citations, and the institutions and geographical locations of authors.

First screening and coding

The next step was to screen abstracts for inclusion or exclusion in the study. We characterized papers as follows:

- Review: a review of papers about SES, theoretical concepts, and/or frameworks;
- Framework: papers that explicitly proposed a framework for understanding SES;
- Framework and place-based: papers that proposed a framework, and also used this framework to analyze a place-based system;
- Theory: articles that did not propose a framework, but focused on understanding an aspect of thinking about SES, or developing SES theory, without focusing on a particular place-based SES;
- Place-based article: empirical studies that focused on place-based SES;
- Irrelevant: studies that very clearly did not make reference to SES as integrated social and ecological systems and were not relevant to the focus of this study, e.g., studies focusing on the psychological social-ecological theories that were not filtered out in the initial search. These articles (124) were not further considered in our review. Removing these articles brought our total database to 5098 records.

Second screening and document analysis

In the second screening of abstracts, we focused only on the documents that were classified as place-based articles (4479 articles). Of these 4479, 37.4% contained the term “social-ecological” in their title, abstracts, and key words, while 61.4% contained the term in their full texts. To keep the analysis manageable, we randomly selected 2000 of these place-based articles, and read the abstract, title, and key words. For each article, we recorded the scale of the SES studied (local, regional, national, multinational, and global), as well as research methods used (as could be derived from the abstract and key words). We did not classify articles where we could not infer methods used from the abstract (293 of the 2000 surveyed documents). This left 1707 read and classified articles. Scopus records the research affiliations and countries of researchers affiliated with papers; we thus had these data for the full dataset, i.e., 4479 articles. However, we also recorded, in the subset of data ($n = 1707$), the names of countries mentioned in the abstract and key words, i.e., the location where the research took place.

Data analysis

Growth and types of SES research

To track the development of the SES research field, we analyzed the growth of all SES publications ($n = 5098$) as a proportion of the total number of publications in Scopus within the same disciplines. We investigated the significance of the relationship between year and relative publications with a Spearman-rank test, and used both change point analysis (R package “changept”), and Bayesian change point analysis, to detect significant inflection points. We used a chi-squared test to statistically analyze the different types of SES papers (namely “theory,” “framework,” “place-based research,” “review”) across all years, against a null hypothesis of equal proportions.

Hotspots of SES research

From the full place-based data set ($n = 4479$), we used the names of countries and institutions associated with each research paper (as denoted by Scopus) to calculate the number of SES publications produced by each country and research institution over time. We weighted these totals by a notional research capacity for each country (number of universities per country as reported in the database of the International Association of Universities (IAU; <http://www.whed.net/home.php>). We compared the average research output/capita per year using ANOVA tests.

To identify hotspots of SES research sites, we calculated the number of place-based studies conducted in each country ($n = 1707$). We created a graduated heat map in ArcGIS 10.5 (ESRI 2017) using raw frequencies, as well as normalized frequencies, accounting for surface area. Countries were assigned to regions. After normalization of country frequencies, data were normally distributed, and we performed a one-way ANOVA to test for statistical significance between regions.

Popularity of journals over time

To assess the development of journals publishing SES research over time, we focused on the five most popular journals over all years. Here we used the full dataset ($n = 5098$). We recorded the proportion of total publications in each time period (1990–1990, 2000–2008, 2009–2012, 2013–2015). Time periods were informed by the results of the change point analysis. We performed a Kruskal-Wallis test to analyze differences in average annual number of SES publications between journals.

Thematic topics in SES research

We used word cloud and frequency analysis of author key words to extract major topics of SES research. We removed all spaces between words of key word terms (e.g., “ecosystem services” became “ecosystemservices”), so that we could run word cloud analysis on terms, rather than single words, using the wordCloud package in R (v3.01). We extracted the most frequent terms (see Appendix 2) from which we constructed a list of thematic topics for place-based SES research. We then searched the abstracts and author key words of all 4479 place-based studies to obtain the frequency with which these terms were used in the abstracts and key words of studies in our dataset. Finally, we constructed a two-by-two matrix of methods, highlighting main associations.

Method extraction and categorization

We manually screened key methods from 2000 abstracts of place-based SES studies, 1707 of which mentioned a research method.

Abstracts varied in the number and detail of methods provided, for example, some would note that they had employed “modeling,” while others detailed the type of models they used. This was particularly true for statistical methods, and data collection. In the first instance, we listed methods as they were listed in the abstract. We cleaned the resulting method list (632 individual methods, after removing of duplicates) by merging very similar methods. We also removed “methods” that we considered broader approaches, e.g., resilience assessment, adaptive management, transdisciplinary. This process produced a list of 311 methods (see Appendix 3).

We clustered these 311 methods into 27 categories, or method typologies, verifying and debating them in a workshop setting, held at the Stockholm Resilience Centre in October 2016. Our motivation for categorizing methods was twofold: (1) abstracts were not consistently detailed in the kind of methods that they highlighted; (2) it was difficult to conduct a meaningful analysis of more than 300 methods in a way that we could service our objective of providing an overview of the field. We assigned each method to a single category, although many methods could fit under several categories. Categories were based on the way that these methods were perceived to be used in SES research by experts at the workshop, and ones that were considered to have a similar function, or that had similar sets of assumptions. Some categories contained only one or two methods, e.g., agent-based modeling, because workshop participants felt that they were either very broadly used in SES research, or fulfilled a unique function. Conversely, other categories, e.g. statistical methods, contained a diversity of methods, but were not seen to play a unique role in SES research, and resources for their use are readily available. The final set of categories are intended to provide an entry point for discussion around methods that are being used in SES research, and not as a definitive list of methods that can or should be used.

To obtain the frequency of method categories in our database, we searched the full set of 4479 place-based studies for the 311 methods we had extracted from the subset of 2000 articles, and classified which categories each record belonged to. We were able to categorize 2742 of our place-based articles in this way. Thus, the remaining 1737 articles (38%) either did not mention the methods we detected in our search, or did not mention any methods in their abstracts. Readers should thus keep in mind that the list of methods identified in this study was not comprehensive.

Features and dynamics of complex adaptive systems

We used Preiser et al.’s (2018) typology of six organizing principles of CAS (Table 1) to qualitatively assess each method category in terms of its ability to account for key organizing principles of CAS. By “account” we mean the extent to which a method’s assumptions and application allow them to investigate systems that are constituted relationally, context-dependent, radically open, adaptive, dynamic, and have complex causality. We chose this typology on account of Preiser et al.’s (2018) clear conceptualization of SES as CAS. We distinguished between method categories that “did not account for this feature of complexity” (0); “can account for this feature of complexity, depending on how it is employed” (1, sometimes); “can account for this feature of complexity, and is usually employed in a way that does” (2, most times); and “explicitly accounts for this

element of complexity in the way it is constituted” (3, always). In our analysis, we considered the ways in which the different types of methods are, to our knowledge, normally used. Each of the authors independently scored the method clusters against each principle, and subsequently debated the scores that we disagreed on. Based on our discussions, we simplified our scores into two categories: “does not usually account for this complexity feature” (0), and “usually accounts for this complexity feature” (x).

RESULTS

Terms used

Of the chosen search terms, “nature society relations” (71.8%), “social-ecological” (31.78%), “man-environment* relations” (29.67%), “socio-ecological” (17.15%), “social-environmental” (12.1%), and “coupled human*” (3.2%) were the most commonly used in the full final result set (n = 5098). Many publications contain more than one of these key words. The term “man-environment* relations” and “human environment” appeared to be more popular in earlier years, whilst the term “social-ecological,” “socio-ecological” and “nature-society relations” have become more dominant in recent years (Fig. 1).

Growth of the SES research space

Our results show that there is a significant increase in the number of publications in the SES space, relative to the growth in all publications over time (Spearman’s rank correlation, $p < 0.01$, $\rho = 0.0823$). Significant change points were detected between 1989 and 1990, between 1999 and 2000, and 2009 and 2010. A single change point analysis revealed the change between 1999 and 2000 to be the most significant change point ($p < 0.05$). Similarly, the Bayesian change point analysis revealed most probable change points between 1989 and 1990 (prob = 0.99, $\chi^2 = 0.0003$), 1999 and 2000 (prob = 0.952, $\chi^2 = 0.002$), but put a third change point between 2012 and 2013 (prob 0.940, $\chi^2 = 0.002$). A fourth change point, between 2008 and 2009, had a posterior probability of 0.604 (Fig. 2). A posterior probability is a term in Bayesian statistics that refers to the conditional probability assigned to a proposition after relevant evidence has been considered (Lee 2012).

Journals over time

We identified 1234 different sources that published papers on SES. The top 20 journals each published between 0.63% and 7.73% of all publications, accounting for 28.05% of publications in total (Fig. 3a). There were significant differences in the median number of publications between the five most prominent journals ($\chi^2 = 32.1302$, DF = 4, $p < 0.0001$), with *Ecology and Society* having significantly more publications (compared to *Ambio*, $p < 0.0001$, *Ecological Economics*, $p = 0.019$, *Global Environmental Change*, $p = 0.01$, *Journal of Environmental Management*, $p < 0.0001$). There were no significant differences between other journals (Fig. 3b). *Ambio* and *Global Environmental Change* published proportionally more papers in the SES field prior to 2000, while *Ecology and Society* has become increasingly dominant as the main journal publishing SES research since 2000 (Fig. 3c).

Types and scale of SES research

There was a significant difference in the type of SES papers published ($\chi^2 = 6589.523$, df = 3, $p < 0.01$). Of the 5098 papers in our final database, 71 (1.39%) explicitly proposed frameworks without applying these frameworks to real-world case studies, or

Fig. 1. Trends in the use of the seven most common search terms in this study, expressed as a proportion of the total number of new social-ecological systems research published in a given time period (as determined by change point analysis, Fig. 2).

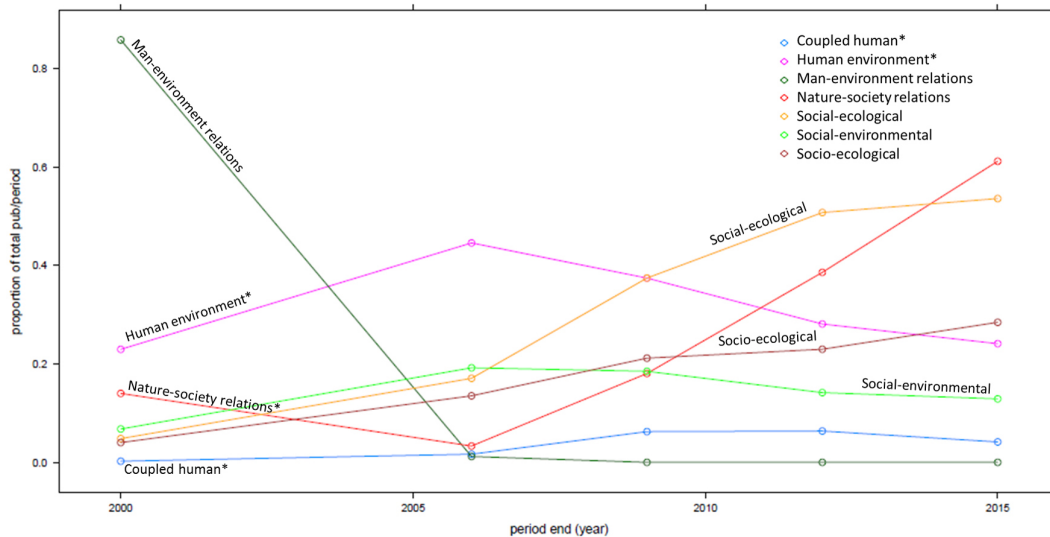
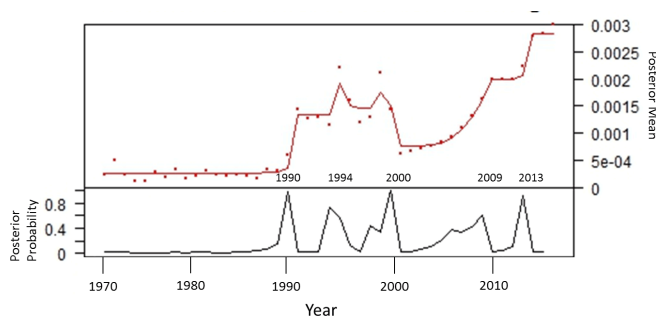


Fig. 2. Social-ecological systems publications as a proportion of all publications in our assessed disciplines in Scopus, plotted over time (y-axis, right). The bottom segment shows posterior probability of change points occurring between each year. Most probable change points (prob < 0.6) are marked with years on the dividing line.



comprised other theoretical discussions. A further 703 papers (13.79%) proposed frameworks and applied those frameworks to place-based research, 3792 (74.38%) of papers focused on place-based research, and 532 (10.44%) were reviews. Our results show that SES research has been more focused on the local scale (45% of all publications) compared to the regional (28%), national (11%), multinational (8%), and global (6%) scales ($\chi^2 = 2802.7$, $df = 4$, $p < 0.0001$).

Hotspots of SES researchers and research

As measured by raw number of publications, European, North American, and Australasian institutions have contributed most significantly to SES research (Fig. 4a, b), with the United States,

Canada, Sweden, Australia, the Netherlands, Germany, the United Kingdom, and South Africa emerging as countries with particularly high number of institutions that study SES. When normalizing institutional paper count by the number of higher education institutions in the country, Kenya, Denmark, and New Zealand were also included as hotspot countries. The lead authors of institutions publishing SES research was most frequently associated with Stockholm University (199 studies), Arizona State University (179 studies), Wageningen University (97 studies), James Cook University (79 studies), and the University of Queensland (71 studies; Table 2).

Whereas institutions conducting SES research were clustered in the Global North, the SES being investigated were distributed more broadly across the globe (Fig. 4c, d). Studied SES were most frequently reported to be located in the United States (422), China (226), Australia (169), India (167), Canada (142), Brazil (134), and Mexico (100). A one-way ANOVA revealed significant differences between regions ($F = 5.068$, $P < 0.001$, $df = 14$; Fig. 5), but a posthoc Tukey test revealed that significant differences were mostly between island regions and mainland areas, and that most mainland areas were not significantly different from each other, on average. Even when accounting for size, the Caribbean Islands were understudied compared to most regions. It had a significantly mean lower normalized frequency than Asia (diff = 0.146, $p < 0.001$), the Middle East (diff = 0.113, $p < 0.039$), North and Central America (diff = 0.186, $p < 0.001$), South America (diff = 0.125, $p = 0.016$), Southern Africa (diff = 0.136, $p = 0.029$), West Africa (diff = 0.101, $p = 0.045$), and West and Central Europe (diff = 0.124, $p < 0.001$). Another region that is poorly studied is Oceania, which was significantly underrepresented compared to both Asia (diff = 0.101, $p < 0.001$) and North and Central

Fig. 3. Journals that most frequently publish research on social-ecological systems (SES). Fig. 3(a) shows the proportion of SES publications published by the 20 top journals across all years. Fig. 3(b) shows the proportion of SES publications published in the top five journals across all years, broken down by time period. Fig. 3(c) shows mean number of SES publications/year for each of the top five journals.

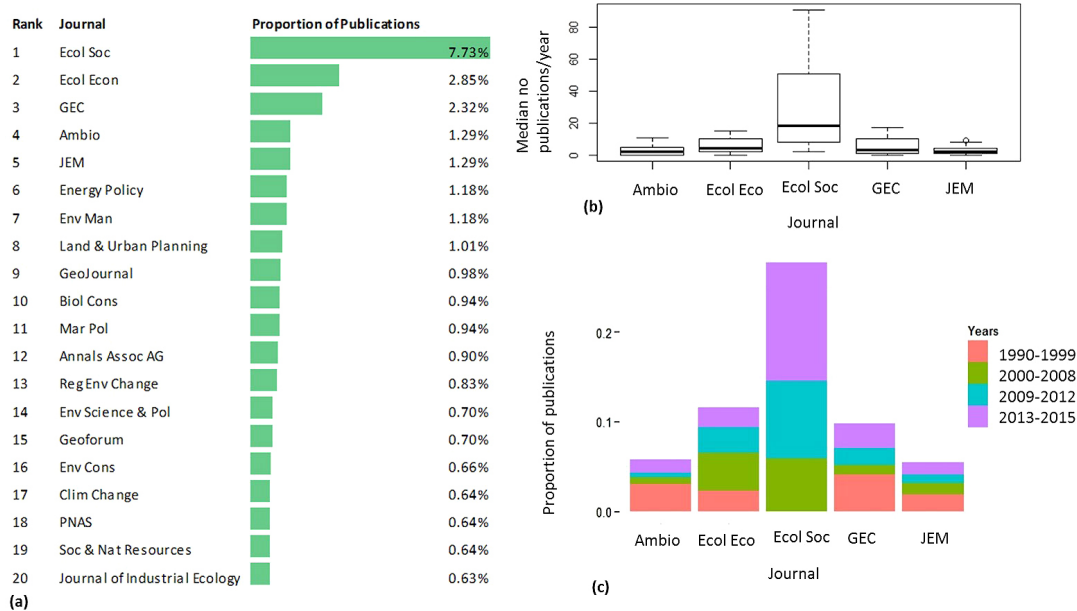


Table 2. Institutions with the highest number of social-ecological systems studies, based on author affiliations in Scopus.

Institution	Country	No. of Studies	Prop. of Publications
Stockholm University	Sweden	199	0.043
Arizona State University	USA	139	0.030
Wageningen University	Netherlands	97	0.021
James Cook University	Australia	79	0.017
University of Queensland	Australia	71	0.015
University of Alaska Fairbanks	USA	68	0.015
University of East Anglia	UK	68	0.015
The University of British Columbia	Canada	63	0.014
University of Wisconsin Madison	USA	60	0.013
Indiana University	USA	59	0.013
University of Oxford	UK	58	0.013
University of Manitoba	Canada	53	0.012
Australian National University	Australia	51	0.011
University of Victoria	Canada	50	0.011
University of California Berkeley	USA	49	0.011
University of Florida	USA	49	0.011
Stanford University	USA	48	0.010
University of Waterloo	Canada	48	0.010
Swedish Royal Academy of Science	Sweden	46	0.010
University of California Santa Barbara	USA	45	0.010

America (diff = 0.142, p = 0.006). Predominantly mainland regions that were significantly underrepresented compared to other regions were Antarctica and South Sea Islands (compared to North and Central America, diff = 0.191, p = 0.03), and Central Africa (compared to North and Central America, diff = 0.159, p = 0.031).

Topics of SES investigation

A word cloud analysis (Fig. 6a) extracted 518 terms that were used more than five times in 2198 of 4479 place-based studies with author-provided key words. We subsequently searched all abstracts and key words of the full dataset of articles (4479 studies) for the identified key words. Searching the full dataset, and combining some key terms (see Appendix 2), changed the prominence of key terms slightly. In the final analysis, the top 20 terms differed significantly ($\chi^2 = 5326.377$, df = 25, p < 0.0001) in the frequency with which they were used in the literature. The terms that were most frequently encountered in author key words were (variations of) “policy” (30.8% of publications), “trade” (23.8%), “conservation” (22.3%), “adaptation” (22.3%), “land use change” (21.9%), “water” (20.2%), “forest loss” (19.9%), “sustainability” (18.8%) and “urban” (18.8%) and “governance and institutions” (17.5%; Fig 6b, Appendix 2).

Methods used

We grouped 311 methods (reduced from an initial list of 632, Appendix 3) into 27 categories (Fig. 7). Frequency of use (in 2742 studies) differed significantly between categories ($\chi^2 = 4231.068$, DF = 26, p-value < 0.001). Spatial mapping and analysis (27.5%), historical profiling and reconstruction (15.7%), interviews (15.5%), futures analysis (13.3%), participatory data collection (11.9%), and impact analysis (11.2%) were the most frequently

Fig. 4. Hotspots of global social-ecological systems (SES) research, and institutions studying SES. Figure 4(a) shows a heat map of raw total number of studies from institutions studying SES, while (b) shows a heat map based on normalized counts. Figure 4(c, raw) and (d, normalized) show the number of SES studies conducted in countries around the world.

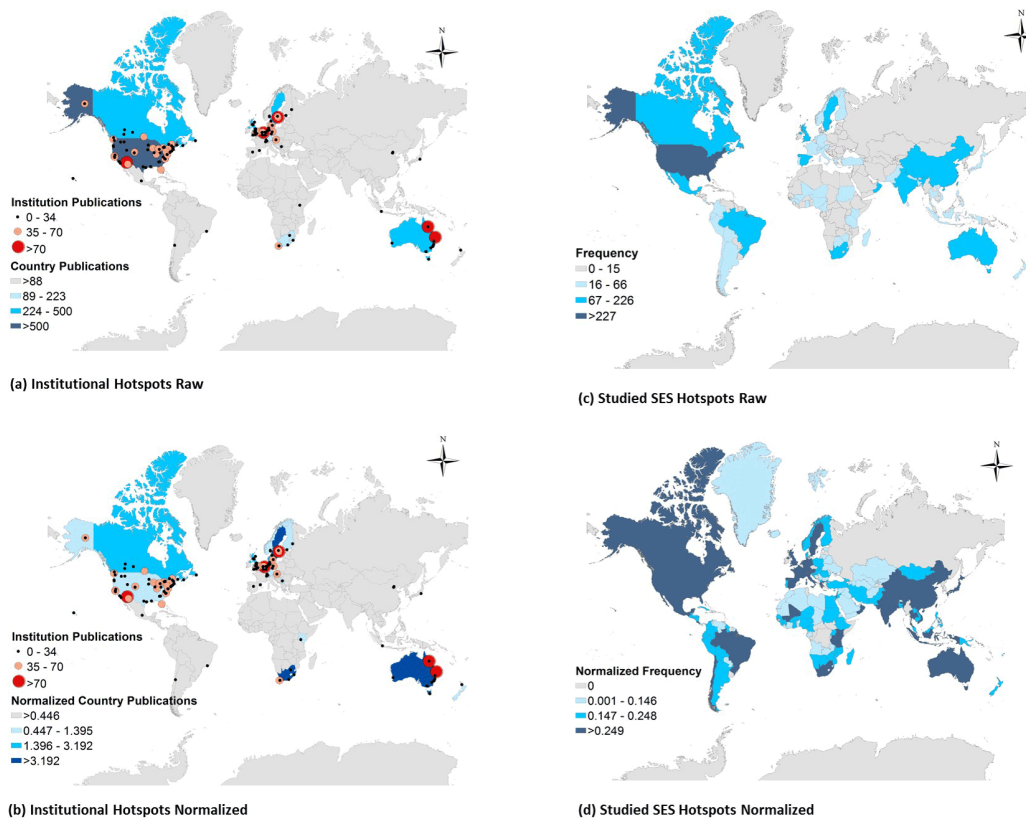
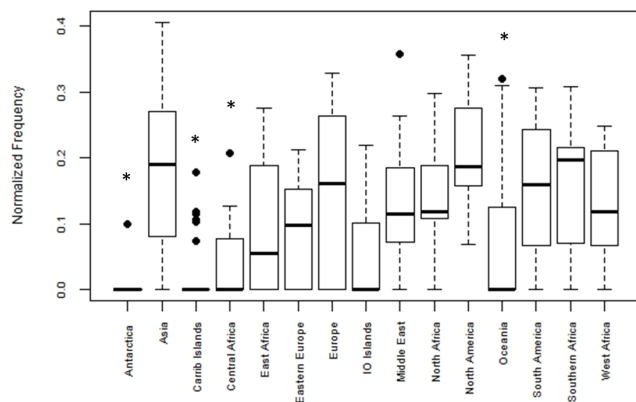


Fig. 5. Mean number of studies conducted in different global regions, per country, normalized by land area. Asterisks (*) denote significant difference.



used method categories (Fig. 7). “Historical profile and reconstruction,” “futures analysis,” “spatial mapping and analysis,” “livelihood and vulnerability analysis,” “impact

analysis,” “network analysis,” “participatory modeling and planning,” and “decision analysis” were the categories that were most frequently associated with the 20 most identified focus topics (Table 3).

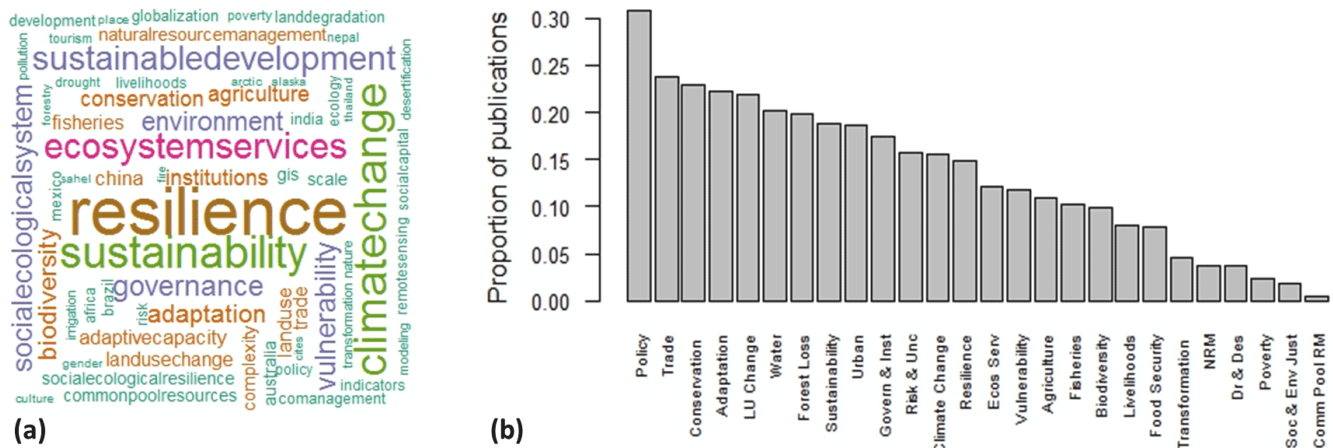
Methods addressing complexity features

Table 4 shows how well each method category scores in terms of its ability to account for each characteristic of complexity, zero (“0”) being “usually not well” and “x” being “usually well,” along with a justification for each scoring decision. We judged “futures analysis,” “comparative case study analysis,” “behavioral analysis,” “decision analysis,” “games,” “systems scoping,” “participatory modeling and planning,” “state-and-transition analysis,” “historical profiling and reconstruction,” “discourse analysis,” and “facilitated dialogues” to be method categories that usually address all six features of CAS (mean score = 1). Method categories “optimization analysis,” “impact analysis,” “quantitative pattern recognition,” and “statistical analysis” were reasoned to address features of complexity least well. The features of complexity that were best addressed were “constituted relationally,” followed by “contextual” and “dynamic,” “adaptive,” “complex causality” and “radically open.”

Table 3. Method categories most often used to investigate topics of concern, ordered from most to least commonly identified focus topics.

Topic	Top three most used method categories
Policy	Futures analysis (12.1%), spatial mapping and analysis (11.7%), historical profiling and reconstruction (10.1%)
Trade	Decision analysis (15%), impact analysis (15%), futures analysis (13.7%)
Conservation	Historical profiling and reconstruction (14%), spatial mapping and analysis (11.7%), futures analysis (9.4%)
Adaptation	Historical profiling and reconstruction (24.4%), livelihood and vulnerability analysis (8.8%), futures analysis (8.8%)
Land use change	Spatial mapping and analysis (20.7%), historical profiling and reconstruction (15%), futures analysis (10.6%)
Water	Historical profiling and reconstruction (18%), spatial mapping and analysis (12.3%), futures analysis (9.5%)
Forest loss	Historical profiling and reconstruction (16%), spatial mapping and analysis (12.6%), futures analysis (9.9%)
Sustainability	Historical profiling and reconstruction (12.5%), futures analysis (10.5%), impact analysis (8.6%)
Governance and institutions	Historical profiling and reconstruction (18.6%), network analysis (8.8%), spatial mapping and analysis (7.2%)
Risk and uncertainty	Impact analysis (16.2%), historical profiling and reconstruction (13.4%), futures analysis (10.8%)
Climate change	Historical profiling and reconstruction (17.4%), futures analysis (16%), livelihood and vulnerability analysis (9.2%)
Resilience	Historical profiling and reconstruction (24.7%), livelihood and vulnerability analysis (10.2%), futures analysis (9%)
Ecosystem services	Futures analysis (14.1%), historical profiling and reconstruction (11.5%), spatial mapping and analysis (10.6%)
Vulnerability	Livelihood and vulnerability analysis (47.2%), historical profiling and reconstruction (13.8%), futures analysis (8.1%)
Agriculture	Historical profiling and reconstruction (15.9%), futures analysis (14%), spatial mapping and analysis (10.2%)
Fisheries	Historical profiling and reconstruction (15.4%), futures analysis (10.7%), participatory modeling and planning (7.6%)
Biodiversity	Spatial mapping and analysis (14.4%), historical profiling and reconstruction (12.9%), futures analysis (8.8%)
Livelihoods	Historical profiling and reconstruction (23.5%), livelihood and vulnerability analysis (11.7%), spatial mapping and analysis (10.1%)
Urban	Historical profiling and reconstruction (15.3%), spatial mapping and analysis (12.3%), futures analysis (9.4%)
Food security	Historical profiling and reconstruction (15.6%), futures analysis (13.7%), spatial mapping and analysis (10%)
Transformation	Historical profiling and reconstruction (20.5%), futures analysis (9.8%), spatial mapping and analysis (9%)
Drought and desertification	Historical profiling and reconstruction (18%), livelihood and vulnerability analysis (14%), spatial mapping and analysis (11%)
Natural resource management	Historical profiling and reconstruction (15.3%), participatory modeling and planning (8.3%), agent-based modeling (8.3%), network analysis (8.3%)
Poverty	Historical profiling and reconstruction (15.3%), spatial mapping and analysis (12.9%), futures analysis (12.5%)
Social and environmental justice	Spatial mapping and analysis (14.6%), historical profiling and reconstruction (12.5%), quantitative pattern recognition (8.3%)
Common pool resource management	Participatory modeling and planning (18.75%), agent-based modeling (18.75%), historical profiling and reconstruction (12.5%), network analysis (12.5%)

Fig. 6. (a) Word cloud showing the key issues, as generated from author key words that are the focus of social-ecological systems (SES) research, (b) shows the proportion of total publications that mention each topic in their author key words.



DISCUSSION

Our study provides insights on trends in the SES research field in terms of the terminology used, journals being published in, the type of research, where it is being done and by whom, topics being investigated, and the methods being used. Although a number of reviews (Brandt et al. 2013, Droste et al. 2018, Herrero-Jáuregui et al. 2018, Partelow 2018, Colding and Barthel 2019) exploring

similar issues have recently been published, our analysis takes a particularly broad view, and specifically focuses on the methods used in SES field through a list of method “categories” or typologies, also assessing the extent to which they account for the underlying organizing principles of CAS. Here we discuss five broad conclusions from these results, and their implications for advancing SES research.

Table 4. Authors' assessment of the ability of different methods to account for the six features of complex adaptive systems. An "x" denotes methods that account well for the relevant underlying principle of complex adaptive systems. Justification for author choices are provided in Appendix 4.

Rank	Method Category	Constituted Relationally	Radically Open	Context Dependent	Adaptive	Dynamic	Complex Causality
1	Spatial mapping & analysis	x	x		x	x	
2	Historical profiling & reconstruction	x	x	x	x	x	x
3	Interviews	x	x	x			
4	Futures analysis	x	x	x	x	x	x
5	Participatory data collection	x	x	x			
6	Impact analysis	x					
7	Livelihood & vulnerability analysis	x		x	x	x	x
8	Statistical analysis	x	x				
9	Decision analysis	x	x	x	x	x	x
10	Network analysis	x		x	x	x	x
11	Agent-based modeling	x		x	x	x	x
12	Dynamical systems modeling	x			x	x	x
13	Participatory modeling & planning	x	x	x	x	x	x
14	Quantitative pattern recognition	x	x				
15	Discourse analysis	x	x	x	x	x	x
16	Behavioral analysis	x	x	x	x	x	x
17	Comparative case study analysis	x	x	x	x	x	x
18	Biophysical, ecosystem, and ecological modeling	x			x	x	
19	Ecological field data collection	x	x	x			
20	Facilitated dialogues	x	x	x	x	x	x
21	Bayesian methods	x	x		x		x
22	Expert modeling	x	x	x		x	x
23	Institutional analysis	x	x	x			
24	Optimization analysis						
25	Games	x	x	x	x	x	x
26	Systems scoping	x	x	x	x	x	x
27	State-and-transition analysis	x	x	x	x	x	x

SES research is growing rapidly, but is still unevenly distributed

Similar to other reviews on SES and related fields (Brandt et al. 2013, Herrero-Jáuregui et al. 2018, Colding and Barthel 2019), we note significant increases in SES research over the last three decades, relative to the growth of scientific publications overall (Fig. 2). SES research is clearly spanning the social and natural sciences in terms of the subject fields of the main journals in which this research is being published (Fig. 3). The interdisciplinary journal *Ecology and Society* has become a dominant outlet, especially in recent years (Fig. 3). Its dominance may be partly attributed to being one of the earliest open access, online-only journals in the SES field. More recently (and not reflected in our results because of the time span analyzed), a number of new journals have been established in the SES field, including *People and Nature* (British Ecological Society), *Ecosystems and People* (Taylor & Francis), and *One Earth* (Cell Press). These provide further evidence of the maturing of the SES field, and potentially broadening the core set of journals publishing SES research. This maturation is perhaps also evident from the analysis of key SES research terms, which reveals a variety of common terms used to describe the interactive relationship between human societies and the natural environment, and appears to currently be consolidating around the terms “nature society relations,” “social-ecological,” and “socio-ecological” (Fig. 1). Consolidation around key terms and concepts is central to the development of new research fields (Guo et al. 2011).

SES research is dominated by a few institutions, notably Stockholm University in Sweden, Arizona State University

(USA), Wageningen University (Netherlands) and James Cook University (Australia). The top 20 research institutions conducting SES are all based in the Global North (mirroring the results of Herrero-Jáuregui et al. 2018), but SES being studied are more globally distributed (Fig. 4). Nevertheless, there are still large parts of the Earth where relatively little SES is being undertaken (Fig. 5). These include island regions such as the Caribbean, Indian Ocean Islands, Oceania, and inaccessible regions such as Antarctica. However, several populous regions are also little studied, including Central Africa, East Africa, West Africa, Eastern Europe, the Middle East, and North Africa. Several of these regions are undergoing rapid population growth and environmental change, experiencing pressing sustainability issues, and increasingly influencing regional and global changes in nature society relations. Better understanding context-specific SES dynamics in these regions to inform local and regional sustainability-related policies and actions is therefore a priority. Encouragingly, however, some of the places with the most SES research include Southern Africa and Asia, regions that are often not that well represented in environmental and social research more generally (Rodríguez-Pose 2006, Trimble and van Aarde 2012).

SES research is dominated by place-based research at local to regional scales

Our results point to the frequent use and development of new frameworks in SES research. Of all 5098 published papers assessed, 15.18% were framework papers, and only 1.39% were purely theoretical. The bulk (13.79%) proposed frameworks that

Fig. 7. Categories of methods used in social-ecological systems research, as categorized by the authors and collaborators in an expert workshop. The “example” column denotes examples within each method category. The “percentage of categorized publications” column indicates the percentage of total classified place-based publications that employed a method within the particular method category.

METHOD CATEGORY	EXAMPLES OF METHODS	PERCENTAGE OF STUDIES
Spatial mapping & analysis	Remote sensing, species distribution modeling, land cover analysis, hotspot analysis	27.50%
Historical profiling & reconstruction	Historical case study construction, historical profiling, landscape reconstruction, adaptive cycle	15.70%
Interviews	Focus groups, household surveys, key informant interviews, structured interviews	15.50%
Futures analysis	Participatory scenario planning, forecasting, backcasting, visioning, foresight analysis, horizon scanning, Delphi method	13.30%
Participatory data collection	Citizen science, photovoice, Q-methodology, pictorial analysis, thematic analysis, participatory mapping, community mapping, participatory videography, participatory rural appraisal	11.90%
Impact analysis	Footprint analysis, life cycle analysis, material flow analysis, virtual water analysis, life cycle impact analysis, life cycle inventory, input output analysis, environmental impact assessments	11.20%
Livelihood & vulnerability analysis	Livelihoods analysis, vulnerability analysis	9.40%
Statistical analysis	Time series analysis, correlation analysis, structural equation analysis	9.30%
Decision analysis	Cost-benefit analysis, multicriteria decision analysis, decision trees, value for information, strategic analysis based on game theory, structured decision making	9.10%
Network analysis	Network analysis (social, ecological)	6.50%
Agent-based modeling	Agent-based modeling, adaptive object modeling	6.20%
Dynamical systems modeling	Systems dynamics modeling, causal loops, differential equations	5.80%
Participatory modeling & planning	Participatory modeling, CoMOD, adaptive environmental management, participatory systems analysis (link to mental modeling)	5.30%
Quantitative pattern recognition	Data mining, social media mining, text mining, bibliometric analysis	5.30%
Discourse analysis	Discourse analysis, critical analysis	3.90%
Behavioral analysis	Participant observation, behavioral economic experiments, social-ecological experiments, simulation experiments	3.40%
Comparative case study analysis	Qualitative comparative analysis, structured case study analysis, Lamin work	3.20%
Biophysical, ecological, and ecosystem service modeling	INVEST, ARIES, Ecopath, ecoSIM, integrated assessment models	3.00%
Ecological field data collection	Vegetation transects, vegetation surveys, species diversity surveys	2.80%
Facilitated dialogues	Stakeholder dialogues, narrative walks, narrative inquiry, Theory U	2.80%
Bayesian methods	Bayesian belief networks, Bayesian learning, Bayesian hierarchical models	1.30%
Expert modeling	matrix modelling, fuzzy cognitive maps, soft system methodology	1.30%
Institutional Analysis	Institutional analysis, IAD, Ostrom SES framework	1.20%
Optimization analysis	Systematic conservation planning, maximum sustainable yields, value of information, systematic frame analysis	1.20%
Games	Gaming, simulations, policy screening, climate simulation game, role playing games, public good games	0.80%
Systems Scoping	Social-ecological inventories, stakeholder analysis, historical inventory, ecological inventory, social inventory	0.70%
State-and-transition analysis	State-and-transition modeling	0.20%

were applied to place-based systems, which may also suggest that the popularization of the term “social-ecological” systems was probably influenced by explicitly place-based frameworks (Colding and Barthel 2019). Although the high number of framework studies might be an indication that SES research is still in a developmental phase (counter to our earlier point), the strong place-based focus in the development of these frameworks suggests that customizing frameworks for new social-ecological contexts may be a characterizing feature of SES research. Colding and Barthel (2019) assert that many frameworks used in SES research are adaptations of three core frameworks; that of Ostrom (2007, 2009), Folke and Berkes (1998) and Berkes et al. (2003), and the robustness framework (Anderies 2004, 2007). All three of these have an explicit CAS-based underpinning.

Although a CAS lens is by no means the only way to conceptualize SES, it has become the most popular (Herrero-Jáuregui et al. 2018, Preiser et al. 2018). Our timeline analysis shows the most significant inflection point in the rise of SES research to lie between 1999 and 2000, which coincides with the establishment of the Resilience Alliance in 1999 (Folke 2006, Parker and Hackett 2012), and the initial publication of their affiliate journal *Ecology and Society*, which has published more SES research than any other journal (Fig. 3). The Resilience Alliance in particular, and *Ecology and Society* by association, relies heavily on CAS and resilience as key guiding frameworks (Herrero-Jáuregui et al. 2018, Preiser et al. 2018, Colding and Barthel 2019). Our results thus align with other studies that have highlighted the dominance of a CAS framing in influencing SES research (Herrero-Jáuregui et al. 2018, Preiser et al. 2018). Given the theoretical maturity of CAS (Preiser et al. 2018), we argue that a definition of SES as CAS, as attempted by Preiser et al. (2018), offers a pragmatic step toward a more universal definition of SES, often lamented as missing in the field (Herrero-Jáuregui et al. 2018, Partelow 2018, Colding and Barthel 2019). This is not to say, however, that CAS thinking is sufficient to support SES research, or that it excludes the use and integration of other frameworks.

SES research is centered on pressing sustainability issues

Key words identified in our study, similar to those found in related reviews (Brandt et al. 2013, Capstick et al. 2015, Droste et al. 2018, Herrero-Jáuregui et al. 2018), emphasize a focus of SES research on pressing sustainability issues such as climate change, biodiversity loss, livelihoods, poverty, policy, land use change, water, and social and environmental justice (Fig. 6). Our change point analysis shows notable inflection points around 1990 and 2000, years that follow calls to address global Earth system changes and move toward “sustainable development of the Biosphere” (Clarke and Munn 1986, Keeble 1988). The smaller upsurge post-2010 can likely be attributed to the integration of SES with broader sustainability initiatives (Herrero-Jáuregui et al. 2018), such as the Sustainable Development Goals (SDGs), the Future Earth initiative and its core research programs such as the Program on Ecosystem Change and Society (PECS), and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES).

A strong integration of SES research with societal issues (Turner et al. 2016) affirms calls for the development of stronger science-society interfaces (Fischer et al. 2015, Tengö et al. 2017) to guide research, knowledge cocreation, and decision making (Turner et al. 2016). However, as many researchers have recognized, taking a knowledge coproduction approach to understanding SES and supporting policy and decision making can be demanding. Aside from the time required to establish relationships with knowledge partners, particularly when operating in transdisciplinary teams that seek evidence from multiple knowledge platforms (Tengö et al. 2014, 2017), challenges also arise from the inherent methodological pluralism that characterizes the SES research field (Turner et al. 2016, Herrero-Jáuregui et al. 2018, Preiser 2018). Furthermore, if we accept that seeking evidence from multiple knowledge traditions (Tengö et al. 2014, Díaz et al. 2015a, b) represents a more ethical approach to understanding SES, we have to be cognizant of the fact that much of our current academic knowledge for understanding SES has been generated in the Global North (also see Herrero-Jáuregui et al. 2018). This

highlights a more general need for developing academic voices from the global south.

Many different methods from a variety of disciplines inform SES research

That methods from many different disciplines are used in SES research is perhaps intuitive, but our study provides a strong empirical validation of this statement, and by virtue of our typology, an accessible overview of the kinds of methods that are used in the field. Our study identified 311 methods (reduced from an initial list of 632) that we grouped into 27 categories, or types, of methods that are commonly used in SES research, providing empirical support for the notion of methodological pluralism in SES research.

Within the place-based studies that we analyzed, we found that spatial mapping and analysis, historical profiling and reconstruction, interviews, and futures analysis were most commonly used (Fig. 7). The use of these methods may be partly driven by the most common SES research topics, including policy, trade, conservation, adaptation, and land use change (Fig. 6b) because they are the most common methods we found to be used to investigate these topics (Table 3). Interestingly, interviews and participatory data collection were much more commonly used than ecological field data collection (Fig. 7), but this may be because ecological field data collection methods are often not articulated in the abstracts of, for example, papers that assess land use change. Economic and other decision-support methods were also quite widely used, including impact analysis, livelihood and vulnerability analysis, and decision analysis. This provides further support for the importance of the increasing emphasis on the science-policy interface and knowledge coproduction in SES research. In contrast, state-and-transition analysis, systems scoping, and games were much more rarely used. These are methods that are particularly well suited to the study of SES (Schultz et al. 2007, Janssen et al. 2010, Provencher et al. 2016, Edwards et al. 2019), but may not have been as well-represented in our dataset on account of their categories containing fewer specific methods, a general limitation of our study.

Our typology of methods spanning different disciplines can provide some orientation to early-career researchers to navigate the methodological pluralism that characterizes the SES field. For new researchers entering the field, a key challenge relates to knowing which methods could be used to investigate a particular SES research question (Haider et al. 2018). Our list of method categories offers researchers a manageable overview of potential tools they might employ in their research, and provides a foundation for scholarly engagement around methodological integration.

Methods used in SES research account for the underlying characteristics of CAS to varying degrees

To gain deeper insight into the suitability of methods used in SES research in accounting for the CAS nature of SES, the authors used a thought exercise to map the different method typologies onto the six organizing principles of CAS, as identified by Preiser et al. (2018; Table 4). There are obvious limitations to such an approach, most notably that our assessment was limited by the knowledge of the author team about different methods and the contexts in which they are applied. Nevertheless, the exercise yielded several insights that could be explored in future research on the nature of SES research.

A number of the methods highlighted in our review, such as network analysis and agent-based modeling, are particularly well suited to explore relationality in SES (Preiser et al. 2018). Both network analysis and agent-based modeling are used extensively in SES research (Fig. 7), and offer integrative frameworks that capture relations and connectivity, can help to develop rich pictures, and deal with heterogeneity and redundancy (Janssen et al. 2006, Bodin and Crona 2009, An 2012, Filatova et al. 2013). Agent-based modeling and network analysis are process-orientated models that rely on decentralized control and automata to detect and create emergent patterns, and so do well to account for the adaptive and self-generating organizational capacities of CAS.

Generally, the methods used in SES research have been sensitive to the context-dependency of SES challenges, probably helped by the notion that SES research has emerged from place-based local-scale studies (Colding and Barthel 2019). Many methods used in anticipatory future studies are adept at adapting frameworks to context, and specifically focus on anticipating adaptation and change (Berkhout et al. 2002, Carpenter et al. 2006, Shaw et al. 2009, Sheppard et al. 2011). These methods, and other participatory research methods that gather multiple evidence-based knowledge (Tengö et al. 2014) can help with observer-dependent framing (Shirk et al. 2012)

Although there are a reasonable number of methods that can account for the dynamic interactions that constitute complex systems and their relations with the environment, it may be difficult to find the necessary data to conduct analyses over sufficient time spans. Nevertheless, in fields such as system and dynamic modeling, there is a notable tradition of developing models that incorporate feedback loops, i.e., account for slow and fast variables (e.g., Levin et al. 2013, Lade and Niiranen 2017), nonlinearity, and unpredictability. Lade and Niiranen (2017) have proposed generalized modeling to be a particularly promising tool in both participatory and research settings to develop process-based understanding of SES dynamics despite limited system knowledge, but acknowledge that there are challenges to overcome. Similarly, Levin et al. (2013) show how essential features of SES have been successfully introduced into optimal management models (particularly in grasslands and coral reefs) and highlight strategies, like modeling fast and slow variables separately where possible, that can improve the suitability of dynamic models to the realities of SES as CAS.

There is mixed evidence for how good current methods are at coping with the radical openness of SES. Although participatory research, which can help with observer-dependent framing (Shirk et al. 2012), is common, as are a host of other methods that gather multiple evidence-based knowledge (Tengö et al. 2014), few methods can truly account for unknown variables that could have important influences on model behavior. Stochastic modeling methods, and research conducted at multiple scales, however, offer promising avenues.

Complex causality seems to be the organizing principle of CAS that methods struggle the most to address. To account for the nonlinearity of cause-and-effect trajectories and contend with emergence and the nature of wicked problems, we need methods that are able to collect large volumes of data, sense-making methods that can explore the implication of different trajectories, and methods that trace causality across scales. Although methods

such as participatory narrative enquiry and dialogue workshops can help highlight nonlinear and cross-scale relationships, understanding how these relationships drive cause and effect or bring about emergent patterns of behavior is an exceedingly more complex and data-intensive task (Levin et al. 2013).

CONCLUSION

In this paper we review several dimensions of the growth of the SES research field, most notably describing it by the methods used in empirical SES research. Methodological pluralism remains one of the biggest challenges in conducting SES research. Our categorized list provides a manageable overview of common methods used in SES research that can serve as a guide to new researchers entering the field, and a first step to more methodological transparency. Our list also offers an opportunity for this field to assess its development into the future, particularly in terms of methodological integration. Assessing methods through the lens of SES as CAS offers a first, if limited, perspective on the alignment between the theory and philosophy that underpins SES research and methods used in the field. More empirical assessments are needed on the suitability of different methods for understanding different elements of CAS in SES research, and it would be interesting to see research on the development of new methods to fill identified gaps. Last, this paper focuses on methods used in SES, but the way in which research is combined in different contexts is perhaps what makes the field most interesting. We hope that future researchers will build on our work to investigate the way in which methods are combined in practice, for different purposes, and on the ethical and ontological contexts that shape our questions and approaches.

Responses to this article can be read online at:
<http://www.ecologyandsociety.org/issues/responses.php/11236>

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Appendix 1. Search query string used to conduct a systematic review in Scopus on 15 July 2015

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( TITLE-ABS-KEY ( "Social-Ecological" ) OR TITLE-ABS-KEY ( "Human-Environment*" ) OR TITLE-ABS-KEY ( "Affective Ecolog*" ) OR TITLE-ABS-KEY ( "Man-Environment* relation*" ) OR TITLE-ABS-KEY ( "Social-Environmental" ) OR TITLE-ABS-KEY ( "Socio-Environmental" ) OR TITLE-ABS-KEY ( "Socio-Ecological" ) OR TITLE-ABS-KEY ( "Eco-social" ) OR TITLE-ABS-KEY ( "Human-environment relation*" ) OR TITLE-ABS-KEY ( "Human-Nature relation*" ) OR TITLE-ABS-KEY ( "Nature-society relation*" ) OR TITLE-ABS-KEY ( "Coupled Human*" ) OR TITLE-ABS-KEY ( "Coupled Human*" ) ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) OR LIMIT-TO ( DOCTYPE , "ch" ) OR LIMIT-TO ( DOCTYPE , "ip" ) ) AND ( LIMIT-TO ( SUBJAREA , "ENVI" ) OR LIMIT-TO ( SUBJAREA , "SOCI" ) OR LIMIT-TO ( SUBJAREA , "AGRI" ) OR LIMIT-TO ( SUBJAREA , "EART" ) OR LIMIT-TO ( SUBJAREA , "ECON" ) OR LIMIT-TO ( SUBJAREA , "ARTS" ) OR LIMIT-TO ( SUBJAREA , "ENER" ) OR LIMIT-TO ( SUBJAREA , "MULT" ) OR LIMIT-TO ( SUBJAREA , "DECI" ) ) AND ( EXCLUDE ( SUBJAREA , "MEDI" ) OR EXCLUDE ( SUBJAREA , "ARTS" ) ) AND ( EXCLUDE ( SUBJAREA , "ENGI" ) OR EXCLUDE ( SUBJAREA , "PSYC" ) ) AND ( EXCLUDE ( SUBJAREA , "BIOC" ) OR EXCLUDE ( SUBJAREA , "COMP" ) OR EXCLUDE ( SUBJAREA , "CENG" ) OR EXCLUDE ( SUBJAREA , "PHAR" ) OR EXCLUDE ( SUBJAREA , "CHEM" ) OR EXCLUDE ( SUBJAREA , "VETE" ) OR EXCLUDE ( SUBJAREA , "MATH" ) OR EXCLUDE ( SUBJAREA , "IMMU" ) OR EXCLUDE ( SUBJAREA , "NURS" ) OR EXCLUDE ( SUBJAREA , "HEAL" ) OR EXCLUDE ( SUBJAREA , "NEUR" ) OR EXCLUDE ( SUBJAREA , "MATE" ) OR EXCLUDE ( SUBJAREA , "PHYS" ) ) AND ( EXCLUDE ( SRCTYPE , "d" ) OR EXCLUDE ( SRCTYPE , "p" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) )
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Appendix 2. Methods Identified in the systematic review are shown in an Excel spreadsheet. The spreadsheet shows the 632 methods originally identified, and a reduced list of 311 methods (categorized here as “analytical methods”, “data collection methods”, “planning methods”, and “representation and communication”. The spreadsheet also lists methods from the original list that were excluded, as well as “methods” that were removed because they were considered to be “approaches” rather than “methods”.

[Please click here to download file 'appendix2.xlsx'.](#)

Appendix 3. Key terms that were identified in a word cloud analysis. Terms that were included, excluded, and combined with other terms in the final analysis are noted.

Table 3.1. List of the top 100 terms as extracted from author—provided keywords in 2198 place-based studies on social-ecological systems, published between before July 2015.

Rank	Concatenated Term	Frequency	Inclusion
1	socialaecologicalsystems	321	Excluded
2	resilience	272	Included
3	climatechange	168	Included
4	sustainability	168	Combined with "Sustainable Development"
5	ecosystems-services	124	Included
6	sustainabledevelopment	113	Included
7	governance	89	Combined with "Institutions"
8	socialaecologicalsystem	85	Included
9	vulnerability	84	Included
10	environment	83	Included
11	adaptation	77	Combined with "Adaptive capacity, adaptive management"
12	biodiversity	73	Included
13	adaptive-management	64	Combined with "Adaptive capacity, adaptive management"
14	agriculture	60	Included
15	institutions	57	Combined with "Governance"
16	conservation	56	Combined with "Protected Areas"
17	china	53	Excluded
18	adaptivecapacity	51	Combined with "adaption", "adaptive management"

19	landuse	49	Combine with "Land use change", "Land Cover Change", "Degredation"
20	deforestation	46	Included
21	politicalecology	44	Included
22	trade	44	Included
23	fisheries	43	Included
24	landusechange	43	Included
25	naturalresourcemanagement	42	Included
26	complexity	41	Excluded
27	humanenvironmentinteractions	38	Excluded
28	gis	37	Excluded
29	scale	37	Excluded
30	socialecologicalresilience	33	Excluded
31	australia	32	Excluded
32	commonpoolresources	32	Included
33	comanagement	31	Combined with "Institutions" & "Governance"
34	development	31	Combined with "Sustainable Development"
35	brazil	29	Excluded
36	landdegradation	29	Combined with "land use change"
37	management	28	Combined with "natural resource management"
38	participation	28	Excluded
39	uncertainty	28	Excluded

40	globalization	27	Excluded
41	india	27	Excluded
42	sociallearning	27	Excluded
43	environmentalpolicy	26	Combined with "policy"
44	internationaltrade	26	Excluded
45	mexico	26	Excluded
46	ecology	25	Excluded
47	landscape	25	Excluded
48	policy	25	Combined with "environmentalpolicy"
49	remotesensing	25	Excluded
50	risk	25	Excluded
51	adaptivegovernance	24	Excluded
52	africa	24	Excluded
53	environmentaleducation	24	Excluded
54	globalchange	24	Excluded
55	industrialecology	24	Excluded
56	socialecological	24	Excluded
57	decisionmaking	23	Excluded
58	environmentalchange	23	Excluded
59	environmentaljustice	23	Combined with "Social Justice" (not shown)
60	foodsecurity	23	Combine with "Food"
61	smallscalefisheries	23	Combined with "Fisheries"
62	developingcountries	22	Excluded

63	ecosystembasedmanagement	22	Combined with "natural resource management" and "management"
64	environmentalgovernance	22	Combined with "Instiutions", "Governance"
65	fisheriesmanagement	22	Combined with "Fisheries"
66	humanenvironmentinteraction	22	Included
67	livelihoods	22	Included
68	socialcapital	22	Excluded
69	collectiveaction	21	Excluded
70	ecosystemmanagement	21	Excluded
71	indicators	21	Excluded
72	irrigation	20	Excluded
73	tourism	20	Excluded
74	archaeology	19	Excluded
75	biodiversityconservation	19	Combined with "Conservation" and "Protected Areas"
76	collaboration	19	Excluded
77	marineprotectedareas	19	Combined with "Conservation" and "Protected Areas"
78	traditionalecologicalknowledge	19	Excluded
79	transformation	19	Excluded
80	adaptivecycle	18	Excluded
81	desertification	18	Excluded
82	drought	18	Combined with "Desertification"
83	environmentalmanagement	18	Combined with "Natural Reseource Management"
84	interdisciplinary	18	Excluded

85	modeling	18	Excluded
86	southafrica	18	Excluded
87	urban	18	Included
88	watermanagement	18	Combined with "water"
89	economics	17	Excluded
90	learning	17	Excluded
91	nature	17	Excluded
92	poverty	17	Included
93	protectedareas	17	Combined with "Conservation"
94	scenarios	17	Excluded
95	environmentaldegardation	16	Combined with "degradation"
96	holocene	16	Excluded
97	invasivespecies	16	Excluded
98	latinamerica	16	Excluded
99	agentbasedmodeling	15	Excluded
100	aquaculture	15	Exclusion

Appendix 4. Author assessment of method categories ability to account for the underlying principles of complex adaptive systems, denoted by an “x”. The “justification” column explains the authors’ reasoning for each score.

[Please click here to download file 'appendix4.xlsx'.](#)
