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Implementing a social-ecological systems framework for conservation monitoring: lessons from a multi-country coral reef program

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ABSTRACT

Multi-scale social-ecological systems (SES) approaches to conservation and commons management are needed to address the complex challenges of the Anthropocene. Although SES approaches to monitoring and evaluation are advocated in global science and policy arenas, real-world applications remain scarce. Here, we describe the first operationalization and implementation of Ostrom's influential SES framework for monitoring practice across multiple countries. Designed to inform management aimed at sustaining coral reefs and the people that depend on them, we developed our SES monitoring framework through a transdisciplinary process involving academics and practitioners with expertise in social and ecological sciences. We describe the SES monitroing framework, including how it operationalizes key insights from the SES and program evaluation literatures, and demonstrate how insights from its implementation in more than 85 communities in four countries (Fiji, Indonesia, Kenya and Madagascar) are informing decision-making at multiple levels. Responding to repeated calls for guidance on applying SES approaches to monitoring and management practice, we outline the key steps of the transdisciplinary development of the framework and lessons learnt. Therefore, our work contributes to bridging the gap between SES science and commons management practice through not only providing an SES monitoring framework that can be readily applied to coral reefs and other commons, but also through demonstrating how to operationalize SES approaches for real-world monitoring and management practice.

1. Introduction

In the face of accelerating social and environmental change, achieving a sustainable future for the world's coral reefs and the people who depend on them requires managing coral reefs as linked social-ecological systems (SES). The SES paradigm emphasizes the interdependent linkages between social and environmental change (Fischer et al. 2015). Thus, an SES perspective implies a system framing that recognizes cross-scale interactions, dependencies, and feedbacks between the social and ecological systems (Liu et al. 2015). Coral reefs represent tightly-coupled SES, with millions of people relying heavily on reef ecosystem goods and services, the provision of which is increasingly under threat given reef degradation driven by a myriad of interdependent local and global stressors (Hughes et al. 2017). Accordingly, numerous papers have called for an SES approach to conservation and management of coral reefs and common-pool resources (hereafter 'commons') more generally (e.g. Fischer et al. 2015, Virapongse et al. 2016, Hughes et al. 2017, Bellwood et al. 2019). Indeed, the SES paradigm is increasingly reflected in international environmental policy, such as the Convention on Biological Diversity and

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the United Nations Sustainable Development Goals, which emphasizes the importance of achieving multiple objectives spanning ecological and social wellbeing.

A substantial body of academic literature uses an SES lens to examine the management of commons (Partelow 2018), including coral reef ecosystems (e.g. McClanahan et al. 2006, 2008, Pollnac et al. 2010, Jupiter et al. 2017). Often undertaken using a case study approach (Partelow 2018), empirical research has identified a large number of characteristics that are likely to influence management outcomes, including those that relate to the ecological (e.g. commons size; Persha et al. 2011), social (e.g. resource dependence; Basurto 2005), and institutional context (e.g. clear property rights; Gurney et al. 2014). Drawing on this literature, a number of frameworks for SES analysis of management have been developed (see Binder et al. 2013 for a review), most notably Ostrom's (2007, 2009) SES framework. Syntheses of case studies (e.g. Cox et al. 2010, Ban et al. 2019) and emerging large-scale comparative approaches (e.g. Cinner et al. 2012, Persha et al. 2011, Chhatre and Agrawal 2009) are beginning to shed light on the generalizability of SES relationships observed in cases (Araral 2014).

However, advances in SES understanding of commons management in the academic literature are only just beginning to be reflected in real-world practice (Virapongse et al. 2016). A key barrier is that monitoring and evaluation practice that considers multi-scale social and ecological systems in an integrated way remains nascent (Selomane et al. 2019; but see Mascia et al. 2017, Jupiter et al. 2017). A lack of integrated SES monitoring inhibits understanding of whether management actions improve social or ecological outcomes and the mechanisms or pathways underpinning these outcomes. Ultimately, this could lead to implementation of inappropriate management actions that fail to halt ecological decline, or worse, have negative or perverse ecological or social outcomes, such as poverty traps (Cinner 2011). Employing an SES approach can avoid these undesirable outcomes, especially if implemented across multiple sites to allow for cross-site comparisons. Given that many of the outcomes of management and the conditions associated with them arise at the site level, coordinated monitoring and subsequent comparative analysis incorporating a large number of sites (i.e. large-*N* studies) can help identify what actions work where and why (Poteeete and Ostrom 2008, Agrawal 2014). Such approaches can help ensure that panacea approaches to management are avoided (Ostrom 2007), increasing the likelihood of achieving ecological and social success, and therefore, the wise use of (usually scarce) funds for management.

Several reasons have been put forward to explain the scarcity of SES approaches to monitoring, and conservation and management practice more broadly. First, the inherent complexity of the SES concept has been cited as an impediment to its implementation (Reyers et al. 2013, Virapongse et al. 2016). The various SES frameworks do distill some of this complexity but little guidance is given for their operationalization (Binder et al. 2013). In particular, guidance is often lacking for how to prioritize among the large number of SES attributes for a particular context and question, a key challenge in monitoring practice that has received little attention (Loomis et al. 2014, Rasmussen et al. 2017). Additional challenges to selecting appropriate sets of SES indicators are posed by coordinated monitoring approaches, including inevitable proliferation of indicators (Pereira et al. 2013) and balancing case-based relevance and universal applicability (Rasmussen et al. 2017, Partelow 2016). Further, SES frameworks are often difficult to operationalize to meet the information needs of management in a way that is feasible given resource and capacity constraints. Addressing these challenges to enable application of SES science to real-world monitoring requires collaborations among academics and practitioners with expertise in social and ecological disciplines. This approach to knowledge production is termed transdisciplinarity (Mauser et al. 2013), and is a form of 'boundary work' (Cash et al. 2003) because it occurs across boundaries among traditionally separated groups, such as those related to disciplines and knowledge types (e.g. academic and practitioner). However, documented examples of transdisciplinary approaches remain nascent, reflecting a major barrier to mainstreaming SES approaches in monitoring practice (Virapongse et al. 2016).

Here, we outline the transdisciplinary development and implementation of an SES framework for monitoring the social and ecological outcomes of coral reef management in four countries (Fiji, Indonesia, Kenya, Madagascar). The aim of this paper is to contribute to bridging the gap between SES science and conservation and commons management practice by undertaking the first operationalization of Ostrom's influential SES framework for practical monitoring across multiple countries (but see Jupiter et al. (2017) for an example of a smaller-scale application across eight communities in Fiji). Responding to repeated calls for guidance on how to apply SES approaches to monitoring and management practice (e.g. Fischer et al. 2015, Virapongse et al. 2016), we document the key steps of our transdisciplinary approach (sections 2.1-2.4.2) and discuss major challenges and lesson learnt to date. Further, we describe our SES monitoring framework, including how it operationalizes key aspects of SES literature, and demonstrate how the resulting data are informing decision-making. Finally, we reflect on how the SES monitoring framework is contributing to advancing both the practice and science of SES, conservation and commons management.

2. Methods

2.1. A transdisciplinary approach

We took a transdisciplinary approach to developing the SES monitoring framework for coral reef management, which involved collaboration between academics and practitioners with expertise in social and ecological disciplines. Transdisciplinary approaches seek to address real-world problems through borrowing from multiple scientific disciplines (i.e. interdisciplinarity) and different kinds of knowledge (e.g. scientific, professional, practical; Jahn et al. 2012). Through the co-production of knowledge, such approaches aim to advance both practice and science through a mutual learning process (Mauser et al. 2013). Thus, transdisciplinary processes are thought to give rise to knowledge that can inform practice because it is likely to be perceived by practitioners as: (1) credible, providing accurate and valid information; (2) salient and relevant to their information needs; and (3) legitimate, being developed through a participatory process (Cash et al. 2003). Following, we describe the key steps of our transdisciplinary approach.

2.2. Real-world problem

The SES monitoring framework was developed to support the Wildlife Conservation Society (WCS), an international conservation non-profit, in taking an SES approach to coral reef management. WCS coral reef programs work closely with local communities and national governments under co-management or community-based governance approaches to promote the sustainability of coral reef systems, conserve biodiversity, sustain fisheries, and support human well-being. Strengthening coral reef resource governance is a key component of WCS's work, and involves, for example, supporting participatory decision-making, local resource access and use rights, compliance monitoring, and conflict resolution.

Beginning in the mid-1990s, WCS coral reef programs recognized the need for strategic engagement with local communities to better understand and approach the human dimensions of resource management interventions. This was catalyzed by the failure of top-down management that seldom fully appreciated the historical authority and long history of resource management that often-preceded proposed interventions (McClanahan et al. 2005, 2006). For example, poor inclusion of local leaders and lack of acknowledgment of their historical authority led to violent conflicts between national park personnel and local stakeholders when implementing a nationally legally-gazetted marine reserve in Diani, Kenya (McClanahan 2007). These experiences reflected ongoing concerns over governance conflicts documented by early investigators, such as Robert Johannes, Robert Pomeroy, and Richard Pollnac, around traditional and community-based marine resource management (Johannes 1982, Pomeroy et al. 1997). Emerging WCS programs in Kenya, Indonesia, and Papua New Guinea began using social questionnaires to understand the human dimensions of resource management, including existing patterns of resource use, management and governance, and social conflicts that were at the root of the ecological degradation (McClanahan et al. 2005, 2006). This led to new understandings and integration of data and people investigating the social and ecological outcomes of coral reef management (Pollnac et al. 2010; Cinner et al. 2012).

By 2014, WCS coral reef practitioners had created the inertia to be funded at the institutional level to build on these previous approaches to social and ecological monitoring to design a standardized SES monitoring approach that would be applicable to different resource management projects and countries. A coordinated approach was recognized to bolster SES management approaches through facilitating generation of SES time-series data over periods of change and contexts, allowing comparison and learning across projects and country programs. Further anticipated benefits of such an approach included developing and maintaining a centralized platform that could increase efficient data entry and analysis, and less time and resources invested in creating indicators for new projects.

2.3. Co-designing monitoring framework objectives

The SES monitoring framework described here was developed over a period of three years (2014 – 2017), and involved refining the objectives of the monitoring framework, selecting focal SES attributes, and viable indicators for those attributes, and piloting in the field that led to further refinement through successive iterations. This process represents the co-design (Mauser et al. 2013) or problem transformation (Jahn et al. 2012) phase of transdisciplinary research. As suggested in the literature, this phase included (1) linking the practical problem or knowledge gap to existing and relevant scientific knowledge; and (2) jointly identifying objectives of the work (in our case, objectives for the monitoring framework).

We identified clear objectives for the monitoring framework through a workshop involving the core team, which included researchers and practitioners from each of the four coral reef country programs and university-based social and ecological researchers studying coral reef systems. Practitioners and program managers expressed the need for the framework to facilitate the demonstration of social and ecological impacts, as well as to support learning within and across country programs as to what management actions work where and why. This practical problem was 'transformed' (*sensu* Jahn et al. 2012) into research questions to articulate clear objectives for the monitoring framework, a critical but often neglected step in developing conservation monitoring (Possingham et al. 2012). These were, "how do WCS-supported management interventions affect the social and ecological state of coral reef systems?", and "what are the contextual and institutional conditions associated with changes in the social and ecological state of coral reef systems?"

2.4. Identifying social and ecological attributes of coral reefs

We aimed to develop a practical SES monitoring framework that distilled coral reef SES down to a minimum set of key attributes relevant in meeting the core objectives and research questions, but which could also be applied across multiple countries and management actions. Our approach reflects an 'Essential Variables Approach', which emerged from systems theory (Pereira et al. 2013, Reyers et al. 2017) to enable coordination of global climate monitoring (Bojinski et al. 2014) and, more specifically, to address the challenge of indicator proliferation. This is an enormous but often unrecognized challenge of developing coordinated monitoring frameworks (Loomis et al. 2014), particularly if it occurs across actors working in different disciplines, countries, or domains (e.g. academia and practice), as in our case. Broadly, the Essential Variable Approach involves identifying a set of variables or attributes that capture system essence, and which describe the key processes and features that are indispensable to meeting the objectives at hand (Pereira et al. 2013, Reyers et al. 2017).

To identify these key relevant attributes of coral reef SES and the indicators to operationalize them, we undertook an interactive iterative process that involved drawing on the relevant academic literature and the understanding of coral reef management from academic and practitioner perspectives. The key bodies of literature that we drew on were those on social-ecological systems in the context of common-pool resource governance (e.g. Ostrom 1990, Ostrom 2007, Agrawal 2014) and program evaluation (e.g. Pressey et al. 2017).

2.4.1. Ostrom's SES framework

We adopted Ostrom's SES framework, using it as a conceptual lens to view coral reef management, support cross-boundary discussions, structure our monitoring framework, and help guide our choice of SES attributes. We selected the latter framework over others that integrate social and ecological systems (see Binder et al. 2013 for a review) primarily because it was designed to be 'theory-neutral' (McGinnis and Ostrom 2014). In recognition of the complexity of SES and that no theoretical perspective is sufficient to analyze all SES situations, Ostrom's framework aims to be diagnostic and thus suggestive of potential attributes and relationships that are relevant in understanding SES in the context of common-pool resource governance (McGinnis and Ostrom 2014). This is in contrast to other SES frameworks that tend to be prescriptive and normative, with a particular focus (e.g. vulnerability; Cinner et al. 2013) or perspective (e.g. humans considered solely as sources of pressures or threats to nature in the 'drivers-pressures-state-impact-response' [DPSIR; Svarstad et al. 2008] framework).

This flexibility to accommodate multiple foci and theoretical perspectives was critical given that our framework was developed to be applicable to multiple resource management projects and social contexts. To select SES attributes, we drew on a range of relevant literatures and theories, including those related to wellbeing (e.g. Gough et al. 2006), social adaptive capacity (e.g. Cinner et al. 2013), and equity (e.g. Sikor et al. 2014; see Table A1, Gurney and Darling 2017). A further critical reason that we selected Ostrom's SES framework was because it emphasizes feedback and bi-directional relationships within and between social and ecological systems and the hierarchical nature of SES.

2.4.2. Regional workshops

The second component of our transdisciplinary process involved drawing on practitioners' and scientists' knowledge of coral reef management through five workshops over a 24-month period (Fig. 1). Workshops were held in each of the four focal countries with national practitioners and scientists, with the objective of identifying decision-making needs and key processes underpinning coral reef management. The number of people at each workshop varied from 10 to 24 (including the authors of this paper). Each workshop involved scientists and practitioners with expertise in coral reef ecology or social science related to coral reef management and/or governance, though those with social science expertise accounted for a smaller proportion of the participants. All of the practitioners were employees of WCS and regularly advise on coral reef management and decision-making at multiple levels, from individual projects to regional policy coordination.

To facilitate discussions, we drew on Ostrom's SES framework and the program evaluation literature, especially theories of change, which describe the assumed causal links between a management intervention, intermediate outcomes and desired management impacts (Pressey et al. 2017). During the workshops, we developed theories of change for

Fig. 1. The transdisciplinary development of the SES monitoring framework involved a series of workshops in Fiji, Kenya, Indonesia and Madagascar with academics and practitioners with expertise in social and ecological disciplines (top left). Theories of change for key management activities were developed to provide roadmaps elucidating which SES attributes are critical to understanding if and how coral reef management has a social or ecological effect (top right) and helped identify decision-making information needs of management practitioners (bottom right). The monitoring framework was piloted in the field (bottom left) in the process of refinement.

different management actions, which provided roadmaps of SES attributes critical to understanding if and how coral reef management has a social or ecological effect. The theories of change were constructed through participatory conceptual modelling (Margoluis et al. 2009) that involved first identifying a management action and its desired impact. The assumed causal links between the management intervention, intermediate outcomes and desired impacts were then mapped, ultimately providing a hypothesis for the management intervention. Next, the conditions or assumptions underpinning each causal link were discussed and added to the diagram, and indicators for each SES attribute present in the theory of change were identified. We also identified coral reef SES attributes that were considered important across all of the four focal countries, and these were categorized in Ostrom's SES framework.

Concurrent with selecting attributes of coral reef SES, we selected indicators that were employed successfully in the past by WCS (many of the social indicators were designed by J.Cinner and R. Pollnac (e.g. Cinner et al. 2013, McClanahan et al. 2008) and in the relevant literature. We selected our social and ecological indicators based on standard criteria, such as reliability, sensitivity, and feasibility (USAID 1998). For the social indicators, we took a mixed-methods approach that included quantitative and qualitative measures and subjective and objective data. Household surveys were conducted using systematic sampling, whereby a sampling fraction of every *i*th household (e.g. 2^{nd}, 3^{rd}, 4^{th}) was determined by dividing the total community population by the sample size possible given survey resource constraints (De Vaus 1991). Key informants included government and traditional leaders and members of resource management groups, and were selected using purposive sampling. All social and ecological surveys were compliant with ethics specified by the WCS Institutional Review Board.

3. Results

3.1. The SES monitoring framework for coral reefs

The resulting SES framework comprises of 90 social and ecological indicators, which are organized under the second-tier variables of Ostrom's SES framework (Fig. 2, Table A1, Gurney and Darling 2017). Aligning with an Essential Variables Approach (see section 2.4 above), these indicators represent the minimum but, comprehensive, set of coral reef SES attributes that we identified as: (1) relevant to understand the social and ecological outcomes of coral reef management actions, and the contextual and institutional conditions under which those outcomes arise; and (2) able to produce standardized and reliable data across different country contexts. The indicators are collected using standard underwater visual census (UVC) protocols, and semi-structured social surveys at the household (or individual) level and with key informants, including community leaders, members of marine resource management groups and fishers. We designed the social surveys with the intention that they be supplemented with management action- and context-specific indicators. Data for a handful of additional contextual indicators [e.g. market access (S5.1, Table A1), climate exposure (ECO1.1)] can be sourced from publicly-available primary and secondary sources.

Drawing on SES theory, our approach allows for the examination of feedbacks, cross-scale relationships and heterogeneity, three key features of SES identified in the literature but which are often difficult to operationalize in practice (e.g. Liu et al. 2007, Reyers et al. 2018,

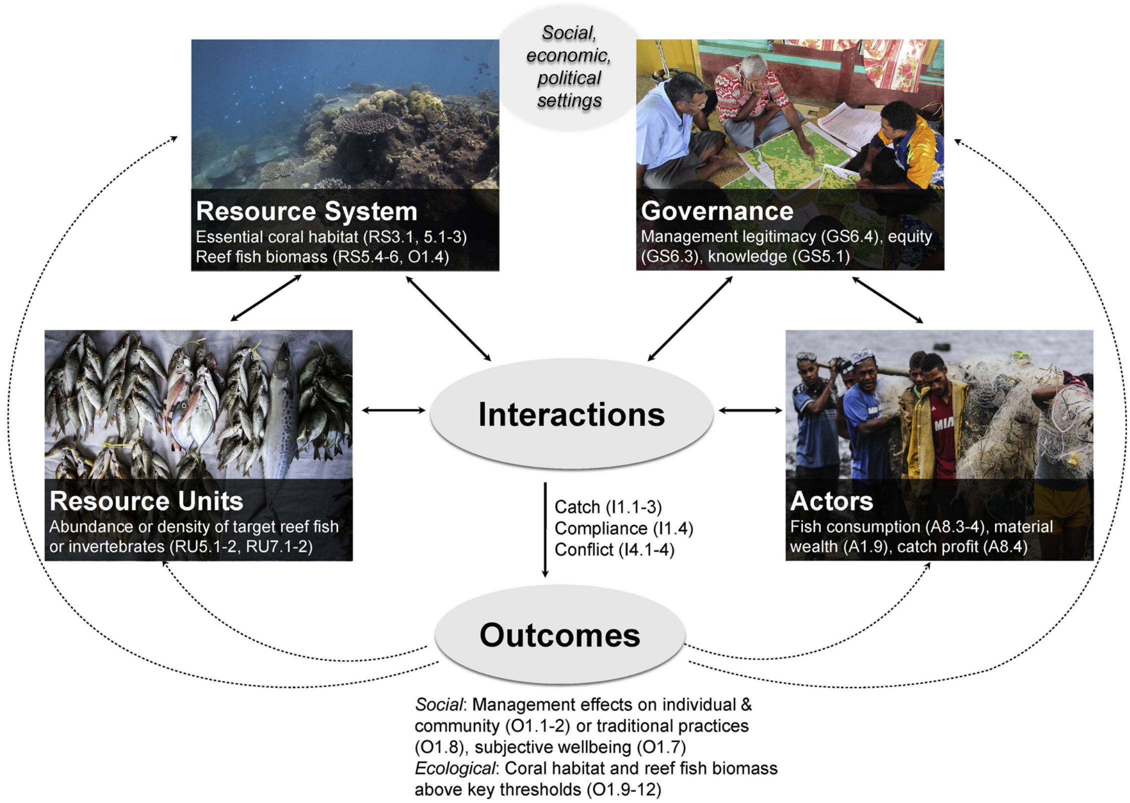

Fig. 2. Ostrom's (2007, 2009) social-ecological systems framework operationalized for monitoring of coral reef management. Example indicators are shown for each subsystem, a full list of indicators can be found in Table A1.

Selomane et al. 2019). Our primary approach to incorporating feedbacks is to include indicators of bidirectional relationships between and within coral reef social and ecological systems that can be used to investigate key hypothesised feedbacks (i.e., dashed lines, Fig. 3) with time-series data. We also include direct indicators of feedbacks, which operationalise the two primary categories of SES feedbacks identified by Kittinger et al. (2012), namely environmental feedbacks (e.g. perceived effect of management on fishing effort [O1.5], perceived effect of management on catch reliability [O1.6]) and institutional feedbacks (e.g. whether management rules changed in response to changes in ecological conditions [GS8.7], individual fisher's response to resource decline [A7.3]).

As emphasized in the SES literature, SES connections can occur across spatial and socio-political levels (Selomane et al. 2019). The SES monitoring framework includes social indicators operating at regional (e.g. market access [S5.1], community (e.g. characteristics of management institutions [GS3-8], household (e.g. household material wealth [A2.9]), and individual levels (e.g. demographics [A2.1-7], perceptions of management effects [O1.1-7]). Ecological indicators can characterize reef-level ecological states and processes (e.g., 10s–100 s of meters) or can be aggregated to describe regional or biogeographic patterns (10s–100 s of kilometres) of function, diversity, and resilience. Incorporating indicators at finer levels of social and ecological organizations allows examination of heterogeneity, an important yet often unclear facet of SES (Selomane et al. 2019). For example, disaggregating data based on socioeconomic characteristics relevant to structuring society in a given context (e.g. gender, ethnicity, resource dependence) allows examination of inequalities insystem outcomes (e.g. Gurney et al. 2015).

We drew on the program evaluation literature to design our approach to attribution, employing a number of different methods for designing evaluations, including theory-based, participatory, and statistical (Woodhouse et al. 2017). Following a theory-based design, which relies on developing and testing causal models, many of our indicators operationalize steps of key theories of change through which conservation and management activities are hypothesized to affect coral reef SES (Fig. 3). Following a participatory approach, a number of indicators draw on project beneficiaries' perceptions of how management affects people (e.g. management effects on individuals [O1.2], communities [O1.1], and the distributional equity of these [O1.3]). Lastly, by taking an Essential Variables Approach to designing our indicators and ensuring that the indicators produce reliable and comparable data across multiple contexts and resource management projects, data are amenable for use in statistical evaluation designs, including longitudinal and comparative analysis.

3.2. SES framework implementation in four countries

Since 2016, the SES monitoring framework has been implemented in the four focal countries (Fiji, Indonesia, Kenya, and Madagascar) in more than 85 communities, with 1-3 key informant surveys and 15-35 household surveys per community. Data were collected using open-source data platforms that allow online-offline entry and management of data, with social data managed in Kobo Toolbox (www.kobotoolbox.org) and ecological data in the built-for-purpose MERMAID (Marine Ecological Research Management AID; www.datamermaid.org) platform.

3.3. SES data informing practice and policy

Data collected using the SES monitoring framework are being used to inform conservation decision-making from local to global levels. At the local level, the framework has been applied to a number of resource management projects, including those addressing food security in Madagascar, shark management in Indonesia, and payments for marine ecosystem services in Fiji. In the latter case, social data arising from the

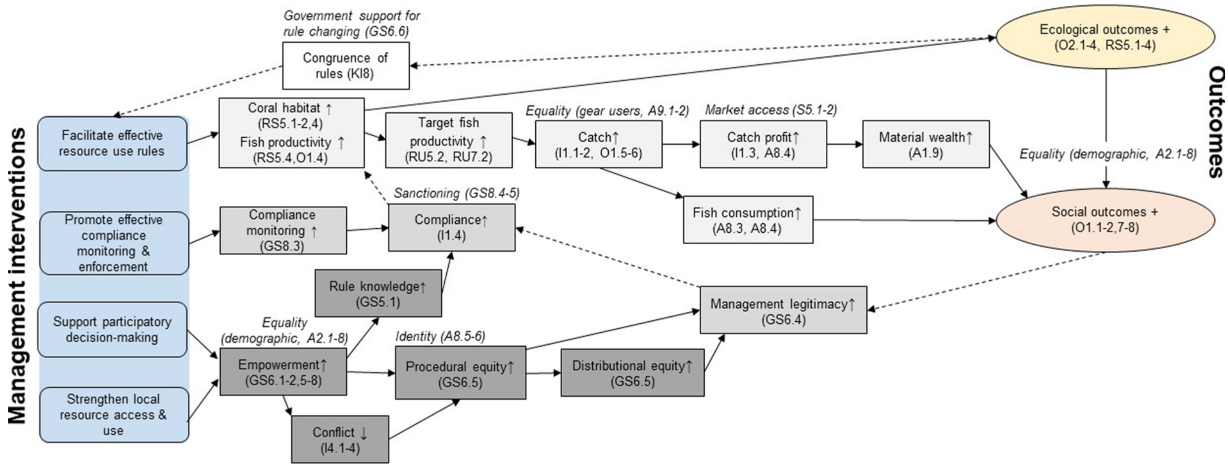

Fig. 3. Example theories of change depicting simplified idealised pathways (solid lines) through which key management activities (blue rounded squares, left) can lead to desired social and ecological outcomes (coloured ovals, right). Numbers and letters in parentheses denote the SES monitoring framework's indicators (see Table A1). Italicized text above boxes provides examples of important assumptions (equal outcomes across different social groups, i.e. equality) or conditions (e.g. market access) underpinning the theory of change step. While all pathways can be interconnected, grey shading indicates different pathways associated with improvements to environmental condition (light grey), rule compliance (medium grey), and empowerment and equity (dark grey). Dashed lines provide examples of key feedbacks.

implementation of the SES monitoring framework revealed that many coastal residents were unsupportive of the project because the distribution of benefits was considered unfair. Further, disaggregation of the data into key social subgroups (e.g. age, gender, education, material wealth, primary livelihood) suggested perceptions of unfairness were particularly high amongst women. These results are currently supporting the project's management committee in ensuring rules governing the distribution of benefits better align with local norms of fairness and developing targeted engagement aimed at increasing women's involvement in decision-making.

At a provincial level, the SES monitoring framework has been applied to the design and management of a network of marine protected areas, encompassing more than 250,000 hectares, in the province of West Nusa Tenggara, Indonesia. In addition to providing a baseline for monitoring social and ecological outcomes, data have been used by community, district, and provincial governments to build a profile of the relevant coral reef SES, diagnose management needs, and tailor zoning regulations and management plans to the local context.

At a global level, data arising from the SES monitoring framework from all four focal countries are being used in a comparative analysis of the social and ecological outcomes of co-management as part of a transdisciplinary project involving researchers, practitioners and policy-makers (https://snappartnership.net/teams/coastal-outcomes/). The project aims to inform the post-2020 framework for the Convention on Biological Diversity; specifically, with respect to providing evidence to support the classification of 'other effective area-based measures' (i.e. marine management not classified as an IUCN protected area) and understanding of where they are likely to be effective in delivering social and ecological outcomes (IUNC WCPA 2019).

4. Discussion

4.1. Advancing science and practice through a transdisciplinary approach

In line with the aims of a transdisciplinary approaches, our SES monitoring work is expected to contribute to advancing both the science and practice of SES, conservation, and commons management. The framework enables an SES perspective to be taken to management practice by facilitating the examination of feedbacks, cross-scale relationships, and heterogeneity, three key features of SES identified in the literature (e.g. Liu et al. 2007, Reyers et al. 2018). While the framework could be most readily applied to other coral reef management initiatives across the globe, it could also be applied to other ecosystems given that many of the attributes are not specific to coral reefs and have been found to be important across a range of ecosystems (e.g. graduated sanctions, compliance monitoring Ostrom 1990).

Further, through describing the transdisciplinary development of the first application of Ostrom's SES framework to real-world management across multiple countries, we advance practice more broadly by responding to repeated calls to address the dearth of guidance on how to employ SES approaches in real-world management (Partelow and Boda 2015, Virapongse et al. 2016). For example, our approach of standardization supplemented with context-specific indicators addresses the tension between case-based relevance and universal approaches that allow comparative analysis and foster efficiency through circumventing the need to develop entirely new monitoring frameworks, data entry and storage for every resource management project. Thus, we provide a means to reconcile contextually relevant case-based research with data comparability, identified as a key future challenge in the SES literature (Partelow 2016) and as a priority by sustainability practitioners (Rasmussen et al. 2017).

To advance SES science, our framework helps address the paucity of large-*N* time-series SES datasets, which has long been recognized as a key barrier to progressing the SES field (Poteete and Ostrom 2008, Agrawal 2014). While much progress has been made with qualitative comparisons of case studies (e.g. Ostrom 1990, Cox et al. 2010, 2014), quantitative comparative analysis offers a complementary approach that helps elucidate causal relationships among SES attributes. Given the difficulties associated with purely academic efforts to develop large-*N* time-series data of SES (e.g. short funding duration, difficulties associated with sharing data or using standard techniques; Mascia et al. 2017), transdisciplinary work such as this may provide an important avenue via which these datasets can be generated. Given that many large conservation and development government and non-government organizations operate in multiple sites (in which they often have ongoing engagement) and tend to be required to conduct monitoring, they are uniquely placed to address this lack of data.

4.2. Key challenges and lessons learned

4.2.1. Transdisciplinary process

Transdisciplinary approaches are costly, requiring more time, money, capacity and personal commitment from participants than other forms of knowledge production (Lemos et al. 2018). These costs have likely hindered uptake of SES approaches for monitoring and evaluation. As our work spans multiple countries, we faced additional challenges, both practical (e.g. coordinating seasonal monitoring, translation of social surveys into multiple languages) and cultural (i.e. different approaches to workplace relations, such as organizational hierarchy, voicing of options, etc.). The diversity of perspectives entailed in transdisciplinary international work results in different priorities, interests, epistemologies (i.e. approaches to knowledge), and thus, a tension as to what constitutes salient, credible, and legitimate knowledge (*sensu* Cash et al. 2003).

To overcome this tension and integrate diverse perspectives, we drew on the concepts of 'boundary objects', 'boundary spaces', and 'knowledge brokers' from knowledge coproduction theory. We used Ostrom's SES framework as a 'boundary object', defining characteristics of which are that they are both adaptable to different viewpoints and robust enough to maintain identity across them (Star and Griesemer 1989). Therefore, the utility of boundary objects lie in their ability to facilitate common understanding and deliberation among diverse actors. Given that Ostrom's SES framework gives similar weight to social and ecological systems and was designed to facilitate the evaluation of multiple hypotheses from alternative perspectives (McGinnis and Ostrom 2014), it provided a shared concept and language to learn about differences across a given boundary.

These cross-boundary interactions amongst our transdisciplinary team – where tacit knowledge becomes explicit and learning and knowledge production across boundaries occurs – form what is termed as 'boundary spaces' (Stange et al. 2016). Multiple boundary spaces involving different actors arose through activities such as field visits, workshops, and meetings with other organizations engaged in similar work. These repeated interactions were also critical for building trust and camaraderie (i.e., social capital), and therefore, the legitimacy of the work. The success of boundary spaces was facilitated by the fuzziness of the distinction between academic and practitioner actors, with practitioners being also scientists and academics having extensive experience collaborating with practitioners. Success was further facilitated by having a funded coordinator, who acted as a 'knowledge broker' to develop cross-boundary relationships and networks (Cvitanovic et al. 2015). Ultimately, the concepts of boundary objects, boundary spaces, and knowledge brokers contributed to facilitating a deliberative and inclusive processes that fostered willingness to learn and compromise, which is critical for transdisciplinary approaches.

4.2.2. Standardized multi-country approach: constraints and trade-offs

To ensure our SES monitoring framework could be applied across multiple countries and management interventions, we were constrained to selecting only those attributes considered as relevant across diverse contexts and to prioritizing breadth over depth of inquiry, using one or few indicators for each type of attribute. A further constraint was the reliance mostly on indicators yielding quantitative data (e.g. closed-ended questions) for the social surveys to help ensure data quality given the large number of survey administrators and data processors across multiple countries. Thus, SES attributes that are easily quantified are better captured than those that are not (e.g. power, values etc.). Therefore, given that indicators and 'measurement does not just record, it shapes, changes and constitutes' (Brockington 2017), there is the risk that these important attributes could disappear from decision-making. Together these constraints necessitated by a standardized approach increase the likelihood of oversimplification and omission of SES attributes critical in a particular context, including local expressions or interpretations of those attributes.

Trade-offs between case-based relevancy and universality applicability are inherent to developing standardized and globally-comparable monitoring and research frameworks. Our approach to reducing this trade-off was to design the standardized SES 'core' framework with the intention that it be supplemented with context-specific components. This approach allows for the inclusion of SES attributes relevant to a particular case and use of a broader range of methodological approaches (e.g. bio-cultural approaches, McCarter et al. 2018). For example, locally-relevant food security indicators were added to Madagascar surveys, while in Fiji, indicators designed to assess the effects of a recent cyclone were added. In sum, the approach of a core set of globally-comparable indicators supplemented by locally-specific indicators enabled us to find a balance between local relevancy and global universality. This approach could be used in any monitoring initiative designed to be implemented across multiple contexts.

4.2.3. Attributing change to management

One of the foremost challenges of designing a monitoring framework is causal inference, in other words, addressing how changes in SES can confidently be associated with management activities. Recently, quasi-experimental designs that evaluate experimental and control sites have been widely advocated in the academic literature as the 'gold standard' (Woodhouse et al. 2016). However, given the ethical, cultural and logistical constraints related to social control sites (Gurney et al. 2015), quasi-experimental designs were and will not often be feasible. Further, the significant technical skill and very large-N (at the community level) datasets required to undertake the statistics underpinning quasi-experimental approaches (i.e. matching) are further barriers to employing this approach (Stern 2015).

In lieu of a quasi-experimental design, we designed our SES monitoring framework to enable triangulation across participatory, theory-based, and statistical approaches. Each approach provides different information that can inform attribution and management (Woodhouse et al. 2016), and in comparison to quasi-experimental methods, can better answer questions of *how* and *why* management is or is not effective (Stern 2015). While the SES monitoring framework can be applied in evaluation designs that use controls (as done so in some sites in Madagascar and Indonesia), we do not rely on this approach to attribution. Instead, our strategy of using a combination of evaluation approaches ensures monitoring is logistically and technically practical, and generates information that is useful for practitioners and that can be quickly employed in the shorttime frames in which real-world decision-making occurs.

4.2.4. Implementation resources and costs

Key challenges relating to implementing the SES monitoring framework include required resources, data quality and efficient data management and analysis workflow. First, the time required by field programs to implement the SES monitoring framework, collect and analyze data is considerable. Despite employing an Essential Variable Approach to identify the minimum number of required attributes, capturing the complexity of coral reef SES systems requires dozens of indicators, which can slow down project timelines and hinder the use of SES insights in adaptive management. However, a standardized framework is also saving practitioners time through minimizing the need to 'reinvent the wheel' for social and ecological monitoring for every resource management project.

Significant financial resources are required to develop a framework across multiple countries. This poses an important barrier, but it appears that donors are increasingly recognizing the need for coordinated multi-country approaches. In our case, the generosity of a single donor (the John D. and Catherine T. MacArthur Foundation) seeking to understand the outcomes of their coastal grant-making across multiple countries supported the development and implementation of our SES framework approach. While the initial financial investment of a coordinated monitoring approach is high, such approaches can be sustained by limited funds from multiple projects over the long term. Undertaking a similar coordinated monitoring approach with less financial resources might involve focusing on community-level social data given that household surveys are more resource intensive and complex to analyze. However, such approaches cannot capture household-level variation in many important social attributes of SES (e.g.

perceptions of management impacts, involvement in decision-making, material wealth) inhibiting empirical assessment of important SES relationships, obscuring issues of equality, and ultimately, may lead to biased or inaccurate understanding of SES. For ecological data, the use of underwater photographs (for benthic cover) or diver-operated videos (for fish) may reduce field costs, which can be high depending on the scale and frequency of monitoring. However, analyzing resulting photographs and videos requires a lot of time. Further, diver operated videos also require a fair amount of infrastructure and specific software and technological skills. A further option when funding is limited is to use people's perceptions of resource health as a proxy, but again, this approach may lead to inaccurate understanding of SES given people's perceptions are often not reflective of reality.

To ensure data quality, we took several steps focused on standardization and reliability, including conducting training in implementing the SES monitoring framework in all four countries and developing a practitioners' guide which has been translated into three languages (Gurney and Darling 2017). Given that most practitioners implementing the SES monitoring framework are trained in the natural sciences, building social science capacity was a particular focus. As conservation and management increasingly look towards SES approaches, organizations engaged in this space will need to build their capacity in the social sciences. A further step taken to ensure data reliability was to develop data platforms for data entry and management.

Given the amount of data generated by the SES monitoring framework, efficiency of data management and analysis workflows is critical to the utility of monitoring data for decision-making (Fox et al. 2014). To avoid ineffectively managed monitoring information, which can hinder the feedback of monitoring results to adaptive management, we used two data platforms (Kobo Toolbox and MERMAID) to improve the speed and accuracy with which data are digitized, managed and accessed. Adopting open-source online tools such as these (also OurFish app developed by Rare Conservation) to collect and aggregate data can make the most of limited resources for analysis and reporting of indicators. Our next steps are to develop near real-time dashboards that provide visualization and simple analyses of social and ecological data, thereby quickly transforming raw data into actionable knowledge that can readily inform practice and policy.

5. Conclusions

Although applying a multi-scale SES approach to conservation and commons management is key to addressing the intertwined social and ecological challenges of the Anthropocene, such approaches are rare (Virapongse et al. 2016). Here, we describe the first transdisciplinary operationalization of Ostrom's SES framework for real-world management across multiple countries. Designed to inform the management of coral reefs for environmental and human wellbeing, our SES monitoring framework has been implemented across 85 communities in four countries, with insights arising from the resulting data informing decision-making at multiple levels. Our work contributes to closing the gap between SES science and management practice through providing an SES monitoring framework that can be readily applied to the management of coral reefs and other commons resources. Further, by outlining the major steps of our transdisciplinary approach and discussing key lessons learnt, we provide much-called-for guidance on operationalizing real-world SES monitoring (Partelow and Boda 2015, Selomane et al. 2019), which is critical to mainstreaming SES approaches in management practice.

Declaration of Competing Interest

This statement is to certify that:

The work is all original research carried out by the authors. All authors agree with the contents of the manuscript and its submission to the journal.

No part of the research has been published in any form elsewhere, unless it is fully acknowledged in the manuscript.

Authors should disclose how the research featured in the manuscript relates to any other manuscript of a similar nature that they have published, in press, submitted or will soon submit to Biological Conservation or elsewhere.

The manuscript is not being considered for publication elsewhere while it is being considered for publication in this journal.

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