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ORIGINAL ARTICLE

Coevolving Ostrom's social–ecological systems (SES) framework and sustainability science: four key co-benefits

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Abstract Research on social–ecological systems (SES) is scattered across many disciplines and perspectives. As a result, much of the knowledge generated between different communities is not comparable, mutually aggregate or easily communicated to nonspecialists despite common goals to use academic knowledge for advancing sustainability. This article proposes a conceptual pathway to address this challenge through outlining how the SES research contributions of sustainability science and researchers using Elinor Ostrom's diagnostic SES framework (SESF) can integrate and co-benefit from explicitly interlinking their development. From a review of the literature, I outline four key co-benefits from their potential to interlink in the following themes: (1) coevolving SES knowledge types, (2) guiding primary research and assessing sustainability, (3) building a boundary object for transdisciplinary sustainability science, and (4) facilitating comparative analysis. The origins of the SESF include seminal empirical work on common property theory, self-organization, and coupled SES interactions. The SESF now serves as a template for diagnosing sustainability challenges and theorizing explanatory relationships on SES components, interactions, and outcomes within and across case studies. Simultaneously, sustainability science has proposed transdisciplinary research agendas, sustainability knowledge types, knowledge coproduction, and sustainability assessment tools to advance transformative change processes. Key challenges for achieving co-beneficial developments in both communities are discussed in relation to each of the four themes. Evident pathways for advancing SES research are also presented along with a guideline for designing SES research within this co-aligned vision.

Keywords Sustainability science · Social–ecological systems · Boundary object · Knowledge types · Framework

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Introduction

The clear interlinkages between social and ecological challenges are shifting the paradigm for the type of research and societal change needed to achieve short- and long-term sustainability (Kates and Parris 2003; Anderies et al. 2007; Domptail and Easdale 2013; Liu et al. 2015; Steffen et al. 2015). Research in social–ecological systems (SES) is evolving to reflect this recognition, proposing inter- and transdisciplinary research agendas with distinct pursuits (Fischer et al. 2015; Schoon and van der Leeuw 2015). First, to integrate and evolve the functional understanding of SES, and second, to use that knowledge to find practical and effective sustainability solutions for real-world challenges.

Academics are increasingly challenged to generate cohesive, multifaceted, and actionable knowledge that is relevant across academic disciplines and for society. In particular, knowledge should be collectively oriented to better understand academic contributions in aiding the transition toward sustainability (Hadorn et al. 2006; Jerneck et al. 2010; Brandt et al. 2013). However, much of the existing research on SES is generated in disciplinary or community isolation, lacking the appropriate tools for it to become mutually aggregate and co-beneficially useful. There is an urgency for SES research to further develop conceptual pathways that guide knowledge generation with consideration for integrable or decomposable characteristics. In particular, tools are needed to effectively support the aggregation of knowledge contributions within the multifaceted academic understandings of sustainability to support the effective implementation of practical solutions (Wiek et al. 2012; Fischer et al. 2015).

Boundary work, such as interdisciplinary frameworks, offers adaptable tools for facilitating the integration between diverging perspectives while remaining robust enough to maintain identity across them (Star and Griesemer 1989). For SES research to continue advancing, boundary tools are needed to effectively collaborate and share knowledge despite a lack of consensus (with pluralisms) on a particular theory, epistemology, or perspective (Bettencourt and Kaur 2011; MacGillivray and Franklin 2015). A boundary object for organizing SES research can facilitate primary data collection and comparability across disciplines, methodologies, and case studies. This can additionally facilitate the development and testing of theory within and between place-based research (Cox and Frey 2015; Hertz and Schlüter 2015). Along with such practical tools, there is a need for intrinsic willingness among academics and the proper incentives to bridge the disciplinary gaps.

This article outlines how two distinct SES research communities, sustainability science and researchers using Elinor Ostrom's diagnostic SES framework (SESF), can co-benefit from explicitly interlinking their development. Through review of the literature, I outline four key co-benefits in the following themes: (1) coevolving SES knowledge types, (2) guiding primary research and assessing sustainability, (3) building a boundary object for transdisciplinary sustainability science, and (4) facilitating comparative analysis. Within the four co-benefit themes, I elaborate on how sustainability science can guide the knowledge development from the SESF to organize disciplinary contributions to SES research. Reciprocally, sustainability science researchers can inherit the SESF's novice proposition as a boundary object for structuring diagnostic sustainability research and interdisciplinary primary data collection. Cohesively structuring SES research through a common lens and language can benefit both pursuits and aggregate the knowledge within the two communities. While literature on the SESF has illustrated the potential for utilizing the framework as a tool in sustainability science, no direct links exist to further progress the coevolution between the fundamental ambitions of both communities. This article's structure, including the four themes mentioned above, is outlined below:

1. A review of key literature on the SESF and sustainability science ["Foundations of the diagnostic SES framework (SESF)" and "Foundations of sustainability science" sections].
2. Four explicit co-benefits from interlinking the two research communities of the SESF and sustainability science ("Co-benefits between the SESF and sustainability science" section; Table 1).
3. Guiding questions and considerations for designing research with a co-aligned vision between the SESF and sustainability science ("Guiding questions for coevolved SES research" section; Table 2).
4. Highlighting key challenges for the SESF, sustainability science and SES research ("Highlighting the challenges" section).

Foundations of the diagnostic SES framework (SESF)

The SESF was proposed for diagnosing the key interacting components and interactions that drive sustainability challenges in SES (Fig. 1; Ostrom 2007, 2009). Many of the framework's components evolved out of research on the design principles, which proposed that certain system conditions would lead to self-organization in common-pool resource systems (Ostrom 1990). It was later recognized that generalized conditions often negate contextual differences within and between systems (Agrawal 2001). In response, the SESF was designed with a dual recognition to build generalizable statements for theory and policy, while also recognizing contextual nuances between cases (Ostrom 2007; Basurto and Ostrom 2009). Components of the framework are merely suggestive of relevance for sustainability and do not propose outcomes based on any condition or state of components in the system. This provides a relatively theory neutral template of SES components, although no framework can remain entirely neutral (McGinnis and Ostrom 2014). Overall, the SESF can facilitate the testing or generation of theory on SES functionality as well as provide a systematic checklist for analyzing system complexity or even characterize systems. This diagnostic process of linking system component interactions to undesired SES outcomes can be related to how medical practitioners treat patients (McGinnis and Ostrom 2014).

The framework's structure (Figs. 1, 2) is organized in multilevel tiers of nested subsystems and components that expand under the first tiers of the Resource System, Resource Units, Actors and Governance. Further first-tier components are suggested to include the broader

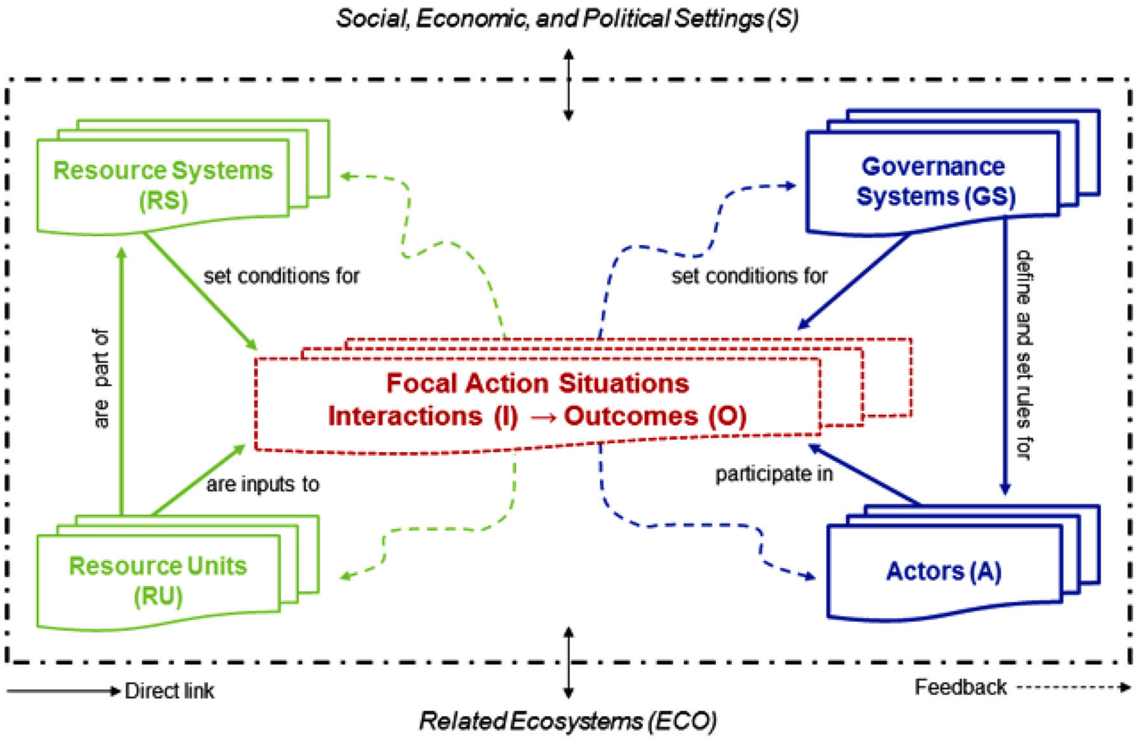

Fig. 1 The diagnostic social–ecological system (SES) framework. Four multilevel first-tier variables are presented in each of the four corners and the template for assessing their interactions and outcomes is visualized. Adopted from (McGinnis and Ostrom 2014)

exogenous context of Ecological Rules (Vogt et al. 2015), External Ecosystems and the surrounding Social, Economic and Political settings (McGinnis and Ostrom 2014). The structure of the Institutional Analysis and Development (IAD) framework (Ostrom 2011) provides the analytical structure to assess system interactions and outcomes with action situations (McGinnis and Ostrom 2014).

The second-tier components of the SESF can guide primary and secondary data collection within a contextual SES case (Fig. 2). Not all second-tier components may be relevant within a SES case, but it provides a checklist for understanding system complexity and potential driving components to consider when designing inductive SES research. The SESF is also used for deductive research to test theory on the role of certain system components, their interactions, and system outcomes (see SESMAD 2014). Expanded and subsequent tiers will need to be added to further investigate SES complexity within certain sectors or systems, and numerous adaptations already exist for contextual use at the local level, in fisheries and food systems (Basurto et al. 2013; del Delgado-Serrano and Andres Ramos 2015; Marshall 2015; Partelow and Boda 2015).

Foundations of sustainability science

Sustainability science is often defined as research in the context of SES (Clark 2007; Agrawal and Chhatre 2011; Lange et al. 2013). The number of researchers and practitioners pursuing inter- and transdisciplinary collaborations have increased significantly since the foundations of sustainability science began in the early 2000s (Kates 2011; Ness 2013). Within its' core agenda, empirical research aims to be problem-driven and solution oriented (Clark and Dickson 2003). To achieve this, sustainability science is envisioned as a multifaceted research process. This process can have diverse knowledge generation and practical phases such as the more normative study or assessment of sustainability. This research process framing includes conceptualizing the coproduction of the research design and knowledge with stakeholders outside of academia to develop and implement solutions for contextual real-world challenges (Bettencourt and Kaur 2011; van Kerkhoff (2014); Wiek et al. 2014).

Knowledge types are used in sustainability science for organizing knowledge generation and research outputs toward fostering sustainability transitions (Hadorn et al.

Fig. 2 Nested components and subsystems of the SESF. Including the four first-tier variables: Resource System, Resource Unit, Governance and Actors as well as the proposed fifth tier of Ecological rules. Action situations and outcomes are also shown. The exogenous Related Ecosystems and Social, Economic, and Political Settings are shown on the bottom and top, respectively. Adopted from Vogt et al. (2015)

Social, Economic, and Political Settings (S) S1- Economic development. S2- Demographic trends. S3- Political stability. S4- Other governance systems. S5- Markets. S6- Media organizations. S7- Technology.		
	Resource Systems (RS)	Governance Systems (GS)
	RS1- Sector (e.g., water, forests, pasture) RS2- Clarity of system boundaries RS3- Size of resource system RS4- Human-constructed facilities RS5- Productivity of system RS6- Equilibrium properties RS7- Predictability of system dynamics RS8- Storage characteristics RS9- Location	GS1- Government organizations GS2- Nongovernment organizations GS3- Network structure GS4- Property-rights systems GS5- Operational-choice rules GS6- Collective-choice rules GS7- Constitutional-choice rules GS8- Monitoring and sanctioning rules
Ecological Rules (ER)	Resource Units (RU)	Actors (A)
ER1- Physical rules. ER2- Chemical rules. ER3- Biological rules.	RU1- Resource unit mobility RU2- Growth or replacement rate RU3- Interaction among resource units RU4- Economic value RU5- Number of units RU6- Distinctive characteristics RU7- Spatial and temporal distribution	A1- Number of relevant actors A2- Socioeconomic attributes A3- History or past experiences A4- Location A5- Leadership/entrepreneurship A6- Norms (trust-reciprocity)/ social capital A7- Knowledge of SES/mental models A8- Importance of resource (dependence) A9- Technologies available
	Action Situations: Interactions (I) → Outcomes (O)	
	Activities and Processes: I1- Harvesting I2- Information sharing I3- Deliberation processes I4- Conflicts I5- Investment activities I6- Lobbying activities I7- Self-organizing activities I8- Networking activities I9- Monitoring activities I10- Evaluative activities	Outcome Criteria: O1- Social performance measures (e.g., efficiency, equity, accountability, sustainability) O2- Ecological performance measures (e.g., overharvested, resilience, biodiversity, sustainability) O3- Externalities to other SESs
Related Ecosystems (ECO) ECO1- Climate patterns. ECO2- Pollution patterns. ECO3- Flows into and out of focal SES.		

2006; Jerneck et al. 2010; Brandt et al. 2013). Three knowledge types have been proposed to facilitate a holistic research process, including: (1) analyzing and describing SES functionality (*system knowledge*), (2) developing meaningful goals and pathways for transitioning toward sustainable human well-being and ecological functionality (*target knowledge*), and (3) guiding and facilitating practical mechanisms to operationalize goals and pathways (*transformative knowledge*) (Hadorn et al. 2006; Jerneck et al. 2010; Brandt et al. 2013). Theoretical developments and case-based empirical approaches have begun to test the generation of all three knowledge types as a holistic research process (e.g., Wiek et al. 2012). However, an accepted methodological procedure to guide the generation of different knowledge types has yet to be widely established. As a result, integrating the knowledge generated from different methodologies or perspectives remains a challenge for aggregating the contributions from SES research within the envisioned sustainability science research process.

Co-benefits between the SESF and sustainability science

Aligning the development of the SESF and sustainability science can work toward developing cohesive boundary work for structuring and operationalizing-integrated SES research within the sustainability science research process. The SESF has an open and decomposable structure that is well situated for integration with other frameworks and concepts (Binder et al. 2013; McGinnis and Ostrom 2014; Nassl and Löffler 2015). Integrating the SESF with sustainability science can provide increased and diversified empirical applications of the SESF, expanding the scope of primary research beyond common-pool resources.

Table 1 Four key co-benefits from integrating the SESF and sustainability science

Co-benefits	SESF → Sustainability science	Sustainability science → SESF	References
(1) Coevolving SES knowledge types	Structured ontology of SES components Theoretical background/support of the SES components and their interlinkages	Structured knowledge types (System/Target/Transformative) that decompose academic contributions to transformational change processes	Jerneck et al. (2010), Brandt et al. (2013), Miller et al. (2013), Hinkel et al. (2014), Kumazawa et al. (2014), Cox and Frey (2015)
(2) Guiding primary research and assessing sustainability	Diagnostic framework with explicit components for guiding primary data collection Analytical foundation for assessing component interactions through action situations	Agenda for stakeholder engagement, knowledge coproduction, and bridging science-society gap Defined sustainability assessment criteria (e.g., inter- and intra-generational equity, livelihood sufficiency and opportunity, resource maintenance and efficiency) and analytical tools (e.g., multi-criteria analysis, environmental impact assessment, and life cycle assessment)	Gibson (2006), Ness et al. (2007), Ostrom (2009), Ostrom and Cox (2010), Ostrom (2011), Mauser et al. (2013), van Kerkhoff (2014), Sala et al. (2015)
(3) Developing a transdisciplinary boundary object	Framework with robust consideration for both social and ecological components; boundary tool to orient SES discussions and data Initial structure and proposed ontological formalization for a common SES language for researchers, practitioners, and stakeholders	Educational programs and established interdisciplinary engagement to enhance development and use Communication and societal engagement as integral to the research process	Kates (2011), Binder et al. (2013), Brandt et al. (2013), Epstein et al. (2013), Kajikawa et al. (2014), O'Byrne et al. (2014), Hertz and Schlüter (2015), Vogt et al. (2015)
(4) Facilitating comparative analysis	Platform for SES theory development and testing Database development	Theoretical and practical approaches for transformative change processes and sustainability transitions (e.g., Mode 1 and 2 transdisciplinarity)	Lang et al. (2012), Frey and Rusch (2013), ASU CSID (2014), SESMAD (2014), del Delgado-Serrano and Andres Ramos (2015), Scholz and Steiner (2015)

Structuring primary data integrated into the SESF with knowledge types would strengthen the capacity of SESF databases to assess SES research contributions. Table 1 further expands on the core strengths of each pursuit and presents co-benefits from integrating their progress and visions. This argumentation is outlined in the text below within four consolidated themes: (1) coevolving SES knowledge types, (2) guiding primary research and assessing sustainability, (3) building a boundary object for transdisciplinary sustainability science, and (4) facilitating comparative analysis.

Coevolving SES knowledge types

Orienting SES(F) research into knowledge types from sustainability science provides a conceptual lens for viewing academic contributions to sustainability through (1) *system knowledge*, (2) *target knowledge*, and (3) *transformative knowledge* (Hadorn et al. 2006; Jerneck et al. 2010; Brandt et al. 2013). The majority of disciplinary-based research in SES is focused on understanding and describing case complexity (system knowledge), with a core challenge of sustainability science being to move beyond description toward engagement and transformation (normative and transformative knowledge) (Lang et al. 2012; Brandt et al. 2013). Sustainability science methodologies have provided the foundations for understanding how to structure SES research but have not fully engaged with a robust multidisciplinary tool for guiding the comparable development of knowledge types (Wiek et al. 2012; Lang et al. 2012). The SESF can be used to facilitate the comparability of knowledge types in primary data collection across cases.

Structuring knowledge generation through the sustainability science lens has not been conceptually explored with the SESF. However, structuring the knowledge generated on component data from the SESF can orient the empirical and comparative analytical contributions to understanding transformative change processes. For example, knowledge generated on the SESF component of ecological system productivity (Fig. 2; RS5) may be explicitly system knowledge, whereas actor leadership (Fig. 2; A5) may contribute to knowledge on community deliberation processes and identify transformative change pathways such as communication networks or educational gaps. Incorporating traditional ecological or local stakeholder knowledge (Fig. 2; A7) into understanding SES functionality may be explicitly system knowledge, whereas the deliberation between stakeholders (Fig. 2; I3) within the theoretical frame of an action situation could be target knowledge in sustainability science. For knowledge coproduction and stakeholder engagement, target knowledge generated with the SESF may be dependent on the methodological approach and the active or passive role of the researcher. Action situations in the SESF are the analytical framework for assessing individual decision-making in interactive SES processes such as harvesting, investment, user conflicts, and deliberation (McGinnis and Ostrom 2014). Different knowledge types can emerge from analyzing actions situations, but the foundational origins of action situations that embody theoretical assumptions of interdependent individual decision-making should be recognized, which may limit the ability to integrate with other perspectives.

Understanding how the SESF contributes knowledge within the knowledge spectrum of sustainability science can advance the frameworks' use as an operational tool to explicitly address research gaps and generate problem-driven research agendas. Explicitly understanding the contributed value of academic knowledge through these combined analytical lenses exemplifies the joint potential for the SESF and sustainability science to cogenerate a useful interdisciplinary boundary object. Reciprocally, where sustainability science lacks a multidisciplinary tool for developing system knowledge through primary research, as well as structuring SES complexity, the SESF can structure interdisciplinary empirical work in sustainability science.

Guiding primary research and assessing sustainability

Guiding primary data collection is a core strength of the SESF, providing key components and interactions to direct empirical focus in a case study. The SESF does not present specific indicators or methodologies for collecting data, but rather a diagnostic checklist to assess specific system components and their interactions for relation to outcomes (Figs. 1, 2). Each SESF component can be seen as a potentially relevant aspect for data collection to analyze SES interactions and sustainability outcomes. Thus, the guiding approach of the SESF expands its' ability to be a boundary object through allowing methodological pluralism. Data from the multiple assessment methods in sustainability science, both quantitative and qualitative, can be structured through the SESF.

The SESF does not outline specific sustainability assessment criteria, leaving them to be contextually diagnosed. This reflects increasing consensus that SES differ substantially from one another, and although there are many similar systems, practical sustainability goals and assessment criteria are mostly likely nontransferable (Liu et al. 2007). Despite this recognition, a lack of clear sustainability outcome criteria [Fig. 2; Outcomes (O)] or an operational procedure to generate them inductively could be considered a limitation of the framework and may lead to confusion about how the framework can be practically applied. Co-beneficially, many contextual sustainability assessment criteria and operational tools have been developed and used within the sustainability science research process (Gibson 2006; Ness et al. 2007; Sala et al. 2015). Using sustainability science's application of assessment criteria along with the SESF's ability to test and validate the link between system conditions and outcomes collaboratively coevolves both pursuits. This would be through the deductive validation of existing criteria or the inductive generation of emergent criteria through the robust comparison of case-based empirical work. Sustainability science may be further able to provide 'sustainability validation' to knowledge produced with the SESF, to assess how certain knowledge types can be specifically utilized for transformational change (Tàbara and Chabay 2013).

Developing a transdisciplinary boundary object

The engagement of academics in sustainability science is continuing to expand across a multitude of research disciplines, from ecology to economics, human geography, engineering, and many others (Bettencourt and Kaur 2011; Kajikawa et al. 2014; O'Byrne et al. 2014). Despite a wide reach, developing transdisciplinary boundary work that can cohesively interlink sustainability science perspectives is conceptually and practically challenging (Polk 2014). Current boundary work has focused on communication channels (McGreavy et al. 2013), knowledge coproduction (Lang et al. 2012), and place-based research (MacGillivray and Franklin 2015) as a harbor for understanding the contextual challenges and inherent trade-offs when deliberating sustainability pathways. With specific importance, knowledge coproduction pursues boundary work through interlinking the perspectives of academics, practitioners, and society. There are many challenges in progressing this nexus including work on mode 1 and 2 transdisciplinarity to couple research processes and outcomes to society (Brandt et al. 2013; Polk 2014; Scholz and Steiner 2015).

Transdisciplinary sustainability science has yet to find its' academic home and is lacking the capacity to integrate into existing institutional structures and decision-making processes (Polk 2014). Broader engagement with the SESF would catalyze a formal academic structure for SES research to become a robust boundary object for creating a common language in SES research coupled with sustainability science. Academically, the SESF can be seen as an initial formal structure for developing an SES ontology for an interdisciplinary research community (Hinkel et al. 2014; Cox and Frey 2015). More practically, the SESF can act as a tool for facilitating communication on SES complexity and research design within transdisciplinary sustainability science projects.

Facilitating comparative analysis

Testing and developing theory through the comparative analysis of common-pool resource systems and SES case studies has been a core driver of the SESF's development. Increased empirical applications of the framework within the sustainability science community will contribute more case data to support the theoretical insights that link component attributes to specific outcomes. Aggregating empirical work through a common ontological language will benefit the ability of SES research to make well-supported theoretical and policy statements. Within sustainability science, comparative outcome analyses has been done through post hoc data assessments, but never through a systematically structured methodology designed for comparative purposes, contributing to theoretical development and contextual analysis.

The proposed ontological structure of the SESF can provide guidance to sustainability scientists to design research and gather SES data that is relevant beyond individual cases. The SESF has been used for two types of comparative analysis, to assess the influence of particular components across a group of cases and to compare broader case interactions and outcomes within a group of cases. The following articles demonstrate both types. Gutiérrez et al. (2011) assess the common influential components in successfully comanaged fisheries, showing that leadership and social capital are common components across cases with successful outcomes. Fleischman et al. (2014) discuss the lessons learned from testing the theoretical assumptions of the Ostrom's design principles across a group of diverse large spatial-scale cases.

Useful databases for comparing SES data have been constructed through the SESF's proposed ontology with both primary and secondary data. Primary data are more reliable for comparative analysis, as it is methodologically generated to address specific research questions in relation to the analysis. Secondary data can also be comparatively useful, if structured with uniformed metrics such as the SESF. Using primary data eliminates uncertainty of data transformation, known methodological limitations, or the suitability of data to answer specific research questions (Hox and Boeije 2005). Primary data collected into the SESF can then later be used as transformed secondary data that are comparable between cases. The nested components of the framework are designed to be adaptive for the inclusion of new contextual case-based or sector-specific component additions. This is based on the ontology the SESF proposes of components and subsystems structured through specific nested relationships (Cox and Frey 2015). To increase the integrity of comparability, guiding principles for developing a structured ontology with the SESF can be used to cohesively build its capacity between researchers (Hinkel et al. 2014; Cox and Frey 2015).

Numerous databases for comparing SES(F) data currently exist. The social–ecological systems meta-analysis database (SESMAD) is a collaborative effort, out of the Resilience Alliance Young Scholars and Dartmouth College (Cox 2014), to accumulate coded secondary SES case data (SESMAD 2014). The SES Library at the Center for the Study Institutional Diversity (CSID) at Arizona State University (ASU) aims to aggregate SES attributes for modeling and comparative analysis of qualitative and quantitative data (ASU CSID 2014). The International Forestry and Institutions (IFRI) project and database collect primary data with standardized methods to allow comparability in SES (IFRI 2013). Additionally, there have been methodological approaches for quantitative analytical comparisons with the SESF, allowing for artificial neural network analysis (Frey and Rusch 2013).

Guiding questions for coevolved SES research

Designing SES research that achieves the presented co-benefits in Table 1 needs to consider the perspectives of both aspects and how they can feasibly be incorporated. In Table 2 guiding questions and considerations are outlined for framing the implementation of case study research with combined aspects of the SESF and sustainability science. Key overlaps between the two pursuits include their problem-driven and diagnostic nature, recognition for the integration of multiple disciplinary perspectives, and interlinking science and society through the inclusion of stakeholders within the research process.

Highlighting the challenges

Improving the SESF

Since Elinor Ostrom introduced the SESF in 2007, there has been continuous work to test and improve its functionality.

Table 2 Guiding questions and considerations for framing sustainability science research in conjunction with operationalizing the diagnostic SES framework

Steps	SESF perspectives	↔ Guiding questions and considerations ↔	Sustainability science perspectives
(1) Framing research			
(a)	Explore multidisciplinary and multi-scale SES data	What is the problem and research question? What type of SES? Are there cross-case characteristics in relation to other SESs? What are the contextual case characteristics?	Is the research problem-driven? What is the interdisciplinary scope? What is the transdisciplinary scope?
(b)	Clearly define scope and scale (boundaries) of the SES. Define SES components	What are the focal (resource) system and the associated goods and services? Who are the actors/users? What are the institutions? What are the environmental bounding principles? Are common diagnostic metrics in the current SES framework available for the components in this SES?	What are the sustainability goals within the SES? Is the research plausible, coherent, visionary?
(c)	Test theory or analyze complexity	What are potential action situations/key drivers in the SES? How will you conduct your analysis? Methods and data types? How will data be transformed? Will you support or build a theory?	What are potential pathways and strategies for practical solutions? Envisioning? Process or outcome oriented?
(2) Diagnostic procedure and implementation			
(d)	Gather existing data on the SES	What are the characteristic components of the Resource system (RS), Resource units (RU), Actors (A) and Governance (GS)? What are the social, economic and political settings? What are the component interactions and inter-dependencies?	Incorporation of multidisciplinary knowledge? How can social learning processes be incorporated? Stakeholder involvement in the research process? Ethical considerations for the active or passive role of the researcher?
(e)	Gather new data and scope framework; construct or orient framework ontology to case context	What data is missing or not well understood? What components in the framework may be missing in relation to explaining the SES case? How to move beyond anthropocentric ecological classification to adapt a holistic ecological understanding?	How is the research adaptive? How does the research deal with uncertainties? How can the different knowledge/data gathered be used?
(f)	Interaction and action situation assessments	How has the social-institutional landscape been shaped through SES interactions? How has the ecosystem (RS and RU components; broader ecological system) responded? What are the key processes that drive (action situations) system interactions? What are the dependent and independent variables? What are the relationships between SES components?	What are the sustainability goals and desire outcomes? What are the implications for reaching sustainability goals? Opportunities for knowledge coproduction?
(g)	Outcomes, implementation and re-assessment	What are the SES outcomes? Why? What can be changed or made adaptive in the system? How?	What was achieved? How is the research shared and communicated? What is the learning orientation?

Adapted in part from Hinkel et al. (2015), Jerneck et al. (2010) and Wiek and Iwaniec (2013)

Much critique has surrounded its anthropocentric or actor-centric framing of the SESF (Binder et al. 2013; Thiel et al. 2015; Vogt et al. 2015). This emerged out of the framework's relationship to the IAD framework, to expand the capacity to analyze institutions and user behavior. Consequently there is a need to further develop the framework's ecological foundations to both understand ecological system complexity and to find potential interdependent explanatory links and interactions between ecological system components and SES outcomes. Ecological expansions have been proposed for the framework to include environmental bounding principles or ecological rules (Epstein et al. 2013; Vogt et al. 2015). Additionally, work that draws on the development of the more ecologically centric ecosystem services concept would be beneficial to enhance the framework's capacity to understand ecological system functionality and the value-domains created from ecosystem services (McGinnis and Ostrom 2014).

Further challenges include how differing methodologies for primary data collection and modified versions of the SESF for specific sectors may inhibit consistency of use and data comparability. There have been many applications of the framework using a variety of mixed-method data gathering and analytical tools (Schlüter and Madrigal 2012; del Delgado-Serrano and Andres Ramos 2015; Hinkel et al. 2015; Leslie et al. 2015; Partelow and Boda 2015). Methodological flexibility is a strong aspect of the SESF's potential for boundary work, but research should continue on how to integrate mixed-method data and how to conduct data transformation for comparative purposes. Second, if there is potential to develop consistent indicators for primary data collection on the framework's components. Additions to the SESF's tiers or components should consider general principles for constructing a useful SES ontology with nested relationships between components (Cox and Frey 2015). Currently there are numerous modified versions of the SESF for specific purposes or sectors with sparse ontological consistency (Thiel et al. 2015).

Pluralisms, integrating perspectives, and consistency

Use of the SESF from sustainability scientists and other researchers should recognize the theoretical foundations of the framework and attempt to embrace the need for consistency in its use. Existing empirical applications of the framework have shown that consistent use through practical applications is lacking (Thiel et al. 2015). The framework's success as a boundary object and comparative analytical tool for SES is largely dependent on consistency of use, largely through common metrics for coding primary data that is useful for secondary comparative analysis (Cox 2014). Engagement from sustainability scientists should recognize the sets of theoretical developments that led to the inclusion of components that structure the framework within a nested system of defined and explanatory relationships (Hinkel et al. 2014). Reciprocally, the comparative and contextual benefits from expanding the framework's broader engagement should be seen as a novel opportunity to orient theory across disciplines (Hertz and Schlüter 2015). Understanding how methodologies used in other disciplines can contribute data to the framework would be useful for the transparency of secondary data use. Beneficial future work could review and summarize all of the existing SESF procedures, including indicators, levels, and scales focused on.

There is a potential trade-off between establishing broader interdisciplinary engagement and developing consistent use of the framework in line with its foundation. This is generally to couple inductive empirical applications of the framework describing SES complexity with deductive motivations to further investigate more generalized explanatory relationships to certain outcomes. So far, practical implementation of the SESF has been varied, with a large focus on using the framework to descriptively analyze SES through inductive explanatory approaches (Thiel et al. 2015). Increasing use of the SESF among sustainability scientists or interdisciplinary researchers should recognize and work to solve the challenge of consistent use, although inconsistency has shown to be more likely in diverse cases (Thiel et al. 2015).

Embracing methodological and epistemological pluralism benefits the interdisciplinary pursuit of SES research through collecting robust data from differing perspectives (Miller et al. 2008; Fischer et al. 2015; Olsson et al. 2015). Sustainability science utilizes a large variety of methods for primary research and sustainability assessments. Co-beneficially, the SESF can structure SES data from multiple methodologies for comparative analysis. The SESF can manage pluralisms by providing a common structure to communicate and compare research across perspectives through its defined components, such as between the natural and social sciences. Further organizing diverse comparable data into knowledge types, that are useful for sustainability transitions, will benefit both pursuits.

Structuring research and data for comparability

In reflection on the "Facilitating comparative analysis" section, designing primary research to gather data into the SESF's components is the most suitable for effective comparisons, leading to useful secondary data. However, secondary data can also be reclassified into the framework. Although transforming secondary data for comparability with the SESF needs to consider the possibility of losing contextual relevance and integrity. Methodological pluralism is not a limitation for data comparability, but transparency and purpose should be clearly stated. If indicators are used to gather data on certain components, providing them would help advance the development of field methods for the SESF. Indicators for boundary work may be difficult to agree upon in an interdisciplinary setting, but new methods should be encouraged to further integrate and analyze different types of data together (e.g., quantitative and qualitative). Currently, there have been numerous applications of the framework using a variety of mixed-methods and indicators for empirical and analytical purposes (Schlüter and Madrigal 2012; Frey and Rusch 2013; del Delgado-Serrano and Andres Ramos 2015; Hinkel et al. 2015; Leslie et al. 2015; Partelow 2015).

Coevolving the SES research community

The SES research community continues to make substantial progress, but much of the literature and developments between them remains separated. There is considerable potential to further interlink sustainability science and the SESF due to their complimentary pursuits, leading to mutual benefits. Key challenges for moving forward include: (1) further closing the gap between research outcomes and the practical implementation of sustainability solutions, (2) finding pathways that embrace pluralisms and facilitating contextually relevant case-based research with data comparability, and (3) up-scaling and mainstreaming inter- and transdisciplinary SES research agendas. Communicating and effectively disseminating the knowledge gained from addressing these challenges needs to further interlink SES research with society. There are many subcommunities in SES research, and along with the SESF and sustainability science, constructive interdisciplinary discussion needs to unify SES research rather than solidify differences that isolate co-beneficial progress toward sustainability transitions.

Conclusion

This article has presented an overview of the co-benefits to SES research from the potential to further interlink Ostrom's diagnostic SES framework (SESF) and sustainability science. Four key co-benefits were highlighted (Table 1) including: (1) coevolving SES knowledge types, (2) guiding primary research and assessing sustainability, (3) building a boundary object for transdisciplinary sustainability science, and (4) facilitating comparative analysis. Achieving these co-benefits will advance the ability for SES research to pursue inter- and transdisciplinary collaborations. Codeveloping the SESF and sustainability science community can build a robust boundary object for SES research that progresses comparable empirical research, structuring knowledge development, and incorporates methodological pluralism. Guiding considerations for designing SES research within this co-aligned vision are presented in Table 2. From a broader perspective, research in SES and sustainability science is advancing considerably but remains ambiguous in its ability to create positive transformational change in the real world. Boundary work that allows SES research to cohesively aggregate and become co-beneficially useful will make considerable progress toward advancing our functional understanding of SES and the practical solutions that can be developed from this knowledge.

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