

Finding sustainability: Advancing multiple methods to apply the social-ecological systems framework

by

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Abstract

The social-ecological systems framework (SESF) was proposed by Elinor Ostrom in 2007 as a diagnostic tool to examine what influences collective action in the commons by identifying the social and ecological variables which interact and shape sustainability outcomes. It has now been more than 10 years since the SESF was first published, providing an opportunity to reflect on its proclaimed usefulness. Ostrom stated that the framework could be a diagnostic tool for empirical research, facilitate cross-case comparisons with a common set of variables, and among other uses, act as a communication tool for interdisciplinary science. Many have since cited the framework as a useful conceptual tool. However, substantially less literature has applied the framework empirically or examined the methodological challenges for using the framework in the ways Ostrom envisioned above. Rigorous exploration and analysis of the different methods and challenges for applying the framework and its conceptual development are largely absent in the literature, but are very much needed to guide future progress. I argue that a primary barrier for future research using the framework is a lack of knowledge on different methods and challenges for applying it. This thesis is a compilation of eight research articles aimed at building this knowledge. In the articles I explore different concepts and methods to continue building a research program with the SESF. The thesis is split into four parts. In Part 1: Introduction, I provide an overview of Elinor Ostrom's research and commons scholarship, and argue that the development of new interdisciplinary methodologies have been an essential feature of past progress and thus need to be an equally integral feature the SESF's progress. In Part 2: Context and Concepts, I present a review article on the field of tropical marine science, to situate the empirical research context of this thesis. Two articles then explore conceptual development of the SESF, linking the framework to the closely associated concepts of ecosystem services and sustainability science. In Part 3: Empirical Research, the core of this thesis is presented in four articles. Each of the four applies the SESF in a different way in three small-scale fisheries cases and one pond aquaculture case. All cases are located in the coastal tropics. Finally, in Part 4: Synthesis and Conclusions, I provide an article which reviews all the existing literature applying the SESF to orient the contributions of this thesis. This then provides a platform to present and discuss the lessons learned from my empirical research and from the literature. This is followed by separate sections, outside the articles, discussing limitations and overall conclusions. The larger picture of this thesis, I argue, is that we have inherited the SESF, a research tool than can help us find the conditions, interactions and outcomes that better enable more effective cooperation and governance for sustainability. We can look to the history of commons scholarship to understand how the evolution of theory and methods that led to the development of the SESF can motivate the same curiosity and rigor for its continued use and development. I conclude that there are many potential parallel uses and development pathways for the SESF, and provide reflection on the current barriers and continuing challenges.

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List of conference, workshop and symposium contributions

2015

Event: Conference – International Association for the Study of the Commons (IASC)

Contribution: Presentation - “Interlinking ecosystem services and Ostrom’s framework through orientation in sustainability research”

Event: Conference - Youmares 6

Contribution: Presentation - “Pollution exposure on marine protected areas: A global assessment”

2016

Event: Leibniz Environment and Development Symposium (LEADS)

Contribution: Presentation – “Operationalizing the social-ecological systems framework in pond aquaculture”

Event: Qualitative data coding workshop at ZMT

Contribution: Organize and participate

Event: Breaking the code: Qualitative data coding and synthesis workshop (SESYNC)

Contribution: Participant

Event: Estuarine, Coastal and Shelf Science Conference (ECSA) conference

Contribution: Presentation – “Operationalizing the social-ecological systems framework in pond aquaculture”

2017

Event: Conference – International Association for the Study of the Commons (IASC)

Contribution: Presentation – “Operationalizing the social-ecological systems framework in pond aquaculture”

Event: Resilience Conference

Contribution: Presentation – “Operationalizing the social-ecological systems framework in pond aquaculture”. Poster – “Diagnosing social-ecological change through co-management in Brazilian mangrove fishery”

Event: Conference – Maritime Studies (MARE)

Contribution: Presentation – “Operationalizing the social-ecological systems framework in pond aquaculture”

Event: EU COST Network for Ocean Governance

Contribution: Participant and presentation - “Social networks, collective action and the evolution of governance for sustainable tourism on the Gili Islands, Indonesia”

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Thesis: Using Ostrom's SES to analyze the implementation of a co-management regime in North Brazil

Part 1: Thesis introduction

Introduction

“The idea of a fixed method that contains firm, unchanging and absolutely binding principles for conducting the business of science meets considerable difficulty when confronted with the results of historical research.”

Paul Feyerabend, 1975.
Against Method (page 23)

Methods are a central feature of science, the foundation for how we observe, measure and analyze the world. Methods provide the building blocks, they derive the inputs (i.e. data) and generate the outputs (i.e. analysis), to support the development of theory. Theory building is arguably the primary goal of normal scientific paradigms (Kuhn 1962), to find more robust and generalizable explanations of how the world works. However, it must be recognized that theoretical development is dependent on the building blocks of methods. Thus, the development of methods to improve data collection and analysis is a necessary foundation for the development of theory, and ultimately the progression of science as a whole.

As Feyerabend stated above, scientific methods are constantly evolving, and in fact *need* to evolve to progress science (Feyerabend 1975). The quote inspires reflection on the idea that scientific methods require constant critique, debate and evolution. Feyerabend argues that this has been a core tenet to scientific progress, especially with hindsight over the history of science. Much of what we now consider as the great leaps in scientific progress, were, with hindsight, initiated by challenging the well accepted and normalized dogmatism of the time with new ideas. New ideas lead to new hypotheses, and often the necessity for new and combined methods to explore them empirically. Feyerabend argued adamantly for this point, supporting the notion of pluralism as a fundamental feature of scientific progress. He argued that multiple new ideas, methods and theories should co-exist to challenge those which are well accepted. From this perspective, he could be considered an epistemological anarchist (Preston 2016), as he largely provided antagonistic writings to challenge and engage with other influential science philosophers on the topics of falsification (Popper 1959), research programs (Lakatos 1978) and normal scientific progression (Kuhn 1962).

Aside from revisiting the philosophy of science, the reason I recall these foundational debates is to motivate some reflection on what has been done before in science, how we got to where we are now and what the next steps forward may be. In particular, to reflect on the role of methodological evolution within specific fields. In section 1.1 below, ‘Inheriting the social-ecological systems framework (SESF)’, I provide a detailed account of this evolution within one particular field, commons scholarship. This is the primary field this thesis is rooted in. The story above is linked to the story below. In both we can reflect on the role that challenging established ideas with new ones has had on the development of new hypotheses, and how this has inspired

new lines of inquiry leading to the development of new concepts and the necessity to integrate and develop new methods to progress theory.

While only the story of commons scholarship is presented below, which is the most relevant story for this thesis; it represents a broader trend and story in the evolution of science occurring today. Scientific progress is now more than ever being motivated in large part by the external forces of a changing world. New questions are emerging about how and why the world is changing, and what we can do about it. The question of how science will evolve to answer these questions has become a central theme within current discourse. Worldwide trends in social and environmental change (Steffen et al. 2015a) are challenging science to develop new concepts and methods to support theory building that can help explain what is changing and why. This evolution is not only about developing new methods, but also about finding ways to integrate and combine existing methods (Poteete et al. 2010).

Ultimately, many argue, current scientific progress should be founded on a normative goal, the goal that knowledge ought to inform a societal transition towards sustainability (Gibson 2006, Jerneck et al. 2010, Spangenberg 2011, Hicks et al. 2016). This task, and the evolution of methods to continue building theory in science, has manifested into discourse arguing for more integrated approaches (Miller et al. 2008, Poteete et al. 2010, Markus et al. 2017). This more proximate discourse argues for scientific progress through multi- and inter-disciplinarity, bridging historically separated fields and disciplines. Multi- and inter-disciplinarity are founded on the idea of integration and the co-evolution of methods for data collection and analysis, and ultimately joint theory building (Poteete et al. 2010, Cox et al. 2016). Combining previously separated concepts and methods can help better explain how and why our world is changing, since it is changing in an integrated way (Liu et al. 2015). Progress is needed that moves beyond the aggregation of separate disciplinary contributions, towards progress that manifests new and previously unforeseen scientific contributions through the integration of different knowledge across disciplines. Efforts to integrate science are seen, in part, as responses and attempts to reconcile and cope with understanding change, and what it means for humanity. It could be said that sustainability is something that many scientists are looking for, trying to observe successful cases and conditions in the world that can inform others to be more sustainable. For example, much of the social science research on sustainability is tasked with identifying the conditions which best enable society to cooperate and govern itself (Ostrom 1990, Bodin 2017), and the earth system, to create equitable opportunities for human development over time (Steffen et al. 2015b).

The evolution of commons scholarship provides an example of one research field that has begun this journey to find sustainability over the last few decades. It has done so by examining human behavior and cooperation related to natural resource use (Ostrom 1990, Meinzen-Dick et al. 2002, Wollenberg et al. 2007, Poteete et al. 2010). It has challenged rational choice theory, which suggests inevitable tragedy of the commons (Hardin 1968), and built collective action theory (Olson, 1965; Ostrom, 1990), which posits collaboration for sustainability. In doing so, the history of commons scholarship demonstrates how new ideas and hypotheses led to the evolution of new and integrated methodological approaches (Poteete et al., 2010). This has led to an

empirically supported theory of collective action, which is now a critical pillar of social theory related to sustainability due to its focus on cooperation and implications for governance (Ostrom 2009, Bodin 2017). I argue below that this legacy is embedded into the social-ecological systems framework (SESF), the central object of examination in this thesis.

The SESF is a tool that can help us find the appropriate conditions that facilitate cooperation for sustainability by guiding observations and analysis of the world in a more nuanced and diagnostic way (Ostrom 2007, 2009). We want to find the drivers of success, what works and what doesn't across cases, and use that knowledge to inform places that struggle to achieve sustainability goals. However, the SESF is not a methodology itself, it is a conceptual framework. Using it requires a detailed and critical exploration into the methods for its application. However, only a few articles have done this so far in selected case studies. There has been no comprehensive examination into the challenges for applying the framework that has drawn from multiple methodologies applied in different ways across multiple case studies. As I show in a review article below, the number of articles applying the SESF is increasing, building on previous reviews (McGinnis and Ostrom 2014, Thiel et al. 2015). This only reiterates the need for critically reflecting on the challenges for the framework's continued application and its usefulness for advancing scientific progress in social-ecological systems and sustainability research.

This thesis advances knowledge in commons scholarship and political science by developing, testing and critically examining concepts and methods to apply the social-ecological systems framework (SESF) (Ostrom 2007, 2009, McGinnis and Ostrom 2014). The various parts of this thesis build on gaps in the literature described above and support the development of my central argumentation. I argue that the primary barriers for advancing the proclaimed usefulness of the framework, and its continued development, are methodological. There is a lack of knowledge on how the SESF can be applied, and for its continued conceptual development.

Thus, the starting point for this thesis is to develop conceptual, empirical and synthesis research that explores a variety of methods and methodological challenges for applying the SESF. All the research in this thesis contributes to this goal. Continued conceptual development of the SESF is needed to layout a vision for future progress. I explore the potential for integration and co-evolution with closely associated concepts by building on the history of commons scholarship that has brought together traditionally separated ideas. On this foundation, I conduct empirical research to further explore how the SESF can actually be applied using different empirical data collection and analysis methods. Critical reflection on this research, and on the current literature, is provided in a final section of the thesis. I have been guided by the following research questions:

Research questions (RQ)

RQ1: How is the SESF situated within, and able to advance, concepts of social-ecological systems research and sustainability science?

RQ2: What are the different types of research that can be done using the SESF?

RQ3: What data collection and data analysis methods can be used to apply the SESF?

RQ4: What are the methodological challenges for applying the SESF?

RQ5: What considerations and reflections are needed to continue developing the SESF as a useful tool for future research?

To explore these research questions, this thesis is divided into four parts. Part 1 presents the history of commons scholarship, where I argue the necessity for its continuation through the SESF. This includes the framework's theoretical foundations in collective action theory and social-ecological systems (SES) research. I then outline the need for research in tropical marine science with a focus on small-scale fisheries and pond aquaculture as case studies. I argue that this context is relevant for continued commons scholarship and provides a suitable context to apply the SESF in a way that generates knowledge with generalizable conclusions. At the end of Part 1 I explain the research design of the thesis as well as the reasoning behind each article. I use this section to explain the contributions of each to the overall goal of the thesis and how they relate to each other.

Part 2 contains three articles, the first of which provides a review of the tropical marine science context. The second two articles explore potential conceptual development trajectories for the SESF. Part 3 presents four articles applying the SESF empirically, each manuscript applying the framework with a different methodology. In Part 4, the final section of the thesis, I present one article that provides a comprehensive review of the different methods for applying the SESF from the existing literature. The article provides a critical reflection on the methodological challenges and future development of the framework, acting in part as a conclusion and reflection article from the empirical research in Part 3. I conclude Part 4 with a brief chapter on the challenges and limitations of the thesis and a succinct conclusion related to each research question presented above.

Inheriting the social-ecological systems framework (SESF)

“If political scientists do not have an empirically grounded theory of collective action, then we are hand-waving at our central questions. I am afraid that we do a lot of hand-waving.”

Elinor Ostrom, 1998.

A Behavioral Approach to the Rational Choice Theory of Collective Action (page 1)

Initiated in large part by her book *Governing the Commons* (1990), Elinor Ostrom and her many colleagues began accumulating empirical evidence on the variables and types of institutional arrangements which were most likely to influence the ability of actors to work together and solve social dilemmas (Box 1). Social dilemmas occur in many facets of society but are particularly problematic within common-pool resource (CPR) systems (e.g. fisheries, forestry, water management) and public goods (e.g. public infrastructure, environmental health). CPRs are the empirical focus of *Governing the Commons* and are characterized by high rivalry and difficulties

with excludability. High rivalry means that each resource extracted leaves less for others, and excludability refers to the ability to exclude other actors from extracting a resource (Ostrom et al. 1994). Many environmental resources are CPRs, and many environmental governance challenges occur due to difficulties with resolving social dilemmas in CPR systems.

The difficulties for governing CPR systems have been historically theorized assuming certain fundamental characteristics about individual and group behavior (Ostrom 1998). Individuals were assumed to be maximizing rational actors, where a ‘rational choice’ was to maximize the extraction of resources for individual gains (Ostrom et al. 1994). In contrast, the interest of the group would be to sustain the long term availability of resources. Under this theoretical scenario, a social dilemma manifests that can lead to the overexploitation of environmental resources, catalyzed by conditions of high rivalry and low excludability. CPR theory helps to unpack some foundational reasons leading to overexploitation and degradation. Using rational choice theory to examine the use of CPRs, it is predicted that actors are unable to solve social dilemmas. Individual rational interests to maximize personal gains (i.e. harvest as much as possible) will collectively undermine the overall group goals (Schlager 2004). Non-maximizing behavior, from an individual perspective, would be ‘irrational’.

Box 1. Social dilemmas

“Social dilemmas occur whenever individuals in interdependent situations face choices in which the maximization of short-term self-interest yields outcomes leaving all participants worse off than feasible alternatives” (Ostrom, 1998, p. 1). Social dilemmas are frequent in many aspects of life. In common-pool resource (CPR) systems, a type of social dilemma called an ‘appropriation dilemma’ exemplifies the challenge of aligning individual and group interests. Appropriation generally refers to the distribution of resources (e.g. the number of fish) among actors who are extracting. For example, every fish extracted reduces the amount available to other fishers (high rivalry), and it is difficult to exclude other fishers from extracting (excludability problem). Solving appropriation dilemmas requires finding ways to distribute resources among actors who are extracting in a way that does not undermine the interest of all actors to maintain equitable and long-term resource availability. A second dilemma is referred to as a ‘provision dilemma’, where all actors benefit when a good is maintained or provided by the group, but the incentive of any individual to contribute is low or costly because they can otherwise receive the good for free from the contributions of others, without contributing themselves. For example, maintaining a healthy environment (e.g. mitigating pollution) or the maintenance of publicly used infrastructure are provision dilemmas. If all individuals follow their individual interest, then the good is not provided/ maintained or under-provided/ maintained, undermining the group interest (Ostrom, 1998). Ultimately both dilemmas can be referred to as collective action problems because people need to cooperate to solve them. The difference is that an ‘appropriation dilemma’ refers to who takes resources and a ‘provision dilemma’ refers to who contributes to providing a resource.

In the mid-20th century, there was an impending urgency to advance knowledge on natural resource governance that was catalyzed by worldwide trends in the overexploitation and degradation of resources during the period of the Great Acceleration (Steffen et al. 2015a). Starting in the 1950’s, the Great Acceleration brought substantial gains for human development through large investments in industry, science and technology. However, it also brought

recognition that natural resources were not inexhaustible, and that few effective management solutions for environmental resources existed at the time (Meadows et al. 1972).

Environmental governance theory, at the time, struggled to explain potential solutions to CPR management challenges. Environmental governance theory is founded on the central questions for political science which “encompass all efforts to understand the institutional foundation for governance, specifically involving efforts to relate philosophical principles and normative values...in real-world political institutions (McGinnis 2011b), p.170.” In 1968, Garrett Hardin wrote a seminal article theorizing potential policy solutions for CPR management to advance environmental governance theory. However, Hardin himself was not a political scientist, he was an ecologist focused largely on controversial overpopulation issues. However, in his most famous writing on environmental governance he made conclusions that CPR dilemmas could only be solved by either privatization or through top-down state regulation by imposing strict rules, monitoring and enforcement on how resources are used. Hardin concluded that if actors were left to use CPRs without any form of privatization or state control, it would lead to an inevitable *Tragedy of the Commons*, a term coined by the title of his article (Hardin 1968).

Hardin assumed that actors could not overcome social dilemmas on their own, due to the rational tendency to maximize their own gains at the expense of the group. However, his conclusions were very simple. He asked readers to imagine a common pasture shared by herders whose rational self-interest would be to put additional cows on that pasture, especially if no controls for excluding users in a growing population existed. With high rivalry in the consumption of grass, and difficulties excluding other herders from accessing the common pasture, the ‘rationality’ of individuals in the group would lead to overexploitation of the common pasture, undermining the group interest of all herders.

The theoretical conclusions outlined in the *Tragedy of the Commons* shaped the evolution of environmental governance theory and public natural resource management policies in favor of privatization and state regulation for the duration of the 20th century, leaving a global legacy of centralized command-and-control governance and property rights prescriptions to environmental problems in its wake (Ostrom et al. 1999). These were simple and broad spanning solutions, so called policy panaceas that could resolve widespread environmental problems. Many CPRs were given generic policy prescriptions irrespective of their differences in context, existing local institutions for management, or whether local actors were included in decision-making processes. Now, with 50 years of hindsight on Hardin’s theories, and in the aftermath of the Great Acceleration, it is not difficult to draw conclusions that generic policy prescriptions for privatization and state-controlled governance have largely failed to provide sustainable environmental governance solutions (Anderies et al. 2007, Ostrom 2007).

Elinor Ostrom’s *Governing the Commons* and the subsequent research careers of many commons scholars directly challenged Garrett Hardin’s conclusions in the *Tragedy of the Commons* (1968). Numerous researchers (McCay and Acheson 1990, Ostrom 1990, Wade 1994, Baland and Platteau 1996) began unpacking Hardin’s underlying assumptions about human behavior in relation to resource use, the management of common property and the characteristics of the system that were influencing individual decision-making. This research built on early work to

theorize collective action solutions (Olson 1965), adding the needed empirical evidence to support theory and to move beyond a rational choice model for resource use decision-making. With the hindsight outlined above, and largely due to advances in commons scholarship, nowadays we view Hardin's analysis as largely flawed. We see this both in its underlying assumptions about what drives human behavior and its failure to account for more complex system interactions.

Ostrom and other commons scholars posited that individuals can work together to solve collective problems, and that their ability to do so is largely driven by their institutions (Box 2). Hardin assumed that actors using shared resources would not interact, or even communicate with each other, and that they would not be able to self-organize the management of resources due to assumptions of their 'rationality' to maximize or develop mechanisms for excluding people. Hardin failed to recognize the role of institutions in guiding resource use behavior. Ostrom's research proposed a theoretical paradigm shift to this logic, setting forth a new direction for environmental governance and political theory. She hypothesized the opposite conclusion that actors could self-organize and develop community-based management institutions to solve collective action problems.

This hypothesis has been well supported empirically and grown into a theory of collective action, which is now an entire research field exploring how societies can work together (Feeny et al. 1990, Agrawal 2001, Poteete et al. 2010). The need for privatization or state control, neither of which were generically effective management solutions on their own, could be challenged with community-based governance approaches focused on institutional arrangements for collaboration. This research program argues that institutions (Box 2) in these societies evolved to reflect the social and ecological system conditions they were embedded in. The better institutions fit the system conditions, and are able adapt to them, the more likely they are to lead to sustainable human-nature relationships (Folke et al. 2007, Galaz et al. 2008, Epstein et al. 2015).

Box 2. Institutions

Institutions are the formal and informal rules that structure society. In the context of commons scholarship, institutions are most often referred to in relation to the use and management of environmental resources, typically CPRs or public goods (McGinnis 2011b). Formal institutions are typically written rules such as laws and regulations, often with formal monitoring and sanctioning mechanisms. Formal institutions may include the number of hours in a work week, rules for participation in governance processes (e.g. voting), or rules related to resource use (e.g., harvesting limits or licensing). Informal institutions are often unwritten but socially mainstreamed 'rules' within groups such as social and cultural norms. Informal institutions may include religious practices, meal times, greeting behavior (e.g. hand-shaking, hugging) and norms for personal expression. What is formal or informal may vary between groups (e.g. villages, countries, religious communities). For example, wearing specific clothing may be a formal institution in some religious communities, a rule that is written down and formally enforced. In other societies, clothing norms are informal parts of culture that are not formally enforced but culturally mainstreamed within the group, often due to strong

group pressures (Schlüter and Theesfeld 2010). ‘Institutional arrangements’ refers to the combination of different formal and informal rules structuring individual and group behavior. The so called ‘rules of the game’ (North, 1990). How and why institutions evolve and change within groups is of particular interest to environmental management because institutions influence behavior related to resource use, cooperation and governance.

Commons scholarship began to examine how self-organized institutions to govern the commons evolved and changed, and how this affected the long-term availability of CPRs. Empirical research in small-scale CPR systems began to unpack the assumptions that actors were always rational in their resource use behavior, using multiple methods to do so. Field and lab experiments coupled with qualitative case study methods provided multi-faceted support for emerging theories of human behavior relating to how actors cooperate. For example, qualitative case studies would identify new variables influencing collective action (e.g. communication mechanisms or system predictability) with thick descriptions of their potential role in a complex system. Lab work could then design experiments to test the role of that variable in controlled settings to examine its influence and interaction effects with other variables. Using multiple methods between the lab (i.e. deductive hypothesis testing through controlled experimentation) and the field (i.e., inductive exploration of variables and outcomes) ultimately complemented one another in building theory. Observing human behavior in the field and then testing exactly what affected it in the lab proved to be a useful mixed methodological approach for unpacking the assumptions in rational choice theory. As a result, complimentary research began to show that actors were bounded in their rationality, acting with incomplete information about how a social or ecological system works, or about the implications of their own actions or the actions of others (Ostrom 1998). These new advancements in behavioral economic theory largely dispelled the notion of the ‘rational actor’. This added layers of complexity to understanding the *actual* reasons why actors made non-maximizing resource use decisions in diverse conditions and contexts.

Resource use behavior was shown to be linked to institutional arrangements (Box 2), and it was demonstrated that institutions structured the behavior of actors in a group. Many actors made resource use decisions that did not undermine group interests (Ostrom et al. 1992), for reasons linked to culture, social norms, established rules and group enforcement mechanisms. New research questions emerged to examine the types of institutional arrangements that were most likely to guide actors towards making resource use decisions that did not undermine the group, and ultimately themselves, increasing the likelihood that social dilemmas are avoided and resource availability is maintained overtime in an equitable way. Subsequently, empirical analysis led to the recognition that CPR systems were much more complex than Hardin imagined (Ostrom 2007, Cole et al. 2014).

A large and continuing contribution of commons scholarship is the recognition for system complexity. As described above, the identification of new variables, i.e., diverse social and ecological conditions influencing collective action, began to grow substantially. It soon became apparent that many social and ecological conditions influence the formation of institutions, and

certain institutional arrangements strongly shaped the behavior of actors and the decisions they made about resource use, while others did less so. Furthermore, this process did not just recognize the role of individual variables, but that many variables interact with each other interdependently, jointly shaping outcomes due to their interactive effects. This included interactions between social and ecological variables, eventually suggesting new hypothesis on the interdependent links between social and environmental change.

The webs of nuanced interlinkages between these social and ecological variables broadened the understanding of CPRs as complex systems, and suggested that a diverse set of methodological tools were needed to analyze the different variables and interactions of such complex systems. It was explicitly recognized “that scholars of commons have discovered far more variables that potentially affect resource management than is possible to analyze carefully,” (Agrawal 2003), p. 244. New conceptual frameworks were needed to address the problem of complexity and help guide future analysis. New methods were also needed to apply these new frameworks.

Influential works in early commons scholarship differed in their methods (Agrawal 2003) using mostly secondary data (Ostrom 1990), highly localized data (Wade 1994) and reviews of case study literature (Baland and Platteau 1996). All identified many variables influencing institutions for collective action, creating difficulties for comparing results between cases and assessing congruence with lab experiments (Agrawal 2003, Poteete et al. 2010). The use of multiple methods to examine new cases needed to be coupled with new methods for data integration and comparison. New conceptual and theoretical frameworks were needed to guide further research in a cohesive and complementary way. Ultimately new methods were and still are needed to better enable the cross-checking of results between different contexts as well as between the field and the lab (Agrawal 2003).

At its core, the foundation of Ostrom’s research program on the commons resulted in substantial empirical evidence supporting an overarching interdisciplinary theory of collective action. To do this, the research program was using multiple methods and beginning to develop new conceptual frameworks to guide the analysis of what are now recognized as complex systems. Ostrom did not show that the *Tragedy of the Commons* was a false threat, it is very much a real one, but she showed that cooperative and community-based solutions have been and can continue to be a solution for sustainable governance.

Collective action theory aims to understand the conditions that best enable self-organized cooperation. Collective action is now a broad theoretical framework. It brings together the many variables that have been shown to have some degree of explanatory power or influence on cooperation. Ultimately, “the theory of collective action is the central subject of political science,” (Ostrom 1998), p. 1. Ostrom showed that the development of institutions (Box1) is an essential condition for sustained cooperation, and that the development of institutions is shaped by both social and environmental conditions. In commons scholarship the focus of collective action has been primarily placed on cooperation related to natural resource use behavior.

Collective action hypotheses shifted the paradigm of environmental governance theory away from the need for generic models of privatization and state-controlled governance, and placed

focus on local actors and context, identifying hindering and enabling conditions that allowed self-organized institutions to emerge. This was in part in response to increasing observations and discussions of state and privatization failures (Acheson 2006, Carothers and Chambers 2012). Ostrom's research and the emergence of collective action theory created a new direction for environmental political theory in general. Commons scholars merged the study of individual human behavior in behavioral economics with the analysis of group behavior and cooperation through the study of institutions, contributing to the field of (new) institutional economics (North 1990, Klein 2009), an interdisciplinary research field. As a result, the relevant research questions began to shift away from improving generalized state regulations and private property arrangements, towards better understanding the place-based conditions that affected how local actors develop, adapt and change their institutions to govern the commons. This research program on collective action aimed to identify how effective institutional arrangements evolved, and how findings could help inform governance in other systems that face similar challenges. Under this direction, commons scholarship began its legacy as an interdisciplinary field in both political science and behavioral economics in the 1990's (Ostrom 1998). The books *Governing the Commons* (Ostrom 1990) and *Institutions, Institutional Change and Economic Performance* (North 1990) catalyzed this process.

Commons scholarship has since explored three core research questions: (1) to identify the different types of institutional arrangements that exist, (2) to identify the social and ecological conditions of a system that influence the formation and performance of institutional arrangements and (3) what types of institutional arrangements are sufficient to ensure sustainable governance. *Governing the Commons* presented an in-depth qualitative institutional analysis of how multiple commons have been governed historically, beginning to answer the three research questions. Ostrom drew on numerous case studies such as the groundwater basin in Los Angeles, California, Turkish in-shore fisheries, and Japanese irrigation systems. She argued that building institutions to govern common resources sustainably through collective action is not an exception, but a historical norm. Self-governance of the commons has occurred in many communities around the world, a path that was deviated from in the 20th century with the advent of globalization, privatization and strong state-controlled governance regimes dominant throughout Europe and North America. Ostrom argued that the self-organized institutional arrangements differ between contexts because they evolved to fit local conditions. However, that despite differences, it was possible to identify common features among successful institutions across cases.

Governing the Commons as well as *Rules, Games and Common-Pool Resources* (Ostrom et al. 1994) set the stage for future collective action research and institutional analysis by identifying numerous social conditions that enabled successful governance outcomes by identifying the common features of success across multiple cases. The eight Design Principles (Table 1) were the first set of theoretical features of institutions that supported hypotheses about which variables, and their conditions, influenced collective action outcomes. Over time the list of variables expanded beyond the eight Design Principles to include both social and ecological variables, as the initial Design Principles only included social dimensions. However, as recognition for the complexity of CPR systems increased with the analysis of more case studies, making generalizable causal claims about the relationship of any variable to a collective action outcome

became a substantial theoretical challenge. Developing a cohesive theoretical framework establishing robust causality was, and still remains, difficult with an increasing number of variables and system complexity. Overall, the loss of generalizability becomes a challenge for theory when recognition for systems complexity becomes a central feature of empirical analysis.

Table 1. Design Principles (Ostrom and Cox 2010).

<p>1a. Clearly defined boundaries: Individuals or households who have rights to withdraw resource units from the common-pool resource (CPR) must be clearly defined.</p> <p>1b. Clearly defined boundaries: The boundaries of the CPR must be well defined.</p> <p>2a. Congruence between appropriation and provision rules and local conditions: Appropriation rules restricting time, place, technology, and/or quantity of resource units are related to local conditions.</p> <p>2b. Congruence between appropriation and provision rules and local conditions: The benefits obtained by users from a CPR, as determined by appropriation rules, are proportional to the amount of inputs required in the form of labor, material, or money, as determined by provision rules.</p> <p>3. Collective-choice arrangements: Most individuals affected by the operational rules can participate in modifying the operational rules.</p> <p>4a. Monitoring: Monitors are present and actively audit CPR conditions and appropriator behavior.</p> <p>4b. Monitoring: Monitors are accountable to or are the appropriators.</p> <p>5. Graduated sanctions: Appropriators who violate operational rules are likely to be assessed graduated sanctions (depending on the seriousness and context of the offense) by other appropriators, officials accountable to these appropriators, or both.</p> <p>6. Conflict-resolution mechanisms: Appropriators and their officials have rapid access to low-cost local arenas to resolve conflicts among appropriators or between appropriators and officials.</p> <p>7. Minimal recognition of rights to organize: The rights of appropriators to devise their own institutions are not challenged by external governmental authorities.</p> <p>8. Nested enterprises: Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprises.</p>

With the continued recognition for system complexity, and the observation that many variables contribute to many different types of interactions among actors, this led to an iterative process of developing new frameworks to organize variable interactions and help guide further empirical analysis. The Institutional Analysis and Development (IAD) framework (Figure 1) evolved from this process. It was one of the first attempts to organize a logical relationship between variables influencing how institutions develop, operate and change over time (McGinnis 2011b). The IAD framework is one of the first frameworks to recognize the role of biophysical conditions and the

local (context dependent) attributes of a community on institutional development and change (Ostrom 2005, Ostrom and Cox 2010). The IAD framework focuses on ‘action situations’, the social interactions among groups of actors guided by sets of social rules. While the IAD framework provided a robust framework to analyze social action situations, there were increasing calls for “a more biophysically sophisticated approach” (Ostrom and Cox 2010), p. 6, to equally recognize the role of social *and* ecological variables to advance empirical analysis of institutions to improve political theory on environmental management (Agrawal 2003).

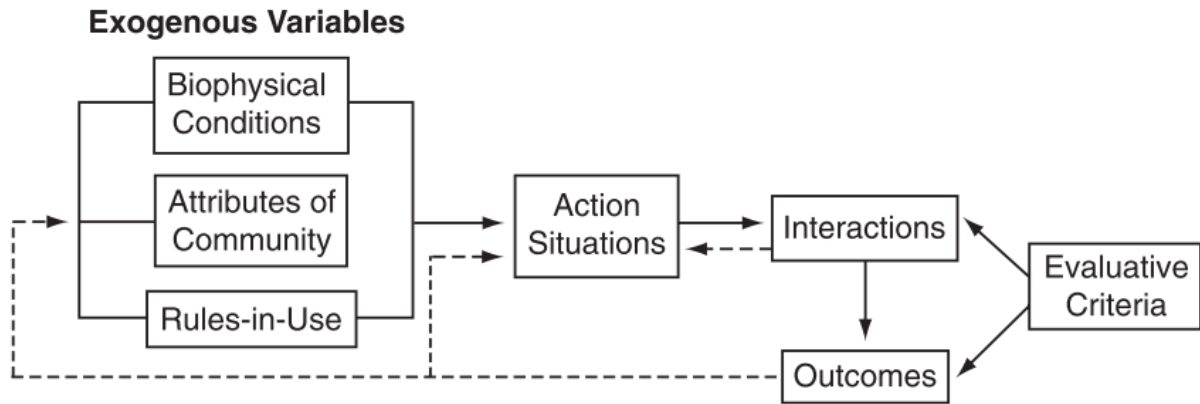


Figure 1. The Institutional Analysis and Development (IAD) framework (Ostrom and Cox 2010).

The IAD framework enabled some of the first systematized large comparative analysis studies using standardized coding forms to examine similarities and differences in institutional arrangements and their resulting effects on environmental outcomes (Tang 1992, Shivakoti and Ostrom 2002, Poteete and Ostrom 2004, Wollenberg et al. 2007). While the IAD framework was useful and provided standardization for comparative analysis, it lacked increasingly recognized biophysical dimensions and a broader conceptual framework for including social-ecological interactions. The only way to ensure continued comparability of diverse data was to rethink the IAD framework to include and conceptualize social-ecological system interactions.

The iterative process of framework development led to the social-ecological systems framework (SESF) (Figure 2). The SESF evolved from the research program that started with the Design Principles and led to the IAD framework (Ostrom and Cox 2010, Cole et al. 2014). The SESF was originally proposed by Ostrom (2007) in a PNAS article titled *A diagnostic approach for going beyond panaceas* and was later expanded in a 2009 Science article titled *A General Framework for Analyzing the Sustainability of Social-Ecological Systems*. These two articles presented the SESF as a list of variables that had been empirically identified as influencing the formation of institutions through collective action to govern the commons (Table 1). The SESF includes a more balanced list of social and ecological variables and a different conceptualization,

or ontological structure, than the IAD framework. However, the SESF does not make any theoretical claims about the influence of any single variable on outcomes. This bypassed difficulty with making a generalizable theoretical framework of collective action that would have explanatory power across many cases. However it still recognized that each variable could play a role in a complex system, but that that role would differ across contexts. Instead of a theoretical framework, the SESF was proposed as a diagnostic tool, a checklist of potentially influential variables to consider when examining complex CPR systems. A diagnostic checklist would allow researchers to check the variables most influential in a system to examine the role each variable plays to find contextually appropriate management solutions. The argument for the SESF was framed as an approach that could be used to avoid generic panacea-like governance policies by finding solutions tailored to context while also learning from successful cases to build theory using the framework's variables as a template across cases (Ostrom 2007).

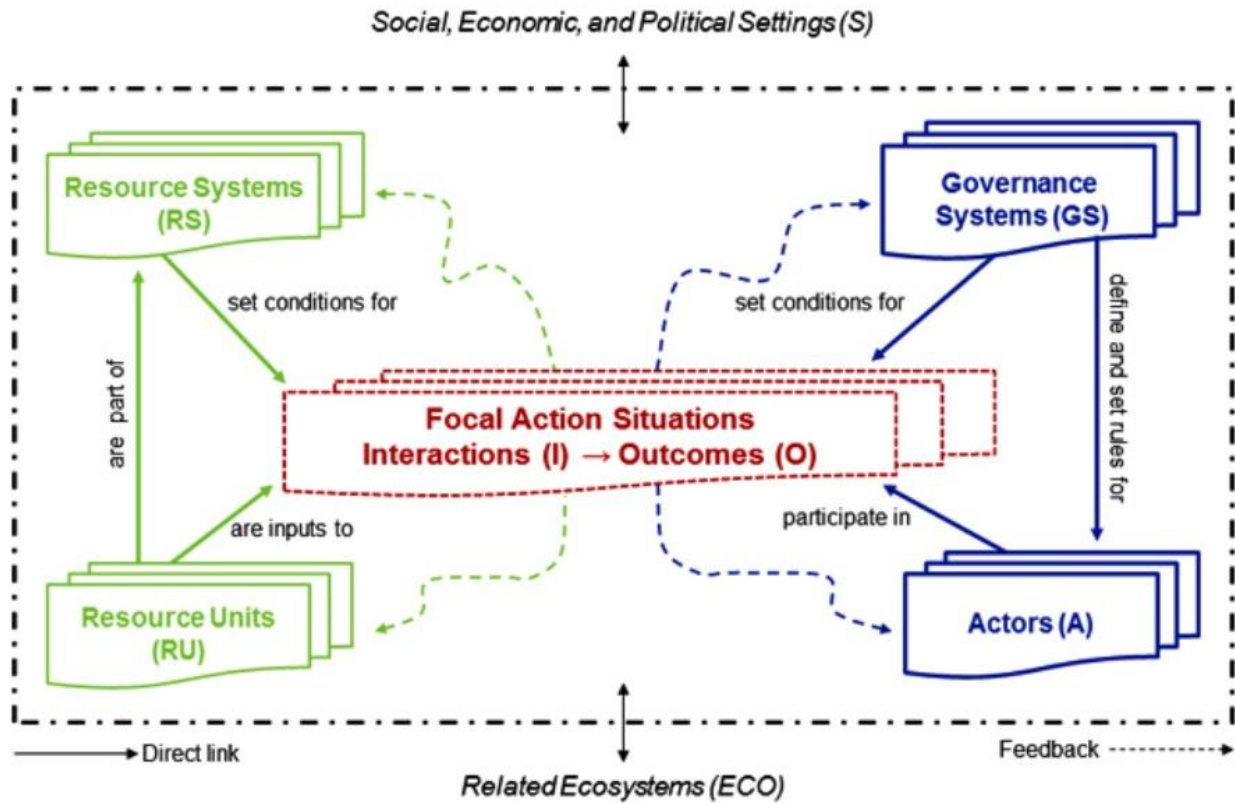


Figure 2. The first-tier variables of the SESF, conceptualized as an interacting system (McGinnis and Ostrom 2014).

Part 1: Thesis introduction

Table 2. The SESF first and second-tier variables from McGinnis and Ostrom (2014).

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) 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	Governance Systems (GS) GS1- Policy area GS2- Geographic scale of governance GS3- Population GS4- Regime type GS5- Rule-making organizations GS6- Rules-in-use GS7- Property-rights systems GS8- Repertoire of norms and strategies GS9- Network structure GS10- Historical continuity
Resource Units (RU) 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	Actors (A) 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
Interactions (I) 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	Outcomes (O) O1- Social performance measures O2- Ecological performance measures O3- Externalities to other SESs
Related Ecosystems (ECO) ECO1- Climate patterns ECO2- Pollution patterns ECO3- Flows into and out of SES	

The SESF conceptualizes a nested set of variables that interact with each other to shape outcomes, and whether those outcomes are sustainable has become a central question (Box 3). The link to sustainability and the development of place-based normative values extends research aims beyond understanding what influences how people cooperate, but why they cooperate, and the normative relating to sustainability they aim to achieve as a group. The processes of how goals are conceived, jointly decided upon and implemented are related to institutions. This progression towards understanding normative goals of cooperation, and their formation through institutions, links the SESF to sustainability research; understanding how institutions manifest

normative goals, and whether those goals align the desired outcomes of local people with general concepts of sustainability (e.g. sustained and equitable resource availability and social wellbeing).

Box 3. Social-ecological systems (SES) and sustainability

The SES concept is grounded in systems thinking and the idea that humans and nature interact through interdependent relationships. The SES concept gained mainstream recognition in the 1990's with the advent of the ecosystem services concept (Daily 1997) and resilience theory (Berkes et al. 2000, Gunderson and Holling 2002). At its core, SES research aims to understand the interdependent linkages between social and environmental change, which necessarily encompasses multi- and interdisciplinary knowledge contributions. An underlying epistemology of SES research is that what we are trying to know about human-nature relationships is if, or how, they can be sustainable. Sustainability itself is a multifaceted and normative concept, but SES and sustainability research are closely related fields. Much of SES research aims to identify the concepts, pathways, definitions and/or manifestations of sustainability in localities around the world.

The SESF, in many ways, is the manifestation of decades of empirical analysis that has shifted environmental governance discourse away from generic policy prescriptions and towards place-based policy development that is tailored to context (Bodin 2017). The analogy of using diagnostic tools similar to medical practitioners is often used to describe the necessity of this paradigm shift in the social sciences, towards the diagnostic analysis of environmental problems (Cox 2011, McGinnis and Ostrom 2014). However, to advance such a research program, new research questions arise. These questions are primarily methodological, asking how a complex framework like the SESF can continue the legacy of interdisciplinary and mixed-methods research by continuing to broaden its analytical scope. The title of Ostrom's 2009 *Science* article suggests this direction, but this is only foreshadowing, an ideal vision for a future research program outlined more than 10 years ago. Decades of commons scholarship led to these conclusions, suggesting a shift towards social-ecological systems analysis and sustainability using diagnostic tools. However, the current missing pieces are methodological.

Despite the successes of commons scholarship and a promising vision for a future research program, environmental problems linked to human activities remain widespread (Halpern et al. 2015, O'Neill et al. 2018). The ability of science to contribute knowledge that can inform practical solutions remains an ambiguous question. Continued efforts are still needed to continue past progress, to fill in the gaps, and to learn by observation and critical reflection. We can start by asking, what does successful governance in the 21st century look like? We have shifted from Hardin to Ostrom, but where do we go from here?

The new directions outlined by Ostrom (2007, 2009) require fundamental shifts in research practice, but her articles are only a starting point. Directions forward include a shift towards broadening the scope of CPR systems analysis towards the analysis of SES. However, there is an assumption within this claim, that the variables and interactions identified by collective action

theories can be a supporting pillar for building further theories within the SES concept related to sustainability outcomes. Although the variables in the SESF have clear roots in collective action theory, there are no causal claims between variables and outcomes in the SESF itself. Thus, the SESF may be able to provide a template of known variables to build new theories that are partly removed from a collective action lens. This is an opportunity for future research. But perhaps more significantly, the SESF may be able to provide a bridge between multiple disciplines and methods in the field of SES research. The SESF was suggested to be a common language of variables and terminology for researchers studying the same systems to compare data from different disciplinary perspectives, with the potential to better enable interdisciplinary analysis.

The extent to which the above claims will manifest remains to be answered. Nonetheless, all of the claims about the usefulness of the SESF have a commonality, they require the development and testing of the framework using data collection and analysis methods from multiple disciplines. However, the development of methodologies to operationalize the SESF has challenged scholars, and there is a general lack of methodological exploration in the literature for applying the framework which mirrors its widespread notoriety as a useful conceptual tool. As examined in review article below, many articles have cited the framework in the literature but far fewer have applied it for empirical analysis (Thiel et al. 2015). Of those articles that have applied it, even fewer have tested a diverse set of different methodological approaches or have reflected on the challenges for future research.

Given the above reflection, it is important to recognize that the challenges for interdisciplinary research are not new to commons scholarship, or unique to the SESF itself. Multiple methods, multiple disciplines and multiple theories have historically contributed to the development of the SESF. In the 2010 book *Working Together: Collective action, the commons and multiple methods in practice* (Poteete et al. 2010), the authors outline the mixed-method research program which guided commons scholarship. The authors outline the necessity of an iterative and collaborative research process where researchers from multiple disciplines work together. Robust interdisciplinary scholarship in part motivated the decision to award Elinor Ostrom the Nobel Prize in Economics in 2009. Reflection on the need for interdisciplinarity is well stated in her autobiography on the Nobel Prize website, “The way we organize the modern American university fragments our knowledge badly. Not only are we divided by discipline, but we are divided by the methods that scholars use (Nobelprize.org).”

We can draw from the history of commons scholarship e.g., (Ostrom 1990, 2005, Ostrom et al. 1994, Agrawal 2003, Poteete et al. 2010). Applying the SESF will require the same iterative, interdisciplinary and mixed-methods approach going forward. Developing and testing methods for integrated social-ecological systems analysis is the next step for applying the framework. Overall, we need to explore how the SESF can be applied in new ways and operationalized in new contexts to continue the research program outlined in this introduction. Numerous efforts have already been made including an updated version of the SESF published posthumously by McGinnis and Ostrom in 2014 titled *Social-ecological systems framework: initial changes and continuing challenges*. They provide the framework’s most recent conceptual developments, a basis for much of the work presented below (Figure 2; Table 2).

The brief history of commons scholarship above leads to the starting point for this thesis. We have inherited the SESF. Those of us who are interested now have the opportunity to test, guide and experiment with its usefulness and development. I argue that there is no right or wrong way forward, only iterative learning and exploration supported by the same rigorous science that was demonstrated by those who came before us. This thesis presents a compilation of peer-reviewed articles and research manuscripts attempting to make a contribution to this aim. These articles explore many dimensions related to the SESF, with a primary focus on exploring its conceptual development and testing methods to apply it for empirical research. The context for the empirical research is situated within the field of tropical marine science, with case studies examining coastal small-scale fisheries and pond aquaculture in Indonesia, Brazil and Costa Rica.

Coastal small-scale fisheries and pond aquaculture in the tropics

Tropical coasts

Tropical coasts contain the highest concentrations of people and biodiversity worldwide. At the same time they are some of the most socially and ecologically threatened areas from human-induced global environmental change (Glaser et al. 2012, Bowen et al. 2013, McKinnon et al. 2014). Ecologically, this includes terrestrial, coastal and marine ecosystems such as estuaries, beaches, seagrass meadows, rivers, coral reefs and mangroves. Socially, this includes numerous groups of actors, cultures, institutions and governance systems related to coastal resource use. Coastal systems contain a wide variety of resources that can be characterized as common-pool resources and public goods. In addition to rivalry and excludability characteristics, coastal commons have additional features that make governance difficult (Álvarez-Romero et al. 2011). They are situated at the land-sea interface (Pittman and Armitage 2016). Processes on land are interacting interdependently with processes in the sea (Glaser et al. 2012). These interdependent interactions are both social and ecological, making coastal commons unique and complex social-ecological systems (Partelow et al. 2018a, Schlüter et al. 2018). Knowledge is needed on both systems, and the connections between them, to develop effective governance.

Small-scale fisheries

Small-scale fisheries provide 90% of the employment and account for 50% of the total fish capture in the global fisheries sector (FAO 2015). Small-scale fisheries do not have a universally applied definition, but in many tropical or developing countries they can be generally characterized by the use of low tech gear, low initial investment barriers, lower catch rates, use of non-industrial or artisanal methods, self-employment and all fisheries for subsistence needs. In many tropical countries, SSF are a central pillar of wellbeing for coastal communities, providing a primary source of food, shaping cultural identity and maintaining an artisanal way of life dependent on local natural resources (FAO 2014a).

Fish are a common-pool resource, and fisheries typify the complex challenges for managing CPRs. Every fish caught reduces the amount of fish available to other fishers, and it is difficult to

know how many fish are available in the sea to appropriate among fishers in a sustainable and equitable way. In addition, it is very difficult to exclude people from fishing. The sea is large and difficult to monitor and enforce, even if rules exist. Self-organized institutions to govern fisheries face substantial challenges for success (Acheson 2006). Those fisheries which have been able to find successful institutional arrangements for governance have often found unique institutional solutions compared to other terrestrial commons (McCay and Acheson 1990, Jentoft 2004). Many different types of rules for fisheries management have been identified, but typical approaches include the assignment of property rights. Property rights can refer to the physical space where an individual or group can fish. This is useful for less mobile or non-mobile species like shellfish which can be managed territorially. In contrast, property rights can also refer to obtaining the right to catch a certain amount of fish within a given space and time frame. This is useful for more mobile species like tuna which are difficult to manage spatially, making the total allowable catch more important. Property rights can be assigned to individuals in a variety of allocation procedures such as creating markets for purchasing or trading them in the case of individual transferable quotas (ITQs) or through lineage based systems where they are passed on within families.

Area-based management systems or territorial user rights to fish (TURFs), forms of property rights, are a common governance approach in many small-scale fisheries (Christy 1982). Local fishers are often assigned or they self-organize the access to physical space, where designated groups of fishers have exclusive rights to fish. Typically, additional regulations for fishing apply within these areas such as minimum catch size or gear restrictions, but boundaries and access rights remain the primary pillar for management. Often such areas are managed by local cooperatives or fishing associations, and sometimes in a co-management arrangement with state authorities. The small-scale fisheries case studies examined in this thesis, in Brazil and Costa Rica, both have area-based co-management arrangements. In both cases, the goal of these areas is to grant exclusive access and harvesting rights to a certain groups of fishers and the goals for the area include both ecological conservation and social wellbeing targets. However, despite their similarities, both have quite different institutional arrangements and face unique challenges for long term management success.

This introduction to small-scale fisheries is continued in the relevant empirical articles below. However, it is important to recognize that the characteristics of small-scale fisheries introduced above only provide a brief and generalized overview. Small-scale fisheries are highly diverse and face myriad of other challenges including pressures from globalization (Kittinger et al. 2013). The integration of small-scale fisheries into global markets can be a blessing and a curse. Fisheries with well-established institutions for governance may be resilient to change, and may be able to benefit from increased market prices that can bring better wages. However, it can also be negative. For example, it can bring increased fishing pressure, or increased numbers of migrant fishers in an area seeking a livelihood. Unregulated fisheries or fisheries with weak institutions can face severe overexploitation in this scenario, under conditions with few alternative livelihood opportunities. Climate change is also challenging the resilience of fisheries to cope with both fishing pressure and the decreasing stability of environmental conditions. In many coastal areas traditionally dependent on wild-catch fishing, aquaculture is becoming a viable alternative.

Pond aquaculture

Human use of marine resources has remained in a period of hunting and gathering into the modern era. Despite the transition towards agriculture on land more than 10,000 years ago, humans are still roving bandits at sea (Berkes et al. 2006). Humans have become so successful at hunting marine resources in the wild that a large majority of fisheries worldwide indicate substantial if not catastrophic decline (Worm et al. 2009, Pauly and Zeller 2016). Such trends beg the question as to when the transition towards controlled fish production through farming will replace the current unsustainable efforts to provide seafood to a growing global population.

In response, aquaculture has been the fastest growing food production sector worldwide over the last 15 years (World Bank 2013, FAO 2016). This has led to approximately half of the world's seafood supply being currently produced through aquaculture (World Bank 2013, FAO 2014b). There are different types of coastal aquaculture, but two main types can be identified: terrestrial pond-based systems and ocean-based mariculture (Swann 1992, Huong and Berkes 2011).

This thesis includes an empirical case study analyzing pond aquaculture as a social-ecological system on Lombok, Indonesia. Pond aquaculture can be characterized as a hybrid common-pool resource system. Historically, commons scholarship has focused on different types of unique systems such as fisheries, forestry and irrigation systems. CPR and collective action theory has evolved analyzing these systems independently and comparing them. Pond aquaculture can be characterized as a hybrid between fishery and irrigation systems, making them unique case studies of a hybrid commons with unique challenges. They have canal infrastructure for water distribution similar to irrigation systems but also coastal boundary fluidity and patron-client systems, among other features, similar to fisheries. In contrast to small-scale fisheries, which face mostly appropriation dilemmas for extraction management, pond aquaculture systems face provision dilemmas to maintain infrastructure and water quality. All pond aquaculture farmers rely on common water distribution infrastructure, but there are varying incentives to contribute to maintaining it depending on the location of a farmer as a head or tail-end in the water distribution system.

Despite the potential for aquaculture to be a renewable source of fish production that can replace wild-catch fishing, the sector faces substantial challenges for sustainability. Coastal aquaculture requires intense coastal development processes which often transform the coastal landscape physically. It also requires new knowledge to inform institutional change for effective governance. While it is evident that these changes are already occurring, not enough is known about exactly how aquaculture can lead a transition towards marine and coastal sustainability. Aquaculture is becoming a central pillar for the global food economy, but remains understudied in both the developed and developing world (Edwards 2015, FAO 2016, Osmundsen and Olsen 2017). A lack of interdisciplinary literature on aquaculture, particularly on governance and institutional change, suggests that the ambiguity of aquaculture's future is primarily due to insufficient knowledge on how these systems function as complex and interdependent social-ecological systems (Eriksson et al. 2015, Partelow et al. 2018b).

Research design and specific contributions

The project supporting this thesis is titled ‘RECODE: Diagnosing and comparing social-ecological systems’. Empirically, RECODE aimed to apply the SESF within existing regions of strategic interest for the Leibniz Centre for Tropical Marine Research (ZMT) in Bremen, Germany with the overall goal to advance knowledge on the sustainable use of marine and coastal natural resources in tropical countries. ZMT has an interest to revisit its previous case study regions and to analyze data in those regions overtime. RECODE and this thesis sought to contribute to that aim as much as possible. Within these regions, the focus of research was specifically directed to small-scale fisheries and pond aquaculture, which are of high relevance in the case study countries: Indonesia, Brazil and Costa Rica.

To support this research, five master’s (M.Sc.) thesis projects and three collaborative research partnerships with universities in the case study countries were established. One M.Sc. student each was a part of the case study research in Indonesia (Research 4) and Brazil (Research 5), and three students in Costa Rica (Research 6, 7). Each case study applied the SESF in a different way, co-designed with the M.Sc. students.

The thesis is a compilation of eight research articles structured for peer-reviewed academic journals, with the addition of two concluding chapters discussing overall limitations and final conclusions. The articles and chapters are shown in Table 2. Further below, each article is explained in how it relates to addressing the overall research questions. The specific details of the research designs are not included in this introductory section, and can be found within each article. This section only aims to provide logic to the links between articles, briefly explaining how each research is related to the SESF.

Table 2. Research articles contributing to this thesis, organized by type of contribution and section of the thesis.

Thesis Section	Type	Link to RQs	Articles, chapters and authors	Status
Part 2	Review of empirical context	--	Research 1 Stefan Partelow, Achim Schlüter, Henrik von Wehrden, Manuel Jänig, and Paula Senff. 2018. “A Sustainability Agenda for Tropical Marine Science.” <i>Conservation Letters</i> 11 (1). doi:10.1111/conl.12351.	Published article
	Conceptual development	RQ1	Research 2 Stefan Partelow. 2016. “Coevolving Ostrom’s Social–ecological Systems (SES) Framework and Sustainability Science: Four Key Co-Benefits.” <i>Sustainability Science</i> 11	Published article

Part 1: Thesis introduction

			(3). Springer Japan: 399–410. doi:10.1007/s11625-015-0351-3.	
	Conceptual development	RQ1	Research 3 Stefan Partelow and Klara J Winkler. 2016. “Interlinking Ecosystem Services and Ostrom’s Framework through Orientation in Sustainability Research.” <i>Ecology and Society</i> 21 (3). doi:10.5751/ES-08524-210327.	Published article
Part 3	Case study in Indonesia	RQ2 RQ3	Research 4 Stefan Partelow, Paula Senff, Achim Schlüter, Nurliah Buhari. 2018. “Operationalizing the social-ecological systems framework in pond aquaculture.” <i>International Journal of the Commons</i> 12(1):485–518.	Published article
	Case study in Brazil	RQ2 RQ3	Research 5 Stefan Partelow, Marion Glaser, Sofia Solano, Roberta Barboza, Achim Schlüter. 2018. “Mangroves, fishers and the struggle for adaptive co-management: Applying the social-ecological systems framework to a Marine Extractive Reserve (RESEX) in Brazil.” <i>Ecology and Society</i> .	Published
	Case study in Costa Rica	RQ2 RQ3	Research 6 <i>Collective action, co-management and small-scale fisheries: Applying the social-ecological systems framework to compare three Responsible Fishing Areas (AMPRs) in Costa Rica</i> Isis Chavez, Stefan Partelow	Article draft
	Case study in Costa Rica	RQ2 RQ3	Research 7 <i>Transforming a social-ecological systems framework into a participatory management and deliberation tool</i> Stefan Partelow, Marie Fujitani, Vignesh Soundararajan, Achim Schlüter	Article draft

Part 4	Review and outlook	RQ4	Research 8 <i>A review of the social-ecological systems framework: Applications, modifications, methods and challenges</i> Stefan Partelow	Article draft
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A general point can be made about all of the articles contributing to this thesis; the central topic that links them all together is the SESF. I have specifically framed my research around concepts and methods for applying the SESF, which I view as the needed foundation for future progress. As foreshadowed above, the SESF can be used for different types of research. Research 8 identifies six ways in which the SESF can be used for research (Table 3). This can be used as a template to orient the different ways in which the SESF has been applied and used in the other articles of the thesis. I explicitly explore five of the six ways to apply the SESF, with the exception of a purely quantitative diagnosis of a case study (Table 3). All other applications are explored in further detail below.

Table 3. Types of research using the SESF (from Research 8) and the contributions from this thesis as a whole.

Six types of research using the SESF	Research contributions from this thesis
(1) Mixed method diagnosis or characterization of a case study	Research 4
(2) Qualitative diagnosis or characterization of a case study	Research 5
(3) Quantitative diagnosis or characterization of a case study	None (Parts of Research 4 and 6)
(4) Meta-analysis of the literature	Part of Research 1
(5) Comparative analysis of case studies	Research 6
(6) As a deliberation tool	Research 7

Research 1: A Sustainability Agenda for Tropical Marine Science

This article provides a systematic review of the literature on tropical and coastal marine science research worldwide. Research 1 uses the general social-ecological systems (SES) concept to identify the gaps and trends in the field, setting the stage to orient the empirical contributions in Indonesia, Brazil and Costa Rica, and the contextual focus within each case. Overall this research review article aims to provide an overview from which the context of this thesis can be evaluated in relation to other trends in the research field.

The results of this review article supports the need for social science contributions in tropical marine science. The social sciences have contributed substantially less knowledge to the field compared to the natural sciences, despite recognition that environmental problems are driven by humans and can only be solved by better understanding governance solutions and human behavior. This review article shows that the empirical contributions in this thesis fill important social science research gaps in tropical marine science, showing the value of and continued necessity for social and social-ecological research in coastal systems to better inform their ability to transition towards sustainability.

This review identifies gaps and trends in the research field and can be used to orient the knowledge contribution of the empirical research in this thesis. My case studies in Indonesia, Brazil and Costa Rica are located within close proximity to coastal mangrove areas. According to our review, social and ecological research within mangrove ecosystems receives far less attention than coral reefs, estuaries or lagoons, but mangrove ecosystems are no less vital for livelihoods and human welfare. In addition, the research in this thesis is situated in a coastal and near-shore context, with focus on near-shore small-scale fisheries and pond aquaculture. Aquaculture, despite being the fastest growing food production worldwide for the last decade (FAO, 2016), has received far less research focus than conservation or extractive marine activities like fishing. Lastly, all case studies are situated within a general development context and include fishers who rely heavily on local natural resources, and to some degree, for subsistence consumption. Development and subsistence research use has received proportionally less focus in comparison to pollution, conservation and commercial resource use. Nonetheless, these case studies also relate to commercial resource use substantially.

Research 2: Coevolving Ostrom's Social-ecological Systems (SES) Framework and Sustainability Science: Four Key Co-Benefits

This article is a conceptual article and attempts to argue that the SESF can be a useful tool for sustainability science by identifying overlapping goals between the history of commons research that led to the SESF and the ambitions of sustainability science. This article presents a broad vision for the SESF, a vision that the empirical case studies can only make initial and preliminary contributions to. Nonetheless the article sets forth a conceptual development path to continue the

tradition of interdisciplinary and integrated research to bring different academic fields together to advance sustainability research. Ostrom brought together the fields of political science and economics to create a new body of theory examining a collective action hypothesis. Linking two fields was arguably a major decision criterion influencing her Nobel Prize in the economic sciences, although she was not a traditional economist herself. This article aims to propose the potential co-benefits of further linking the SESF and sustainability science as related but mostly separate fields, and to initiate some momentum in further conceptual development with the framework. Overall, this article is largely exploratory and conceptual. It provides a basis for exploring the development of new conceptual and empirical ideas in other parts of this thesis, particularly Research 7 which uses the SESF as deliberation tool.

Research 3: Interlinking Ecosystem Services and Ostrom's Framework through Orientation in Sustainability Research

This article explores and attempts to clarify the different epistemological perspectives and types of knowledge that have the potential to be generated between conceptual frameworks, or even discourses, within the field of social-ecological systems research. To support this argument we analyze the similarities and differences between the SESF and the ecosystem services concept. While the article takes its own path in exploring these details, its contribution within this thesis can be viewed as situating the SESF epistemologically, to be critically reflective on its benefits and limitations for generating certain types of knowledge. The SESF is not a panacea conceptual framework. Arguably conceptual frameworks like ecosystems services and the SESF are useful for structuring entire research programs. However, they can also be restrictive in terms of limiting a field to a certain worldview by creating path dependencies in discourse and knowledge generation. This article provides critical reflection on how the knowledge generated by applying the SESF is situated within specific discourses within SES and sustainability research.. It should also inspire new directions for the framework, as exemplified in Research 2 and Research 7. Further exploration of the epistemology of the SESF is discussed in Research 8, continuing the discussion.

Similarly to Research 2, this article attempts to explicitly develop a conceptual link and compare research fields with similar aims but through different means and histories. Bringing together traditionally separated ideas, concepts and conceptual frameworks should be a part of the SESF's future, as much as it was part of its past.

Research 4: Operationalizing the social-ecological systems framework in pond aquaculture

This article applies the SESF to a case study of pond aquaculture on the island of Lombok, Indonesia. The purpose of the article is to test methods for applying the SESF through a mixed-method and interdisciplinary diagnosis of a case study, and to outline the challenges. We demonstrate a diagnostic research approach to identify the variables, develop contextual indicators and collect social and ecological data at multiple levels of the system. This study largely mirrors the approach taken by Leslie et al., (2015), but aims to apply these methods on a local level and in a new context. We use quantitative data collection methods to measure biophysical variables and use qualitative data collection methods to measure social variables. Due to the heterogeneity of data, we demonstrate how to transform the data into normalized quantitative social-ecological scores to compare data (i.e. outcomes) across individual aquaculture ponds as distinct units of analysis. Secondly, we use qualitative data to analyze the broader social drivers affecting collective action at the community level. Thus the study analyzes two units of analysis at different levels of the system.

Within the methodological framing of this thesis, the overall contribution of Research 4 is a demonstration of potential methods and a reflection of the challenges for mixed-method diagnosis of a case study, which are applicable beyond the context of the case. The challenges include developing appropriate indicators to measure each variable, integrating heterogeneous data, and interpreting the results of a mixed-methods analysis across multiple levels of a system. In addition, the case study demonstrates how to operationalize the framework in a new context for coastal commons research, namely pond aquaculture, which is globally relevant within tropical coastal development, food security and mangrove research.

Research 5: Mangroves, fishers, and the struggle for adaptive co-management: Applying the social-ecological systems framework to a Marine Extractive Reserve (RESEX) in Brazil

This article applies the SESF using qualitative data collection and analysis methods to diagnose a case study considering temporal change. Brazil has an institutionally unique type of co-management arrangement called Extractive Reserves (RESEX). The article focuses on a mangrove crab fishery with a RESEX area and analyzes numerous challenges related to its co-management. The study uses the SESF as a diagnostic tool. A primary methodological contribution of the research is how the data is analyzed and presented using the SESF as a qualitative coding framework. In this sense, the article explores how the SESF can be used as an analytical framework, and not just a conceptual and diagnostic tool. Following from this, the first and second-tier variables can also be used to structure the presentation of analyzed data in an article, which we demonstrate. In addition, the article focuses on how interactions between variables of the SESF can be qualitatively analyzed in a complex system. Many of the variables

of the SESF are examined through rich description, with focus on how variables interact to shape overall co-management outcomes overtime.

Research 6: Applying the social-ecological systems framework to compare collective action in three small-scale fisheries in Costa Rica

This article conducts a comparative analysis of three case studies using the SESF. One of the main claims of the SESF is that it can provide a common set of variables that can be examined across cases, better enabling the comparability of data. This article attempts to do this by conducting a qualitative comparative analysis of three small-scale fisheries in the Gulf of Nicoya, Costa Rica. Each fishery is trying to establish Responsible Fishing Areas through community-based co-management with state agencies. We use the SESF to show how the fisheries face unique challenges due to their local conditions and complexity, and, that despite perceived homogeneity in their characteristics and close spatial proximity to each other, they require contextualized solutions for management.

This article demonstrates that the SESF framework can indeed be a useful tool for comparative analysis using common variables. However, many methodological challenges exist related to defining variables, indicators and the degree of influence each variable has in each case. This leaves many difficulties for data comparability. We compared three relatively similar small-scale fisheries, but comparing more diverse cases, particularly in different sectors or localities will be significantly more challenging and would require a high degree of standardization in definitions, data collection and analysis across cases. Many of the lessons learned are derived from this study, and from the thesis in general, in Research 8; where they are summarized as ‘methodological gaps’ to think about when applying the SESF.

Research 7: Transforming a social-ecological systems framework into a deliberation tool

This article develops a new potential use for the SESF. We develop a methodological process to transform the SESF into an image-based tool to help facilitate knowledge exchange and to support the structure of deliberative processes related to natural resource management. This articles presents why it may be useful to think outside-the-box in relation to how we view the usefulness of the SESF, and the potential role it could play in applied research, particularly from the perspective of sustainability science. This article is foreshadowed in Research 2.

The SESF (Figure 2) conveys a systems thinking perspective, a checklist of key variables and social-ecological interactions in a way that is more understandable for actors in a local context. We argue that this method may be generalizable if explored in other settings. The article additionally explores field experimental methods to test how to measure the impact this tool has on individuals who use it in deliberative settings. Overall, the article shows how the SESF can be

a tool for transdisciplinarity and applied research beyond its normally perceived uses. The article presents a potential new direction for the SESF which should be further explored beyond this proof-of-concept study.

Research 8: A review of the social-ecological systems framework: Applications, modifications, methods and challenges

This article reviews the existing literature applying the SESF. It identifies the different ways in which the framework can be applied and then proceeds to discuss the methodological challenges related to variable definitions, indicators, data collection methods and analyses. As such, it acts as a core part of the methodological conclusions from the literature and the empirical research in this thesis.

This article can be seen as a guidepost for future research and a critical discussion on research with the SESF going forward. It provides reflection on the diverse ways in which the empirical research in this thesis has applied the SESF in relation to other studies. No other large research project, to my knowledge, has attempted to apply the SESF in multiple ways with the purpose to examine the more detailed methodological challenges for mixed-method and interdisciplinary research. While the discussion section of this article is framed, and of course, part of the review, it simultaneously acts as the summary conclusions to the methodological lessons learned from all of the empirical research in this thesis. In addition, some of the discussion relates to the broader discourse on SES and sustainability research, linking back to topics in Research 2 and 3, as many of the methodological challenges are not unique to the SESF.

Part 2: Context and concepts

Research 1: A sustainability agenda for tropical marine science

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Abstract

Tropical coasts face unprecedented sustainability challenges for advancing human welfare and maintaining ecosystem functioning and diversity. These coupled social-ecological processes exist within interdependent relationships across multiple levels and scales. Reflection is needed on the knowledge tropical marine science generates to advance a research agenda for sustainability. In this article we systematically review 753 social and natural science articles conducted within the tropical coastal marine sector. Our results are organized in five themes. (1) The spatial distribution and disciplinary composition of research is not homogeneous across regions. (2) A third of all research lacks a stated problem orientation and coral reefs dominate the ecosystem focus. (3) Research is primarily conducted on selected subgroups of levels and scales. (4) The social and natural sciences focus on a varying diversity of system processes that indicate different degrees of inter- and intra- disciplinary research. (5) Statistically clustered terminology usage across all articles indicates that distinct research communities exist across a social to natural science gradient. The social and natural sciences generate different types of knowledge associated with terminology at different scales. This analysis attempts to provide a guidepost for discussing the challenges and pathways forward to progress a sustainability agenda in tropical marine science.

Keywords

Systematic review | Social-ecological systems | Tropical | Marine | Coastal | Interdisciplinary

Introduction

Tropical coasts contain the highest concentrations of biodiversity and people worldwide (Glaser et al. 2012, Bowen et al. 2013, McKinnon et al. 2014). Human populations on tropical coasts experience a high degree of dependence on local natural resources, widespread poverty, and face immediate threats from climate change including rising seas and increased storm intensity (MEA 2005, Worm et al. 2006, IPCC 2007). Simultaneously, ecosystems face reciprocal pressures from increasing resource exploitation, pollution, ocean acidification and increasing sea surface temperatures (Halpern et al. 2015, Graham et al. 2015). This quagmire of interdependent relationships has shifted the paradigm through which we conceptualize sustainability in an interconnected world, to one where people and nature are coupled in social-ecological systems (SES) (Ostrom 2009, Kittinger et al. 2012, Fischer et al. 2015), necessitating a cohesive response from both science and society.

Tropical marine and coastal SES are confounded by contextual complexity at multiple levels and scales (Glaser and Glaeser 2014, Leslie et al. 2015). In ecological subsystems, coral reefs, mangroves, seagrasses, open seas and estuaries each contain contextually unique functional processes (McMahon et al. 2012, Yeakel et al. 2015). Biodiversity supports functional diversity and redundancy for maintaining baseline ecosystem functions (Bowen et al. 2013, Mouillot et al. 2014). The resulting ecosystem services sustain coupled social-ecological integrity (Arkema et al. 2015). In social subsystems, human behavior and institutions shape the provision and appropriation of goods and services (Ostrom 2009, Cinner et al. 2012). Institutional prescriptions or collective action typically govern society through formal and informal rules (Ostrom 2009, Horan et al. 2011). The coupled outcomes of coastal and marine systems thus result through an exchange of social-ecological interdependencies, with interactions occurring simultaneously within and across biophysical and socially constructed levels and scales (McGinnis and Ostrom 2014, Leslie et al. 2015).

Normative ambitions for tropical marine science propose that knowledge generation should collectively advance sustainability (Grorud-Colvert et al. 2010, Cinner et al. 2012, Glaser et al. 2012). The foundations of such a sustainability agenda need to recognize place-based challenges, but also commonalities (Ostrom 2009, Wilcox et al. 2015). Linkages between livelihood security, global markets and rapid natural resource exploitation have been coined as pandemic (Berkes et al. 2006, Eriksson et al. 2015). Coastal communities and biophysical systems with low resilience thresholds can face sudden and irreversible changes from anthropogenic impacts (Graham et al. 2013, Troell et al. 2014). Such systems are often characterized by a new social-ecological condition, with rapid biodiversity loss and decreasing livelihood opportunities (Worm et al. 2006, Cardinale et al. 2012). In response, achieving sustainable development may require reconciling trade-offs between place-based needs and overarching goals (United Nations 2012), necessitating a well-informed scientific agenda with operational solutions.

Towards an agenda for sustainability science

Operationalizing a sustainability agenda for tropical marine science will require the generation and integration of diverse knowledge types (Glaser et al. 2012, Leslie et al. 2015), from both science and society. In particular, we recognize the role of non-western scientific knowledge in informing sustainability agendas such as local ecological and traditional knowledge (Berkes et al. 1995). However, this review solely focuses on the state of published scientific knowledge and how it shapes current agendas, but this nonetheless presents a challenge to comprehensively examine the diversity of literature across disciplines.

Here we aim to inform future agendas in tropical marine science by analyzing existing literature. Furthermore, we categorize the knowledge needed to inform sustainability into three types: system, target, and transformative (Hadorn et al. 2006, Jerneck et al. 2010, Brandt et al. 2013). System knowledge analyzes and describes system functioning. Target knowledge understands how system knowledge passes through the interpretations, visions, goals and normative directions of society. Transformative knowledge understands how to convey system and target knowledge into practical change mechanisms such as policy, education and communication.

In practice, the need for science is escalated in times of increasing social and environmental change. However, the role of science in society is increasingly ambiguous. Without undermining the diversity and integrity of scientific practice, structuring an agenda for science to cumulatively advance sustainability requires reflection into how and why knowledge is generated (Spangenberg 2011). Communicating how knowledge can be oriented to real-world problems and inform practical solutions is recognized as a key step for advancing sustainability contributions within and beyond the scientific discourse (Perrings 2007). Moving towards a conscious research agenda for sustainability requires examining the agendas that are established, why they have evolved in this direction and to propose what is needed to inform a sustainable future.

In this article we systematically examine tropical marine and coastal research from 753 peer-reviewed articles across the social and natural sciences. This review aims to provide a guidepost that can orient discussion and contribute to reflections on how and why marine and coastal research agendas can advance sustainability. To do this we examine knowledge contributions across disciplines and contexts. We outline our methods below and present our results quantitatively. Our discussion highlights key gaps and trends in the literature, and attempts to provide a starting point for critical discussion including trends in regional disparity, the role of problem orientation, multi-dimensional systems, the types of knowledge needed and differences between the social and natural sciences.

Methods

Our systematic literature review draws on established methods (Brandt et al. 2013, Luederitz et al. 2015). We assessed 1,995 peer-reviewed articles of potential relevance which were distilled down to 753 articles for full review within our scope. Our search string and scope related to peer-reviewed academic literature within social, ecological or social-ecological research in the marine and coastal tropics. However, we recognize that this review cannot be considered fully exhaustive. Our step-by-step protocol is shown in Table 3 (Supplementary material). We distinguish that a case study or the relevant context of the research must fall within the Tropical latitudes of 23.5 N and 23.5 S. Articles needed to have a direct connection to the marine or coastal environment but could relate to this context through a wide variety of research ranging from land-based social research to exclusively marine natural system processes or land-sea connectivity across any scientific discipline.

Review categories

We defined 13 review categories for data collection (Table 1). Categories follow our research focus and draw on existing frameworks, including levels and scales (Cash et al. 2006), research processes (Glaser et al. 2012) and knowledge types (Hadorn et al. 2006, Jerneck et al. 2010, Brandt et al. 2013). However, classes within each category were defined through a combination of framework definitions and inductive assessment during the review process through consensus among coders. If a framework was used as a starting point for a category, classes remained inductively flexible to include the full spectrum of data from articles, with an open-text ‘Other’ option for each category. None of our review categories were mutually exclusive except year. This allowed the coding for each category to avoid forced classification. However, coding was conservative, only classifying an article if it was directly relevant to the primary research outcomes or argumentation.

Table 1. Review categories and subclasses.

Category	Description of sub-classes used
Year	Year article was published
Discipline/ perspective	Biology, Ecology, Political science, Economics, Sociology/ Anthropology/ Ethnography, Geography, Chemistry/ Biogeochemistry, Sustainability science, Physics, Geology, History
Location	Physical location where research was conducted or relates to was classified by World Bank sub-regions .
Ecosystem type	Coral reef, Rocky reef, Mangrove, Soft bottoms, Open sea, Estuary/ Wetland/ Lagoon, Intertidal, Coastal, Sponges, Seagrass
Problem orientation	Subsistence/ Recreational resource use, Commercial resource use, Tourism, Conservation, Pollution/ Degradation, Aquaculture, Development, Climate change, Restoration, Mining
Level focus	Local, Regional, Global
Scale focus	Ecosystem, Jurisdictional, Knowledge, Temporal, Spatial, Institutional, Network, Management
Social processes	None, Demographic change, Distributive and procedural justice, Participation and decision making, Rules and rights transparency & implementation, Conflict resolution, Social learning, Knowledge generation and communication, Social networking, Historical societies, Community and cultural development, Socio-economics and livelihoods, Social perceptions and behavior, Rule-making & institutional change
Ecological processes	None, Habitat connectivity/ Migration/ Mobility, Recruitment, Litter processing, Carbon & nutrient cycling, Functional diversity, Functional redundancy, Biological or Ecological response to pollution, Oxygen consumption & production, Population connectivity, Sedimentation/ Erosion, Biomass prod./ Transfer/ Reproduction, Sediment oxygenation/ Nutrient mixing, Calcification, Species interactions, Hydro/ Oceanographic processes, Bio./ Eco. extreme events response, Ecosystem integrity and change, Climate change processes, Land-sea connectivity, Biophysical characteristics
Social- ecological processes	None, ES provision, Self-organization, Resource use & degradation, Adaptation and coping, Knowledge integration, Scale development, Values & trade-offs, Local ecological knowledge, Management, Mapping, Research
Knowledge types	System, Target, Transformative
Publication terminology	All words from each article were individually extracted, filtered for relevant terminology and associated with knowledge types.

The disciplinary composition of the social and natural sciences used in this paper is shown in Figure 1. Regional groups are World Bank sub-regions (World Bank 2015) (Figure 2). Melanesia, Micronesia and Polynesia were grouped into the Pacific Islands. West Asia and South Asia were merged into Southwest Asia, and Hawaii as its own sub-group. Levels are defined as local, regional and global. Scales are defined from Cash et al., (2006) and Glaser et al., (2012). They are defined in short form as spatial “geographic space”, temporal “time frames”, institutional “hierarchies of rules”, jurisdictional “organized political units”, knowledge “generalized to context specific”, management “hierarchy of tasks and strategies”, networks “structures of [social or ecological] associations” and ecosystem “functions, services, benefits and their distribution”. Our starting point for system processes (Table 1) to include was derived from Glaser et al., (2012), but additional processes were added inductively to not limit the range that exist in the literature.

Analytical procedures

Nearly all articles focus on at least one system process, and they can be classified into a domain typology of either social, ecological or social-ecological (Glaser et al., 2012). Each article was classified into the domain typology shown in the Venn diagram (Figure 6) based on their process focus. Articles with a focus on multiple processes from different domains (e.g. one social and one social-ecological) are colored red in Figure 6 and further analyzed in Figure 7. Articles with a focus on one or multiple processes in the same category (e.g. one or two ecological) are colored black in Figure 6 and further analyzed in Figure 8.

We analyzed two aspects of the articles that focused on multiple processes (Figure 7; Figure 8). First, how often two processes occur in the same article (connectivity in circle), and second, the total occurrence of each process in multiple process articles (proportion of circle edge). Multi-process articles from different domains were analyzed as inter-domain, representing a connection in Figure 7. A connection in Figure 8 represents an article that examined two processes within the same domain. Process connectivity in both was derived through generating an adjacency matrix from the dataset. Two insights can be drawn from Figure 7 and Figure 8. First, the relative occurrence of each process in the literature, and second, the total connectivity between processes represented by co-occurrence in an article (For further details see Supplementary Material).

The terminology and knowledge type plot (Figure 9) was calculated by extracting all individual words (terminology) from each article into a data matrix. The presence and recurrence of words was statistically clustered based on their abundance across all articles, using an indicator species analysis to identify words that characterize groups into statistically distinct clusters (Dufrene and Legendre 1997). In order to visualize these words and the groups they characterize, we used a detrended correspondence analysis of the whole data matrix (Hill and Gauch 1980). Words (terminology) with a relevant knowledge context were manually classified as representative of system, target or transformative knowledge based on a word typology developed by Abson and colleagues (2014). Knowledge types were plotted in direct relation to the statistically clustered terminology distribution.

Results

Our analysis presents results within five themes. (1) The spatial distribution and disciplinary composition of research across regions. (2) The current problem orientation, ecosystem focus and time-evolution of the literature. (3) The level and scale focus related to the units of analysis in each article. (4) The system process focus in the social and natural sciences. (5) The knowledge types generated and the communication of knowledge through examining terminology in the literature.

Spatial distribution and disciplinary composition of research across regions

The disciplinary composition of scientific effort is shown in Figure 1, dominated by ecology in the natural sciences. In addition, the spatial occurrence of research is not homogeneously distributed (Figure 2). Some regions receive far less research focus comparatively, including West Africa, Middle Africa, Southwest Asia and sub-regions of the Pacific Islands. In contrast, a third of all research occurs in two of twelve regions, Southeast Asia and Australia. Within Australia, a large majority of the research is conducted on the Great Barrier Reef. The Pacific Islands, Central America and the Caribbean receive relatively equal focus. However, our analysis does not consider effects of coastline length, population density, resource dependencies or differences in specific regional characteristics. It is not in the scope of the article to analyze the reasons for regional disparity. The scientific effort distribution shows a dominance of natural science across nearly all regions (Figure 2). Social sciences are more relatively abundant in Southwest Asia, East Africa and Southeast Asia.

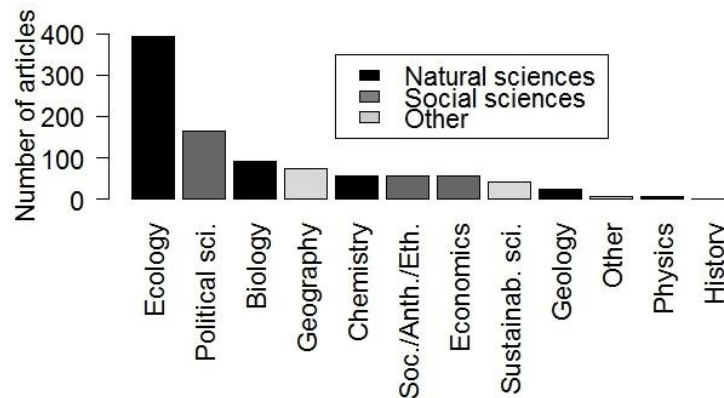


Figure 1. The total number of articles from each discipline. The disciplinary composition is shown in the Natural sciences, Social sciences and Other. This is used to aggregate disciplinary contributions when mentioned in the text and in Figure 2, Table 2, and Figure 4c.

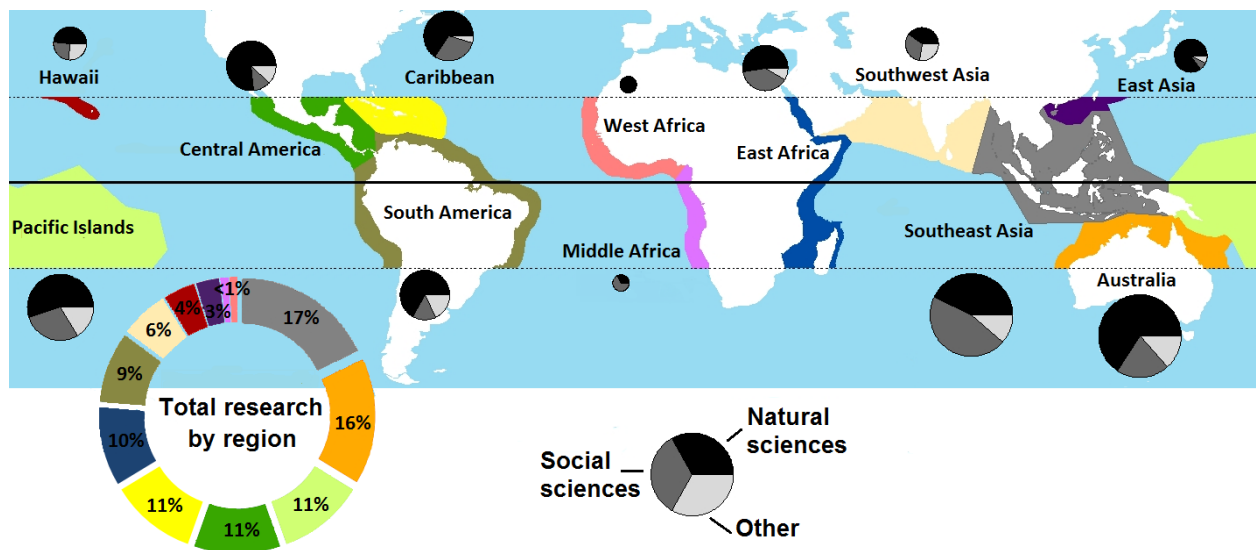


Figure 2. Total percentage of research by tropical coastal marine region. Spatial extent of region boundaries is only for visual purposes. Scientific focus by region is presented in pie charts. Pie chart size is representative of total N. Natural sciences include: biology, ecology, chemistry, biogeochemistry and geology. Social sciences include: political science, economics, sociology, anthropology and history. Other includes: geography, physics, sustainability science and all others.

Problem orientation, ecosystem focus and time-evolution

A third of all research lacks a stated problem-orientation that links its purpose to a problem outside an academic discourse. The natural sciences have a very low proportion of articles with a stated problem orientation compared to the social sciences (Table 2). However, this is not a distinction between basic and applied research, only the stated purpose or motivation to conduct the research. The type of problem orientation is rather homogenous between the sciences, with the exception of pollution in the natural sciences. Conservation and tourism are emphasized in the social sciences (Table 2). Focus on conservation, commercial resource use and pollution is homogenous across regions (Figure 3a). Specific regions exhibit a proportionally higher focus in specific areas such as development in Southwest Asia, tourism in the Caribbean, subsistence resource use in East Africa, restoration in the Pacific Islands, and aquaculture in Southeast Asia (Figure 3a).

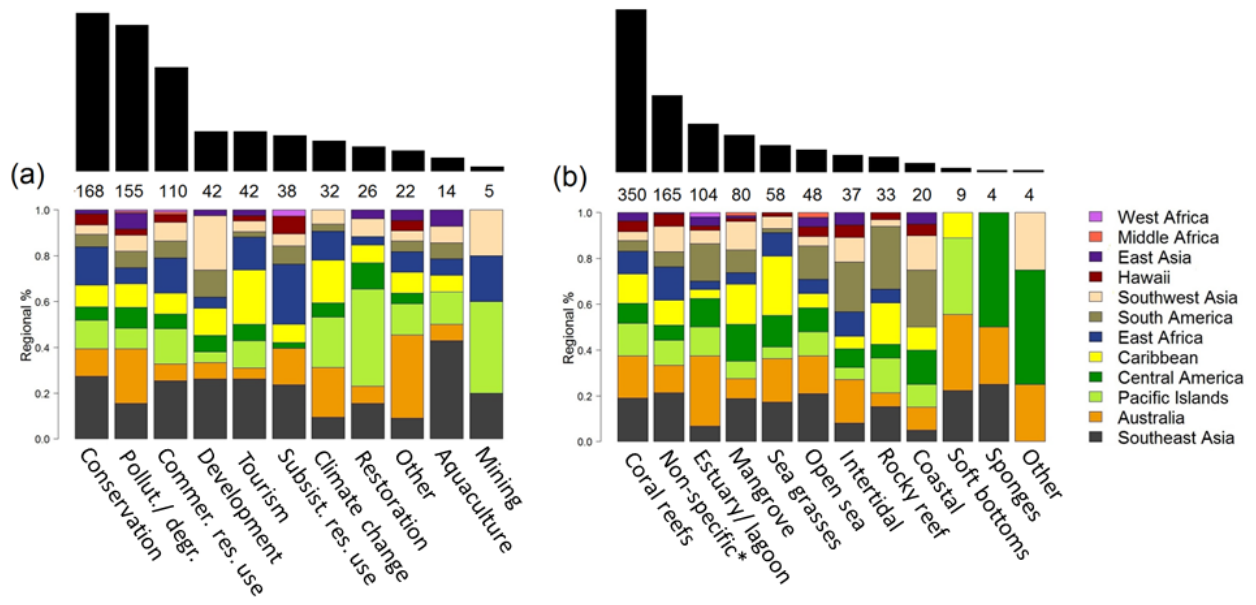


Figure 3. Percentage of problem-orientation and ecosystem focus by region. Total number of problem-orientation and ecosystem type across all articles. Regional colors correspond to map colors in Figure 2. **(a)** Conservation, pollution/ degradation, and commercial resource use dominate total-N problem-orientation across regions. **(b)** Coral reefs dominate total-N ecosystem focus across regions. *Non-specific ecosystem focus comes from articles that did not directly indicate relevance to a specific ecosystem type. The total-N = 248 for articles with no problem-orientation.

Considering the diversity and importance of all ecosystem types, 38% of all research is conducted on or in relation to coral reefs (Figure 3b). Estuaries, wetlands and lagoons combine for the second highest focus at 10.7%, followed by mangroves at 9%. All other ecosystems account for only 6% or less of the total research, including sea grasses, open seas, rocky reefs, soft-bottoms, intertidal, and all other coastal zones. Research not explicitly linked to a specific ecosystem is classified as non-specific.

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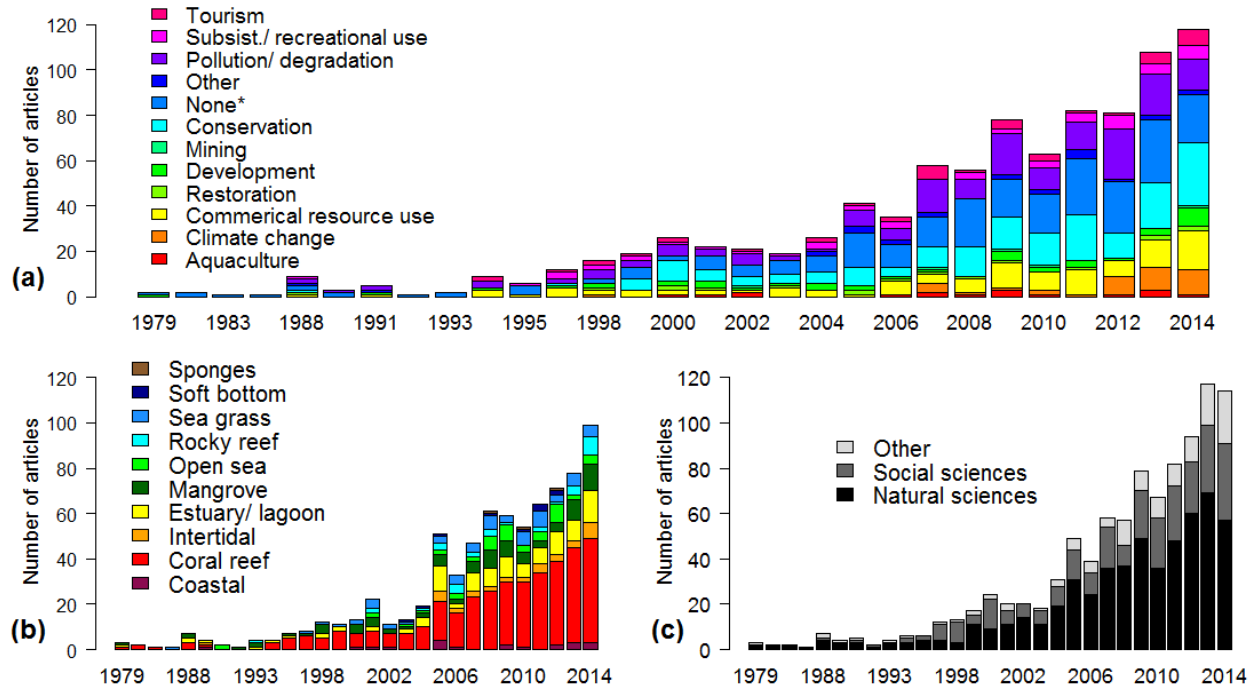


Figure 4. Publication trends over time. The number of publications in each year is divided proportionally by the number of articles in each theme. (a) Time-series of problem-orientation. (b) Time-series of ecosystem focus. (c) Time-series of total publications by broad scientific effort.

Figure 4 shows a time-series analysis of problem focus (4a), ecosystem focus (4b) and the general publication trend of included articles from 1979 to 2014, which includes the proportion of articles in the social and natural sciences (4c). The natural sciences maintain a dominant proportion of the research focus. The proportion of social science research has increased slightly over time (Figure 4c). Coral reefs, conservation, commercial resource use and pollution/ degradation have maintained a dominant focus over time. Literature on climate change has increased since 2010.

Table 2. Percentage of total articles sorted by their stated problem orientation. * indicates no stated problem orientation. Disciplinary composition is shown in Figure 1.

Problem orientation category	Natural sciences %	Social sciences %	Other %
Aquaculture	1.4	2.3	2.0
Climate change	5.2	2.6	5.1
Commercial resource use	9.1	19.7	10.6
Development	3.9	7.2	7.6
Mining	0.6	0.5	0.5
Conservation	10.9	30.9	17.2

None*	37.0*	5.6*	21.7*
Other	2.2	3.5	2.0
Pollution/ Degradation	23.0	9.0	15.7
Restoration	1.7	1.2	2.0
Subsistence/ Rec. resource use	3.2	7.9	8.6
Tourism	1.7	9.7	7.1

Level and scale focus

This section of the analysis examines if empirical research reflects the conceptual understanding that social-ecological systems are multi-dimensional. We observe that the research focus at different levels and scales is uneven (Figure 5). The total level focus across all scales is 7% global, 36% regional and 57% local. In combination, a large proportion of all research (30%) examines a unit of analysis on or related to an ecosystem or spatial scale at the local level. There is significantly less global level focus across nearly all scales. However, the proportion of regional level research is relatively similar across scales. The proportion of research examining explicit social system scales (i.e. institutional; jurisdictional) are comparatively even across levels, although their total N is disproportionately low. Articles focusing on knowledge, institutional, jurisdictional, or network scales cumulatively account for only 27% of all articles.

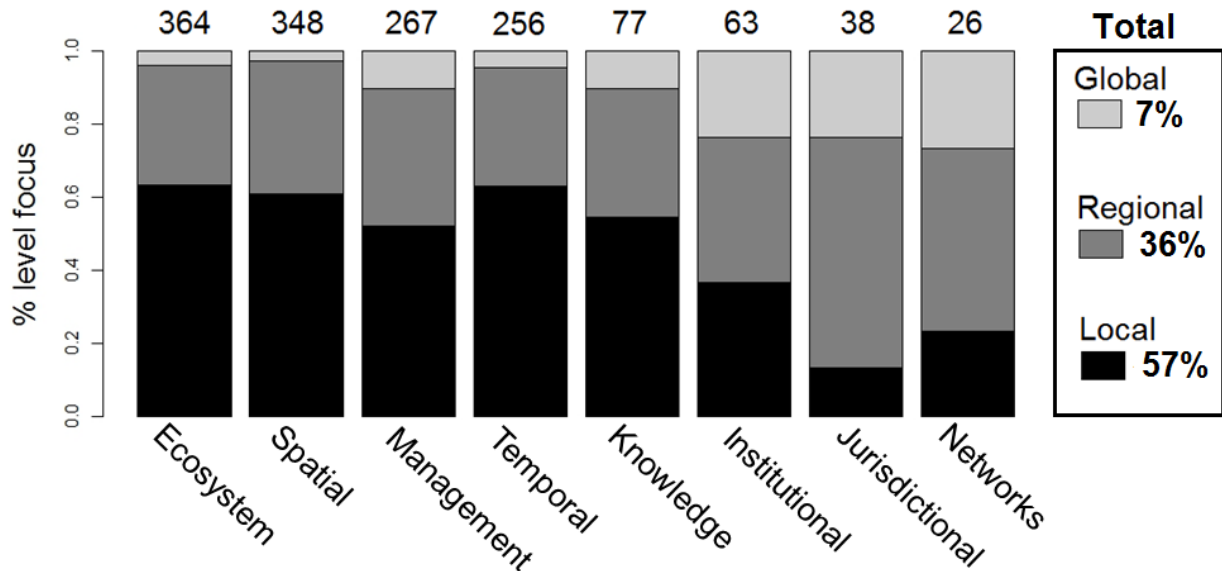


Figure 5. The total number of articles is shown on top of the stacked bar for each scale. The bar for each scale is stacked by the percentage of focus at each level. Total focus at each level is displayed as a percentage on the right.

System process focus in the social and natural sciences

The number of domain processes we examined in articles include ecological (n=20), social (n=13) and social-ecological (n=11) (Table 1; Figure 7). We analyzed process focus within articles and between domains. A focus on two or more processes from different domains could be interpreted as an indicator for multi- or inter-disciplinary research. Considering all inter-domain processes that occur in combination, the highest total-N link occurs between the ecological and social-ecological domains (Figure 7). Similarly, research within the ecological domain is more frequent than research in the social or social-ecological domains (Figure 6). However, despite lower total-N connectivity, articles focusing on social processes have a higher proportion of connectivity to social-ecological and ecological domain processes (Figure 6). We analyze the intra-domain connectivity (Figure 8), and indicate the dominant empirical connections between research processes (Supplementary material). More broadly, there is a larger proportion of knowledge being generated on natural systems compared to social systems (Figure 6; Figure 7; Figure 8).

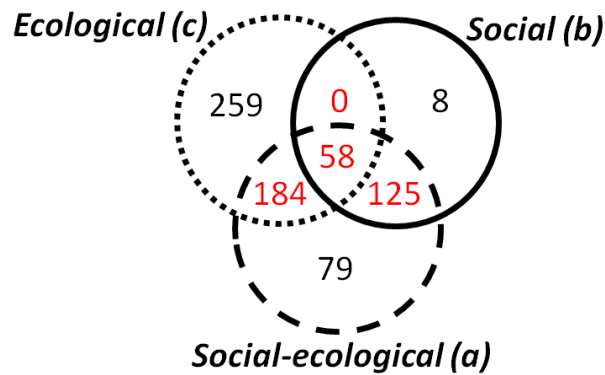


Figure 6. Total-N of singular articles broadly classified into domains by the singular or multiple processes focused on. Each article is only classified once, with a total-N=713. The articles with multiple processes outside of a single domain are highlighted in red, and further analyzed in Figure 7. Intra-domain connectivity is further analyzed in Figure 8 and matched with (a), (b), (c) labels represented by the different circular patterns of each domain in this figure.

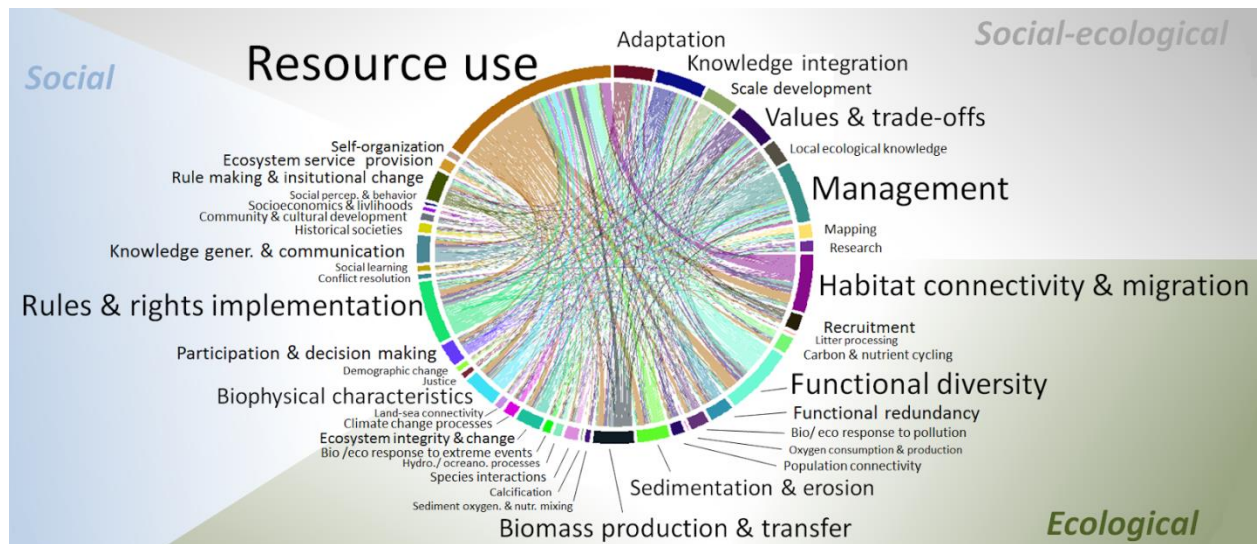


Figure 7. This figure presents a visualization of current multi-disciplinary or inter-disciplinary research between the domains including social, ecological and social-ecological processes. Only articles that examine at least two different tropical marine system processes in different research domains are included, which are the highlighted red articles in Figure 6. The figure is grounded on the quantitative analysis of two aspects, indicating two broad themes: (1) The proportion of the research focus that each process receives within multi- or inter-disciplinary research is shown. This is visualized by the font size and the size of the colored segment of the circle. (2) Process connectivity is shown. A connection between processes in this graph means that both processes were examined in the same article. This visualization can be interpreted as a representation of how current research is examining interconnected social-ecological systems. The actual values of connectivity between specific processes are attached as a data matrix in the Supplementary Material.

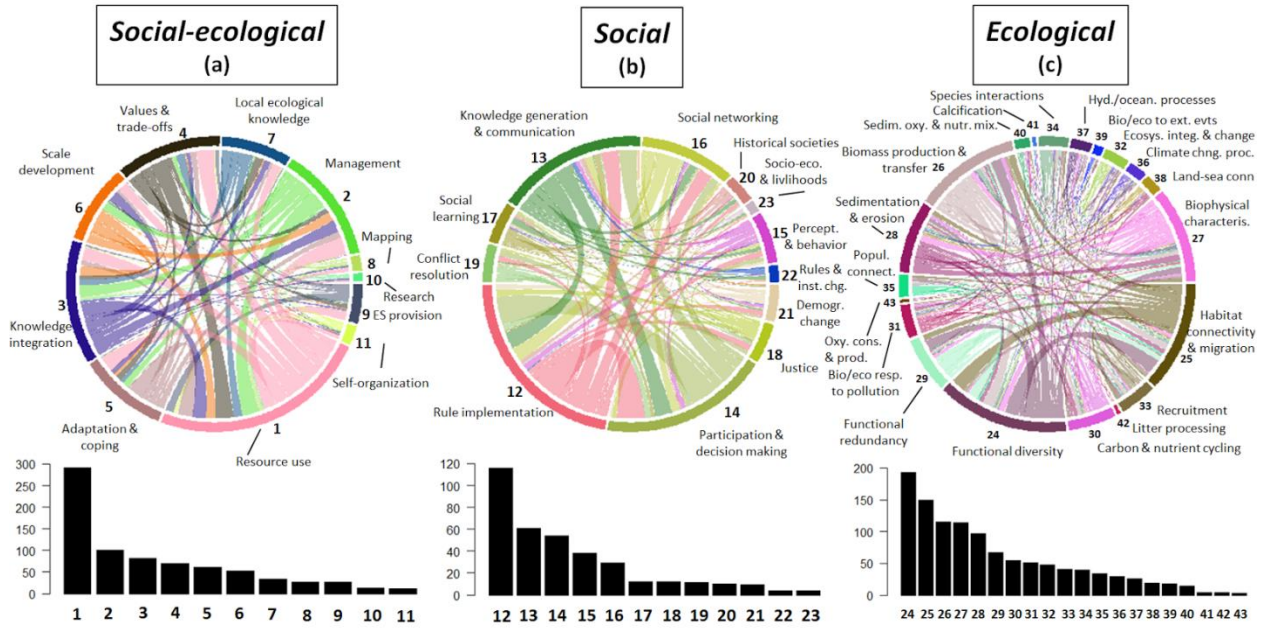


Figure 8. Intra-domain connectivity of processes researched. Total-N of each process regardless of connectivity shown subsequently in the bar charts with number labeled references. Domains include social-ecological, social and ecological processes. The figure is grounded on the quantitative analysis of two aspects, indicating two broad themes: (1) The proportion of the research focus that each process receives within intra-disciplinary research is shown. This is indicated by the size or proportion the process has in the circle segment. (2) Process connectivity is shown. A connection between processes in this graph means that both processes were examined in the same article.

Knowledge types and terminology

The statistical distribution of meaningful terminology across articles indicates a wide degree of terms associated with scale (i.e. spatial) heterogeneity in the natural sciences. This is indicated on the Y-axis (Figure 9). In addition, natural science terminology indicates a wider range of disciplinary heterogeneity compared to the social sciences. This is indicated on the X-axis. Distinctly separate article groups based on common terminology are indicated by colored word clusters (Figure 9). There is a higher diversity of terminology in the natural sciences compared to the social sciences. However, the natural sciences associate almost exclusively with system knowledge generation, although with more distinct disciplinary agendas (indicated by grey dots in Figure 9). The social sciences generate a more robust profile of all three knowledge types (as indicated by grey crosses and dark diamonds). However, the social sciences use more homogenous terminology to generate this knowledge. More generally, there are few similarities in the dominant terminology used between the social and natural sciences. This analysis shows the dominant role the social sciences play in conveying system knowledge through target and transformative knowledge.

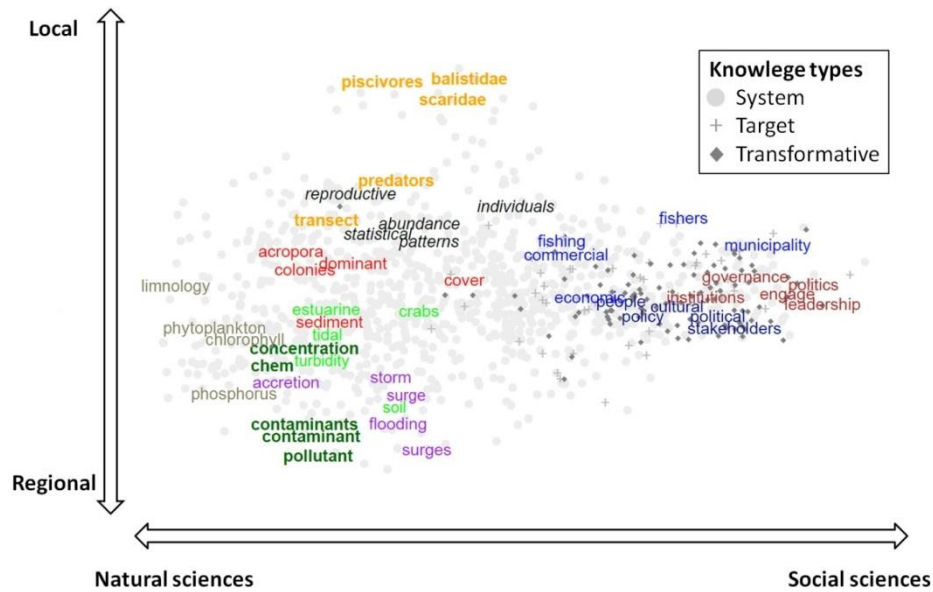


Figure 9. Statistically clustered distribution of terminology and knowledge types in articles. Only words with the highest frequency in each cluster are shown. Colored clusters are distinguished statistically by the recurrence of common words in their articles, and interpreted as thematic groups of research articles. The distance between word clusters indicates the similarity (close together) or dissimilarity (far away) of the common terminology used in articles. The X-axis is interpreted as a gradient from the natural to the social sciences. The Y-axis is interpreted as a gradient from the local (individual) to regional (societal) level. The knowledge types generated within all articles are plotted against the clustered article groups with shaded symbols (circle = system knowledge; cross= target knowledge; diamond= transformative knowledge). The relationship between research clusters and the knowledge types they generate can be examined. Articles were corrected for length in the word usage analysis. Knowledge types were assessed by indicator words (Abson et al., 2014).

Discussion

Distribution of research across regions

Our analysis shows that the regional focus of research is unevenly distributed. This can be partly explained by the recognition that each region contains different contexts of interest for different disciplines and research questions. There is a clear emphasis on specific ecosystem types, problems and system processes related to regions they occur in, which we discuss in the following sections. From an organizational perspective, deciding on a location to conduct empirical research can be potentially biased by travel logistics, language barriers, historical relations, funding parameters, infrastructure availability and relationships with partner institutions or path dependencies (Luks and Siebenhuner 2007, Pimm 2007, Fisher et al. 2010). Although these barriers exist, certain regions remain minimally researched despite substantial social and ecological importance. In particular, we draw attention to Western and Middle Africa. A similar pattern of regional disparity has been observed within coastal ecosystem services research (Liquete et al. 2013). In contrast, Australia and Southeast Asia demonstrate a large proportion of all tropical marine research and exhibit wide research agendas. In Australia, this may be explained by funding

availability and the number of research-based universities and organizations compared to other tropical regions (Costello and Zumla 2000). In Southeast Asia, we observe a relatively equal balance of research in the social and natural sciences compared to other regions dominated by the natural sciences. This may in part be explained by social science interest in societal connections and dependence on local marine and coastal resource use in the region (Pomeroy 2012, Richards and Friess 2015). For the natural sciences, Southeast Asia contains vast coral reef ecosystems with high measures of biodiversity and conservation priorities (Fisher et al. 2010). We discuss the emphasis on coral reefs compared to other ecosystems in the following section.

Ecosystem focus

Research on coral reefs dominates the research focus. Reflection is warranted on whether the biophysical, sociocultural and economic values of coral reefs are proportional to such a dominant focus when compared to the values of, and threats to, other ecosystems demonstrated by existing research (Moberg and Rönnbäck 2003, Orth et al. 2006, Knowlton and Jackson 2008, Rocha et al. 2014). We do not suggest lessening the focus on coral reefs, but rather examining why other ecosystems have received less focus and how a future agenda would justify and improve a problem-driven ecosystem focus. Disproportionate ecosystem focus may be related to current debates on the relative emphasis of biodiversity in contrast to the societal importance such as livelihood dependence when justifying scientific effort on certain ecosystems such as coral reefs (Cinner 2014). In particular, debate continues on the trade-offs and potential synergies between ecocentric and anthropocentric justifications for research on conservation (Fisher et al. 2010, Mace 2014, Wolff 2015). This debate likely originates from differences in problem orientation and how research results are directed to inform potential solutions from different disciplinary or political agendas (Miller et al. 2011).

A stronger focus on mangroves, seagrasses, estuaries, wetlands and lagoons seems necessary as knowledge from these habitats is proportionally lower. Knowledge gaps on ecosystems provide considerable opportunity to better understand how social-ecological relationships evolve and diversify between them. In particular, how unique ecosystem functions and biophysical conditions respond to and shape resource use patterns as well as institutions and human behavior (Pollnac et al. 2010, Arkema et al. 2015, Richards and Friess 2015). In contrast, the impacts from anthropogenic activities such as pollution and climate change vary substantially between different ecosystems and the regions they are located in (Roff and Mumby 2012, Partelow et al. 2015). These distinctions often relate to their resilience, which may affect how societal adaptations such as conservation can be appropriately planned in response to change (Folke et al. 2010, Graham et al. 2013, Arkema et al. 2015).

Problem-orientation

A large proportion of all research lacks a stated problem orientation, and there are clear differences between the social and natural sciences. The natural sciences have a much lower proportion of articles with a stated problem orientation. This does not reflect on the relative importance of the social or natural sciences for a sustainability agenda. However, this may in some part reflect the differences in the need to orient scientific knowledge around particular discourses or epistemologies shaped by disciplinary-driven research agendas (Miller et al. 2008). Among other reasons, funding requirements and publishing norms likely play a considerable role in shaping how science is communicated and how the knowledge is conveyed in academic literature (Schoolman et al. 2012). While the orientation of research to disciplinary

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agendas is essential, building momentum towards a sustainability agenda would aim to additionally orient results and their implications to relevant problems for humanity (Jerneck et al. 2010). Many different disciplines can, and need to contribute to this advancement (Spangenberg 2011). We expand on this proposition below, and attempt to clarify how this could be done considering the diversity of disciplinary contributions. We follow by discussing how gaps and trends in the current literature reflect the perspectives on and efforts to address current challenges.

We propose that the primary purpose of a sustainability agenda be driven by understanding problems within their relevant context across all scientific domains. Statements of problem orientation should be transparently communicated within scholarly publications with clear linkages to how the research relates to or informs system, target or transformative knowledge (Brandt et al. 2013, Partelow and Winkler 2016). Considering this proposition, it should be stated that not all research needs to be, or should be situated within a discourse of how results can be practically applied or what the transformative contributions may be. In addition, not all research warrants an interdisciplinary research design. However, it is envisioned that a sustainability agenda should structure otherwise unconnected or isolated knowledge to a common purpose, through linking the type of knowledge generated to a problem orientation.

Beyond the recognition that certain problems simply exist in certain regions, further examination is needed into the variation of drivers, impacts and responses related to them as they occur across diverse contexts (Schlüter et al. 2013). Stating a problem orientation may assist in linking all research to a common purpose and context, and attempt to make science more effective in practice by identifying such context specific variations. Conservation is the dominant problem orientation in current agendas; it provides an example for further critical discussion below.

Conservation is a dominant focus within current agendas. However, this does not indicate congruence between how different disciplinary agendas inform conservation practice. In particular, there remain contrasting perspectives on how to reconcile the support of livelihoods depending on marine and coastal resources with the need to maintain ecosystem functioning and diversity (Miller et al. 2011, Fox et al. 2012, Wolff 2015). From a sustainability perspective, the central purpose of conservation would be to benefit the continued well-being of humanity. The underlying question then becomes, who benefits from conservation (Mace 2014)? Then secondly, what are the different positions that current scientific agendas support (Chan et al. 2007)? It can be generally assumed that conservation practice should meet and be implemented in accordance with normative societal goals (Miller et al. 2011, Mace 2014). Discourses on inter- and intra-generational equity as well as distributional and procedural justice provide useful conceptual frameworks to orient such discussions (Gibson 2006, Loos et al. 2014). However, societal perspectives on how to implement conservation may differ substantially across contexts. They may conflict with scientific knowledge on what influences effective conservation more generally (Pollnac et al. 2010, Edgar et al. 2014, Partelow et al. 2015).

Level and scales

Within each scale, research occurs at multiple levels. However the proportion of research at each level is not equal between scales. Ecosystem and spatial scale research at the regional and global level is disproportionately low (Glaser and Glaeser 2014, Cavender-bares et al. 2015). This likely infers that research on the connectivity between regional and global ecosystem and spatial scales is also lacking. A ~7.5% focus on global level processes indicates significantly less scientific effort on sustainability challenges that originate at and across multiple levels. Further research is needed to examine social-ecological systems are interdependent across multiple levels and scales, and the existence of

teleconnections (Scholes et al. 2013). In particular, further focus on institutions and governance should consider how social system scales influence or respond to change across levels (Ostrom 2005, Epstein et al. 2015). However, we recognize that regional and global level research often requires more capacity to conduct, including logistically intensive collaborative endeavors. We discuss the justification for level and scale focus in the Supplementary Material, and now discuss how the system process focus provides a more detailed look into gaps and trends in the research focus.

System process focus in the social and natural sciences

Our analysis shows clear distinctions in the heterogeneity of research between disciplines in the literature. The natural sciences focus on a wider variety of system processes, including how those processes are researched in combination. For comparison, the social sciences are more homogeneous in the system processes they examine. Three aspects can be discussed. First, the most evident commonality in the context of social science research is human beings, which all social sciences address some aspect of. Nearly all social settings are characterized by the same features such as culture, mental models, networks, economies, institutions, rules and decision-making processes, among many others (Ostrom 2005, Castree et al. 2014, Stojanovic et al. 2016). Second, the natural sciences analyze a wide range of different organisms, which suggests that they are characterized by a larger diversity of features. However, this does not reflect on the immense diversity in which these common features likely exist in diverse contexts and contain nested dynamic processes.

Third, the understanding of social system diversity may be less advanced than for natural systems due to less scientific effort given to them over time. As a result, social conceptual frameworks may be less developed (Binder et al. 2013, McGinnis and Ostrom 2014, Stojanovic et al. 2016). There is simply a larger amount of published literature and scientific effort from the natural sciences. Although the social sciences have slightly increased their relative contributions over time, funding availability and publishing norms seem to have favored natural science outputs in this analysis. This does not infer advancing the social sciences over the natural sciences or aim to exacerbate a competitive atmosphere. We suggest a more general shift to rethink how research programs can become more inclusive and collaborative in order to develop problem driven research agendas that can generate the relevant knowledge needed to advance sustainability.

Knowledge types and terminology

Our analysis shows clear epistemological differences in the knowledge generation agendas in tropical marine science, reflecting what can and should be known to advance sustainability. The field has contributed most substantially to system knowledge, the objective descriptions and analysis of components and processes. Target knowledge, the understanding of more subjective preferences, values and opinions among relevant stakeholders, is less studied. A comprehensive sustainability agenda should aggregate and link together the full spectrum of knowledge around relevant problems within and between disciplines, including transformative knowledge on how to better apply scientific knowledge in decision-making, education and policy. We reflect on a few key points. System knowledge in the natural sciences needs to improve problem orientation. Target knowledge in the social sciences needs consideration for more diverse and non-western perspectives on tropical coasts (Drew 2005, Hornidge 2012, Poe et al. 2014). Transformative knowledge is lacking and is needed to inform social-ecological change at multiple levels and scales (Richmond et al. 2007, Knight et al. 2008). In combination, the social and natural sciences need

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unified and urgent efforts to integrate their contributions as they currently exist across the knowledge spectrum, particularly in conservation (Chan et al. 2007, Gruby et al. 2015).

Mechanisms to bridge communication and establish collaboration will play an integral role in structuring future agendas. Progression towards common languages through conceptual frameworks will assist data comparability and communication as well as the identification of gaps (McGinnis and Ostrom 2014, Partelow 2016). However, although many conceptual frameworks exist, orientating and integrating the knowledge between them is a barrier (Binder et al. 2013, Partelow and Winkler 2016). Furthermore, the development of operational procedures to make conceptual frameworks useful for natural resource management or conservation practice is lacking (Leslie et al. 2015, Partelow 2015).

Conclusion

This analysis attempts to provide a guidepost for advancing a sustainability agenda for tropical marine science. A few key points can be mentioned. Research can better address sustainability challenges when clearly linked to a stated problem orientation in both the social and natural sciences. A comprehensive agenda would necessarily propose disciplinary diversity to address problems and knowledge gaps between ecosystems and contexts. Knowledge gaps remain at numerous levels and scales, including the interactions between them, particularly at the regional and global level. There is a distinct divide in how the social and natural sciences conduct and communicate their published research as connected to other research within and outside their own disciplines and agendas. As a result, a strong dissimilarity exists in the generation of knowledge and use of terminology across many disciplines. Common languages and conceptual frameworks can aid these challenges but need to be further developed to advance the synthesis and analysis of knowledge on interconnected social-ecological systems. Moving forward, progressing a sustainability agenda will involve further discussion and critical debate between all academic and non-academic stakeholders involved on how to integrate diverse types of knowledge to better inform societal problem solving in the appropriate contexts.

Research 2: Co-evolving 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 non-specialists 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) Co-evolving 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 co-production, 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

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. 2015b). Research in social-ecological systems (SES) is evolving to reflect this recognition, proposing inter- and trans-disciplinary 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 towards 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 (Frey and Cox 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) Co-evolving 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 co-evolution between the fundamental ambitions of both communities. This article's structure, including the four themes mentioned above, is outlined below:

- A review of key literature on the SESF and sustainability science (Section 1.1 & 1.2).
- Four explicit co-benefits from interlinking the two research communities of the SESF and sustainability science (Section 2; Table 1).
- Guiding questions and considerations for designing research with a co-aligned vision between the SESF and sustainability science (Section 3; Table 2).
- Highlighting key challenges for the SESF, sustainability science and SES research (Section 4)

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 (Figure 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).

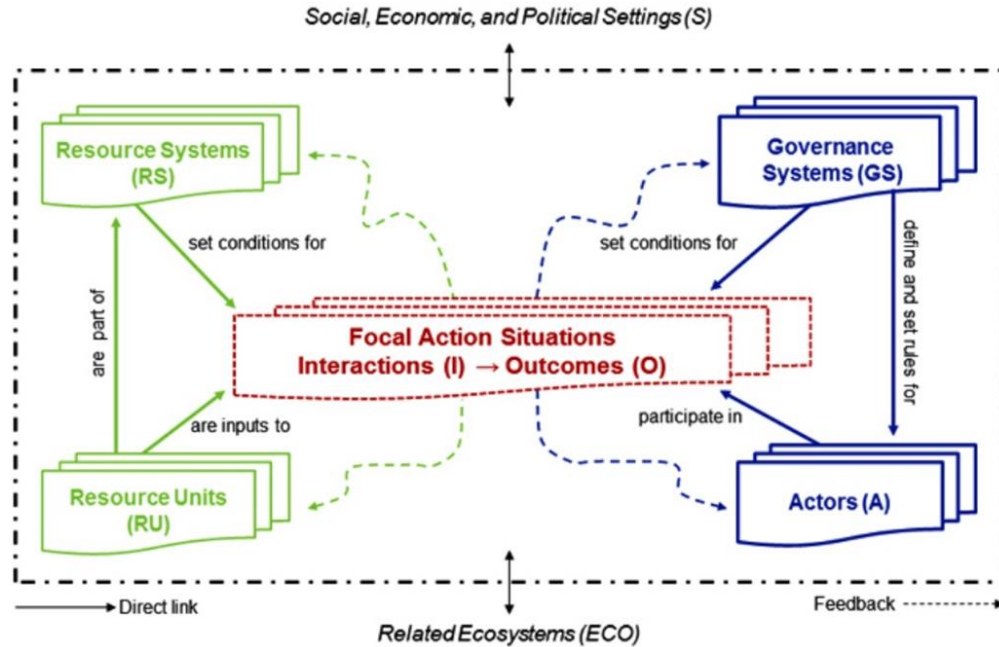


Figure 1. The diagnostic social-ecological system (SES) framework. Four multi-level first-tier variables are presented in each of the four corners and the template for assessing their interactions and outcomes is visualized. Adopted from (McGinnis and Ostrom 2014).

The framework's structure (Figures 1 & 2) is organized in multi-level tiers of nested sub-systems 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 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).

Table 1. Nested components and sub-systems 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)	GS1- Government organizations
RS2- Clarity of system boundaries	GS2- Nongovernment organizations
RS3- Size of resource system	GS3- Network structure
RS4- Human-constructed facilities	GS4- Property-rights systems
RS5- Productivity of system	GS5- Operational-choice rules
RS6- Equilibrium properties	GS6- Collective-choice rules
RS7- Predictability of system dynamics	GS7- Constitutional-choice rules
RS8- Storage characteristics	

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RS9- Location	GS8- Monitoring and sanctioning rules
Resource Units (RU) 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	Actors (A) 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
Interactions (I) 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	Outcomes (O) O1- Social performance measures O2- Ecological performance measures O3- Externalities to other SESs
Ecological Rules ER1- Physical rules. ER2- Chemical rules. ER3- Biological rules.	
Related Ecosystems (ECO) ECO1- Climate patterns ECO2- Pollution patterns ECO3- Flows into and out of SES	

The second tier components of the SESF can guide primary and secondary data collection within a contextual SES case (Table 1). 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 sub-sequent 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, 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 trans-disciplinary collaborations have increased significantly since the foundations of sustainability science began in the early 2000's (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 co-production 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, Kerkhoff 2013, Wiek et al. 2014).

Knowledge types are used in sustainability science for organizing knowledge generation and research outputs towards fostering sustainability transitions (Hadorn et al. 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 towards 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 towards 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. 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) Co-evolving SES knowledge types, (2) Guiding

primary research and assessing sustainability, (3) Building a boundary object for transdisciplinary sustainability science, and (4) Facilitating comparative analysis.

Table 2. Four key co-benefits from integrating the SESF and sustainability science.

Co-benefits	SESF → Sustainability science	Sustainability science → SESF	References
1) Co-evolving SES knowledge types	<ul style="list-style-type: none"> Structured ontology of SES components Theoretical background/ support of the SES components and their interlinkages 	<ul style="list-style-type: none"> 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, Frey and Cox 2015)
2) Guiding primary research and assessing sustainability	<ul style="list-style-type: none"> Diagnostic framework with explicit components for guiding primary data collection Analytical foundation for assessing component interactions through action situations 	<ul style="list-style-type: none"> Agenda for stakeholder engagement, knowledge co-production and bridging science-society gap Defined sustainability assessment criteria (e.g. inter- & intra-generational equity, livelihood sufficiency & opportunity, resource maintenance & efficiency) and analytical tools (e.g. multi-criteria analysis, environmental impact assessment, life cycle assessment) 	(Gibson 2006, Ness et al. 2007, Ostrom 2009, 2011, Ostrom and Cox 2010, Mauser et al. 2013, van Kerkhoff 2014, Sala et al. 2015)
3) Developing a transdisciplinary boundary object	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Platform for SES theory development and testing Database development 	<ul style="list-style-type: none"> Theoretical and practical approaches for transformative change processes and sustainability transitions (e.g. Mode 1 & 2 transdisciplinarity) 	(Lang et al. 2012, Frey and Rusch 2013, ASU CSID 2014, SESMAD 2014, Delgado-Serrano and Andres Ramos 2015, Scholz and Steiner 2015a)

Co-evolving 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 towards 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 multi-disciplinary 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 (Table 1; RS5) may be explicitly system knowledge, whereas actor leadership (Table 1; 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 (Table 1; A7) into understanding SES functionality may be explicitly system knowledge, whereas the deliberation between stakeholders (Table 1; I3) within the theoretical frame of an action situation could be target knowledge in sustainability science. For knowledge co-production 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 co-generate a useful interdisciplinary boundary object. Reciprocally, where sustainability science lacks a multi-disciplinary 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 (Figure 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 non-transferable (Liu et al. 2007a). Despite this recognition, a lack of clear sustainability outcome criteria (Table 1; 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 co-evolves 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 co-production (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 co-production 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 2015b).

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, Frey and Cox 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 co-managed 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 is 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 Boeijs 2005). Primary data collected into the SESF can then later be used as transformed secondary data that is 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 sub-systems structured through specific nested relationships (Frey and Cox 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, Frey and Cox 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 2014a), 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 co-evolved SES research

Designing SES research that achieves the presented co-benefits in Table 2 needs to consider the perspectives of both aspects and how they can feasibly be incorporated. In Table 3 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.

Table 3. Guiding questions and considerations for framing sustainability science research in conjunction with operationalizing the diagnostic SES framework. Adapted in part from Hinkel et al. (2015), Jerneck et al. (2010) and Wiek and Iwaniec (2013).

(1) Framing research			
Steps	SESF perspectives	↔ Guiding questions and considerations ↔	Sustainability science perspectives
a)	Explore multi-disciplinary 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?

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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 multi-disciplinary 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 co-production?
g)	Outcomes,	What are the SES outcomes? Why?	What was achieved?

	implementation and re-assessment	What can be changed or made adaptive in the system? How?	How is the research shared and communicated? What is the learning orientation?
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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. 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, 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. Secondly, 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 (Frey and Cox 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 2014a). 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 Section 2.4, designing primary research to gather data into the SESF's components is 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, Delgado-Serrano and Andres Ramos 2015, Hinkel et al. 2015, Leslie et al. 2015, Partelow 2015).

Co-evolving 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 sub-communities 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 towards 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 2) including: (1) Co-evolving 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 trans-disciplinary collaborations. Co-developing 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 were presented in Table 3. From a broader

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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 towards advancing our functional understanding of SES and the practical solutions that can be developed from this knowledge.

Research 3: Interlinking ecosystem services and Ostrom's framework through orientation in sustainability research

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Abstract

Structuring integrated social-ecological systems (SES) research remains a core challenge for achieving sustainability. Numerous concepts and frameworks exist but there is a lack of mutual learning and orientation of knowledge between them. In this article, we focus on two approaches in particular: the ecosystem services (ES) concept and Elinor Ostrom's diagnostic SES framework (SESF). We analyze the strengths and weaknesses of each as well as discuss their potential for mutual learning. We use knowledge types in sustainability research as a boundary object to compare the contributions of each approach. Sustainability research is conceptualized as a multi-step knowledge generation process that includes system, target and transformative knowledge. A case study of the Southern California Spiny Lobster Fishery is used to comparatively demonstrate how each approach contributes a different lens and knowledge when applied to the same case. We draw on this case example in our discussion to highlight potential interlinkages and areas for mutual learning. We intend for this analysis to facilitate a broader discussion that can further integrate SES research across its diverse communities.

Introduction

Social-ecological systems (SES) thinking represents the coupled interactions and outcomes between human and natural systems (Walker and Salt 2006, Liu et al. 2007, Ostrom 2009). Researchers have developed a variety of concepts and frameworks to help analyze, describe, and communicate SES components and processes (Newell et al. 2005, Binder et al. 2013). Notable developments include the ecosystem services (ES) concept and the diagnostic social-ecological systems framework (SESF). Although both are used in SES research, they lack common structures to orient and compare knowledge between them (Ostrom 2009, Mollinga 2010, Hinkel et al. 2014).

Integrating knowledge between multiple concepts and frameworks is a challenge for building academic consensus that can inform sustainability (Spangenberg 2011, Fischer et al. 2015, Ruppert-Winkel et al. 2015). However, much of the SES literature continues to generate knowledge that is uncoupled from other research efforts. Orienting the contributions within SES research is difficult when knowledge cannot be compared or integrated (Newell et al. 2005, Ostrom 2009, Bohensky and Maru 2011). Without structures for knowledge orientation opportunities to co-benefit between SES research efforts are missed (Scholz 2011).

For comparative purposes, we categorize the knowledge SES research can generate into three types that can inform sustainability: (1) *System knowledge* analyzing and describing SES functionality and subsystem processes, (2) *Target knowledge* assessing meaningful goals, visions and pathways for sustainable human well-being and ecosystem functioning, and (3) *Transformative knowledge* for implementing practical solutions (Hadorn et al. 2006, Jerneck et al. 2010, Brandt et al. 2013).

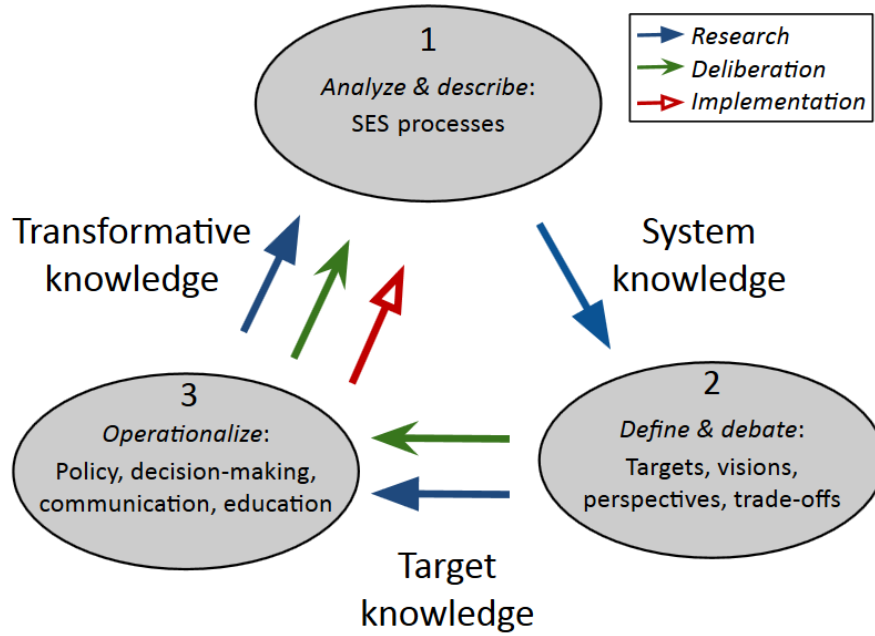


Figure 1. Conceptual interpretation of a circular multi-step knowledge development process for SES research. SES research can generate three knowledge types: (1) *System knowledge* in order to analyze and describe the functionality SES and their subsystem processes, (2) *Target knowledge* to develop meaningful goals, targets and pathways for sustainable human well-being and ecosystem functioning, and (3) *Transformative knowledge* for implementing those goals into practical solutions (Hadorn et al. 2006, Jerneck et al. 2010, Brandt et al. 2013).

The goals of SES research are better achieved when knowledge from different research efforts can inform and advance each other (Fischer et al. 2015, Bull et al. 2016). We use the three knowledge types as a boundary object to orient different SES research contributions (Figure 1). Different combinations of knowledge types will be generated depending on the concept, theory, model, or framework used. However, conducting research that can generate or orient all three knowledge types remains elusive.

Box

System knowledge: Objective knowledge of social-ecological subsystems and components as well as their interactions, functions, processes, and inter-related dynamics. Including aspects in relation to risk, uncertainty, and resilience.

Target knowledge: Subjective perspectives, deliberative and/or experienced knowledge relating to the implications, targets, visions, desired directions, and outcomes for SES. This can include the concepts of human well-being, conservation, justice, ethics, efficiency, and sustainability goals.

Transformative knowledge: Actionable pathways for implementing SES change and/or target knowledge through normative mechanisms such as policy, decision-making, education, communication, participation, and motivation.

SES thinking: Recognition for linked and interdependent natural and social system dynamics, particularly human dependence on ecosystems and the need to facilitate multi-domain research that engages with non-academic society to achieve sustainability (Fischer et al. 2015).

Boundary object: “Objects which are both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites.” (Star and Griesemer 1989, p.393). See also, (Hertz and Schlüter 2015, p.15).

Ecocentric: Consideration of an “ecological system based on its internal functioning” and diverse values (Binder et al. 2013), where human life is dependent on existing and intact ecosystem functioning and biodiversity (Mace 2014).

Anthropocentric: Consideration of an ecological system based on its utility for humans (Binder et al. 2013), focused on maintaining the ecological functioning that provides human value.

In this article, we focus our analysis on comparing and facilitating mutual learning between the ecosystem services (ES) concept (Millennium Ecosystem Assessment 2005, Haines-Young and Potschin 2012, Díaz et al. 2015) and Elinor Ostrom’s diagnostic SES framework (SESF) (Ostrom 2007, 2009, McGinnis and Ostrom 2014). After an overview of the ES concept and the SESF, we orient the contributions of ES and the SESF in facilitating system, target, and transformative knowledge. Next, we compare the two approaches in a case study of the Southern California Spiny Lobster Fishery. Last, we provide a synthesis of both approaches and analyze the potential for mutual learning and compatibilities between them. Definitions are provided above for reference to terminology used in this article.

Overview

Researchers have begun to explore linkages between ES and the SESF in recent studies. Ban et al. (2015) demonstrate how the co-consideration of multiple ES in an analysis structured with the SESF can help to better understand complexities in a large-scale marine system. Grêt-Regamey et al. (2014) suggest incorporating Ostrom's tiered structure of multi-level interactions to map ES assessments. In addition, others have used the SESF to diagnose Payment for Ecosystem Services (PES) schemes (e.g. Addison and Greiner 2015, Bennett and Gosnell 2015). Despite preliminary efforts, considerable gaps exist for exploring how the ES concept and the SESF can be used in an integrated analysis. As separate entities, they have been considered as potential boundary objects within SES research (Abson et al. 2014, Hertz and Schlüter 2015, Schleyer et al. 2015).

Ecosystem services

Since the publication of the Millennium Ecosystem Assessment in 2005, ES research has exponentially expanded through broad usage in ecology and economics (Seppelt et al. 2011, Orenstein 2013, Chaudhary et al. 2015, Luederitz et al. 2015). The concept embodies an ecocentric framing in the sense that humans depend on the services nature provides (Mace 2014). One of the latest conceptualizations, the ES cascade (Figure 2), shows a multi-step process describing the supply of ES to humans and the reciprocal effects of humans on ecosystems through a governance feedback loop (Haines-Young and Potschin 2010, 2012). The ES cascade is widely discussed (e.g. Spangenberg et al. 2014) and has been further developed (e.g. Martín-López et al. 2014). However, current research largely focuses on the directional flow of ES provided to humans, while human actions affecting ecosystems have received less attention (Davies et al. 2015, Comberti et al. 2015). Additionally, governance mechanisms and institutions influencing the provision and appropriation of ES is sparse (Nassl and Löffler 2015, Primmer et al. 2015).

Numerous ways of utilizing the ES concept have evolved in the literature. The economic approach is the most widely-recognized, including e.g. the TEEB report (2010) and Payment for ES (PES) schemes, which mostly try to internalize external effects. However, ES research is manifold and thus it is shortsighted to limit the potential of the concept to a purely economic perspective (Schröter and van Oudenhoven 2016). The ES concept can serve as a communication tool to engage the science-policy-society interface (Everard 2015, Díaz et al. 2015, Bull et al. 2016).

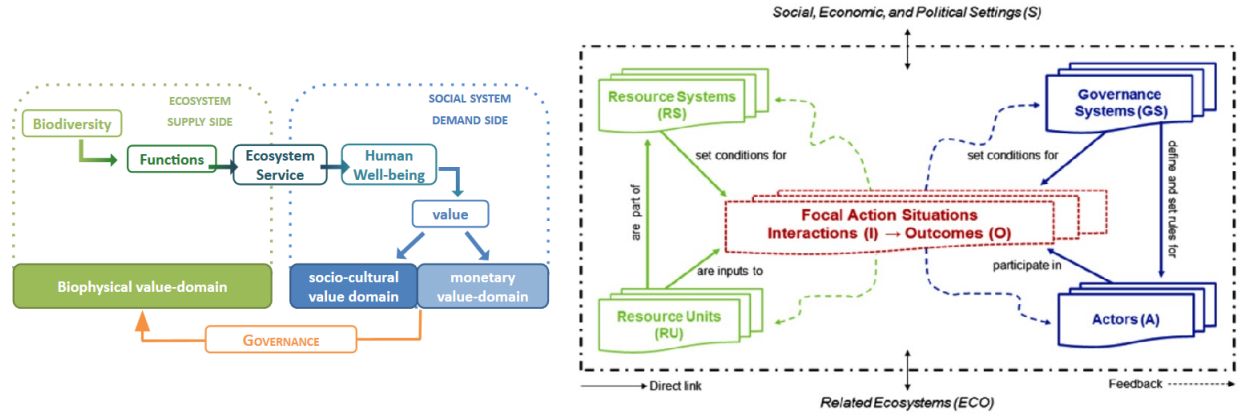


Figure 2. Side by side comparison of the ecosystem services (ES) cascade (left; Martín-López et al. 2014) and diagnostic SES framework (SESF) (right; McGinnis and Ostrom 2014). Both conceptual frameworks focus on the interactive processes between social (blue) and ecological (green) subsystems. There are more specific components that are nested within the categories of each, but they are not shown here.

Ostrom's diagnostic SES framework

The SESF is a diagnostic checklist of potential interacting SES components with multi-tiered nested relationships to each other (Ostrom 2007, 2009, Frey and Cox 2015, Hinkel et al. 2015). The framework is tailored for, but not limited to, understanding collective action in a shared common-pool resource system. The framework's ontology is organized into four subsystems: the *Resource System*, *Resource Units*, *Governance* and *Actors* (Figure 2). Externally, these four subsystems interact with the *Social, Economic and Political settings*, and *Related Ecosystems*. *Action situations* occur when components in the SES create *Interactions* that shape *Outcomes* (Ostrom 2007, 2009). Action situations originate from the Institutional Analysis & Development (IAD) framework, where sets of criteria and rules theoretically frame social-institutional processes to distill individual and group decision making (Ostrom 2005, McGinnis and Ostrom 2014). SES can have polycentric interactions, with multiple action situations occurring simultaneously (McGinnis 2011a).

The SESF is envisioned to serve two reinforcing purposes. First, to contextually diagnose complex SES cases through a common and structured language. Second, to generate comparable data that can use large-N case comparisons to explore commonalities across case studies for theory generation and policy. The framework does not provide a methodology for empirical data collection, but rather a common structure to orient collected data into a comparable SES language. Guidelines for operationalizing research with the SESF and further developing the framework for use in specific sectors has been suggested (e.g. Delgado-Serrano and Andres Ramos 2015, Leslie et al. 2015, Marshall 2015, Partelow 2015).

Orienting knowledge in sustainability research

System knowledge

System knowledge is the “classic” knowledge produced by science. This is objective research for understanding system components, functional processes, and inter-related dynamics as a foundational base. The development of system knowledge is often a descriptive methodological and analytical process that does not require the development of normative direction, communication or practical engagement beyond the discourse of science.

There is a vast body of literature that has generated system knowledge in ES research. Although the ES concept has always stressed the human-nature relationship, so far, most research focuses on single or small set of ES. The majority of used methods originate from the fields of ecology and economics to identify and describe the ES (Seppelt et al. 2011). Such technocratic approaches privilege easily quantifiable ES such as crop provisions or flood protection (Turnhout et al. 2013, Reyers et al. 2013). When limited by easily quantifiable ES, the approach produces primarily system knowledge. In contrast, less tangible ES are often neglected due to difficulties in interpreting data through measureable indicators (Milcu et al. 2013, Fagerholm et al. 2016). Nevertheless, scientific-technical research plays a crucial role for the governance of ecosystems and their ES (Primmer et al. 2015). For example, system knowledge that identifies trade-offs between different ES and their effects on ecosystems are important for practitioners to make informed decisions (de Groot et al. 2010).

The primary strength of the SESF is generating system knowledge through a diagnostic approach. This can be compared to medical practice. For example, when a physician diagnoses the ill-health of a patient by identifying the components and processes of the body that may be causing the problem, typically through indicators such as body temperature and blood pressure. The SESF currently has more than 50 components and interactions, that act as a checklist, to diagnose sustainability problems in a SES (McGinnis and Ostrom 2014). Using the framework involves gathering data that can describe the characteristics of each component, if present, and how they interact and shape system processes. For some components, indicators may need to be developed that contextually represent the component in a system. The SESF suggests components that might be important for system outcomes e.g. property rights. However, it does not claim that a particular state or status of a component leads to certain outcomes. Thus, the framework does not incorporate theory to link system conditions to outcomes, but provides a common structure of components that can be used to generate theory when system conditions and outcomes are identified (Ostrom and Cox 2010). The usefulness of the framework will vary depending on the depth of data gathered to describe the system conditions through its suggested components and processes. Adding components and processes to the SESF is likely necessary through further empirical investigations that can identify the relationships between new and existing components

in different contexts (Frey and Cox 2015). Overall, facilitating structured system knowledge with consideration for broad social and ecological components is a strength of the framework.

Target knowledge

SES research is suitably positioned to move beyond the generation of system knowledge and to transition research into a more active role in society (Fischer et al. 2015). This transition will generate target knowledge. Building on system knowledge, target knowledge captures the subjective perceptions, goals, and visions that shape a normative direction. This can include the concepts of ethics, morality, and justice. Without this knowledge, there is the possibility that decision-makers hold a great amount of system knowledge, but lack the ability to translate that knowledge into socially relevant and accepted decisions. Informing decision-making and planning processes with target knowledge aids the inclusion of stakeholder perspectives and increases the acceptance of (sometimes unpopular) measures (Scholz and Steiner 2015a). Robust and contextually relevant target knowledge is important for successful adaptive governance approaches (Gadgil et al. 1993) and for long-lasting solutions (Millennium Ecosystem Assessment 2005).

The generation of knowledge on diverse societal perspectives on ES is less developed compared to ecological aspects (Davies et al. 2015). However, ES researchers have realized that sustainable solutions cannot be solely based on system knowledge, but that there is high relevance for the inclusion of norms, values and subject perspectives relating to ES demand (Jordan and Russel 2014, Görg et al. 2014, Primmer et al. 2015). Specifically the ES concept attributes values to biophysical, socio-cultural and monetary value domains (Figure 2). Cultural ES recognize the social and relational values gained from ecosystems, e.g. sense of place or recreation, allowing subjectivity to enter ES assessments and valuations (Chan et al. 2012b, 2016, Daniel et al. 2012). In addition, social-cultural valuation is often conducted through participatory methods (Scholte et al. 2015, Winkler and Nicholas 2016) (Figure 3). Local level research projects are well situated for assessing target knowledge due to the more iterative nature of the process between the producers and users of ES knowledge (Haines-Young and Potschin 2014, Förster et al. 2015).

The SESF has numerous components, including action situations, that facilitate target knowledge generation. However the SESF is more diagnostic and analytical than value oriented (Figure 3). The diagnosis of action situations identifies social-ecological processes, almost entirely driven from the social system side in the SESF such as deliberation, investments, self-organization, lobbying and information sharing (McGinnis and Ostrom 2014). Understanding action situations is in part dependent on target knowledge, why stakeholders make decisions based on their goals and values. There are two types of action situations: 1) an appropriation action situation, where actors face a collective action challenge to avoid overuse of a resource, good or service; and 2) a provisioning action situation, where actors face a collective action challenge to provide, maintain or create a resource, good or service (Hinkel et al. 2015). Either situation could be influenced by numerous actor characteristics that should be acknowledged in a diagnosis. Many diagnostic components of the SESF nested in the 1st tier Actor subsystem facilitate target knowledge. These include social norms/ capital, mental models/ knowledge of SES and leadership, among others.

Individual and community values as well as perceptions towards society and the environment will be understood through conducting descriptive research on such components.

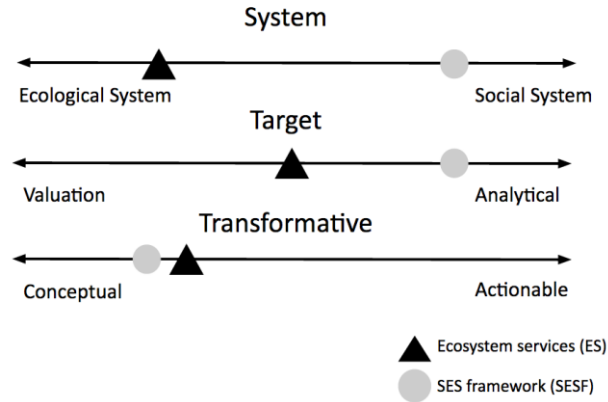


Figure 3. Conceptual orientation of both approaches showing their generalized contributions to generating each type of knowledge. Each approach is crudely placed on the scale of each knowledge type as an interpretation of their relationship.

Transformative knowledge

Transformative knowledge informs contextually relevant change pathways towards a desired (target) SES state (Jerneck et al. 2010, Brandt et al. 2013, Abson et al. 2014). It is often generated in a transdisciplinary setting, incorporating multiple academic domains and societal perspectives in the research process (Scholz and Steiner 2015). Transformative knowledge results from the coupled analysis of system and target knowledge. In sustainability science, this aims to transition academic contributions towards implementing practical solutions for society. A vision for SES research is to progress the ambitions of sustainability science (Bodin and Crona 2009, Scholz and Steiner 2015, Schoon and van der Leeuw 2015). However, research on transformational change remains primarily conceptual, particularly regarding political and socio-cultural engagement.

So far, little research is published on transformative knowledge production within ES. Often it is assumed that existing system knowledge will lead to policy or management decisions that change the unfavorable status of ES, but this has not proven effective (Primmer et al. 2015). However, the ES concept can serve as an approach to motivate innovations (Haines-Young and Potschin 2014). It engages different disciplines and non-academic stakeholders through a neutral language that is not yet “captured” from any interest group (Abson et al. 2014, Davies et al. 2015, Everard 2015). Studies using the concept in real world situations show the usefulness of the approach when working with practitioners and individuals. In the landscape planning context, it helps

various stakeholders to understand different perspectives and demonstrate their own needs (Hauck et al. 2013, Karrasch et al. 2014).

The SESF can facilitate the diagnosis of SES components that can inform transformative knowledge. However, the SESF has not been discussed in the literature or used empirically as a tool for facilitating practical change processes. The primary potential exists to analyze the linkages between system and target knowledge through empirical investigation of the framework's components in a case study. This flow of knowledge towards transformative change (Figure 1) can only be achieved through in-depth knowledge of the case study context. Additionally, there is potential for the SESF to act as a common language or medium for information exchange between researchers, stakeholders and practitioners or policymakers. Also, as a framework for actualizing the ambitions of sustainability science (Partelow 2016). Delgado-Serrano and Ramos (2015) show that the SESF was useful for communicating co-designed SES research and identifying shortcomings of the process at the local level with stakeholders. However, these ambitions remain largely conceptual within the broader literature.

Comparing approaches in a cases study: The Southern California Spiny Lobster Fishery

In this section, we use the Southern California Spiny Lobster Fishery to compare the differences between ES and the SESF (Figure 2) when applied to the same case. We demonstrate how each can facilitate the generation of different knowledge types (Table 1; Table 2). Through using both approaches, the analysis of the lobster fishery is shown through two lenses. Similarities, differences and potential for mutual learning are highlighted below and in the following section.

The Southern California Spiny Lobster Fishery is located in the Pacific Ocean along the southwest United States. The broader area is part of the Southern California coastal marine zone, which extends south across the Mexican border into Baja California. The fishery can be referred to as small-scale and has six stakeholder groups: Commercial (C), Recreational (R), Non-consumptive (N), Environmental (E), Marine science (M) and the Federal Government (G). There are approximately 150 commercial fishing licenses and more than 30,000 recreational (Partelow and Boda 2015). The Spiny lobster (*Panulirus interruptus*) habitat is embedded into a diverse coastal zone, including intertidal, sandy beach, rocky reef and seagrass habitat. The coastal zone includes extensive conservation and habitat restoration efforts, generates revenue from tourism and is an embedded feature of the Southern California cultural identity. A co-management committee was formed between the stakeholder groups, mandated and facilitated by the California Department of Fish and Wildlife to generate sustainable policy recommendations for the state legislature.

Part 2: Context and concepts

The ES approach provides an ecocentric understanding of the fishery. The ecosystem provides a diverse range of goods and services, including lobster and many others. Lobsters are a part of the larger ecological system, playing a role in the maintenance of the ecosystem functions and the biodiversity (Table 1). Lobsters are of central focus for management, but there is a diverse range of other ES also provided to different stakeholders and opportunities for human well-being. Among the different stakeholders, socio-cultural and relational values from the ecosystem and the lobsters are derived both directly and indirectly.

Currently, the ES cascade does not provide a standardized analysis of the functional components of governance. This is the feedback loop connection from the social system to the ecological system (Figure 2). Other ES approaches are needed to allow for a useful social system analysis as its own entity (e.g. Diaz et al. 2015, Chan et al. 2012a). As a result, ecological system knowledge can be primarily facilitated as well as target knowledge on the values and potential trade-offs that exist between stakeholder groups (Table 1). The basic facilitation of identifying social system components beyond values is absent. Transformative knowledge on reconciling trade-offs in policy can be facilitated, but is limited to conceptual interpretation due to a lack of concrete social system components to analyze within the ES cascade.

Table 1. A demonstrative assessment of the Southern California Spiny Lobster Fishery using the ecosystem services concept. Steps of the ES cascade are matched with case study data from the fishery and the knowledge types generated. *Stakeholder groups: commercial (C), recreational (R), non-consumptive (N), environmental (E), marine science (M) and government (G).

Cascade step (Figure 2)	Southern California Spiny Lobster Fishery	Knowledge types
Biodiversity/ ecosystem functions	Species diversity & functional role Carrying capacity Habitat Biomass production Reproduction dynamics	<i>System</i> - understanding of the ecological functioning of the system.
Ecosystem services (based on CICES)	<u>Provisioning</u> Lobsters and fish (food); Kelp (materials); Cooling water for energy production (energy) <u>Regulating & Maintenance</u> Coastal upwelling (Hydrological Cycle); Salinity and temperature fluctuations (Biophysical conditions); Pollution from urban runoff; Micro and regional climate regulation ; Maintaining habitats <u>Cultural</u> Sense of place (Physical and experiential interactions); Recreation; Intellectual and representative interactions Symbolic	<i>System</i> - assessment of existence and status of ecosystem services
Human well-being (based on (Chan et	+/- Material & Employment: Economic opportunity (C)* +/- Activity & identity: Socio-cultural opportunity (R,N)	<i>Target</i> - identification of perceived ES benefits for

Part 2: Context and concepts

al. 2012a)	+/- Existence/ bequest: Environmental health (E) +/- Knowledge: Scientific scrutiny & impact (M) +/- Social capital & cohesion: Public interest & legality (G)	well-being
Governance (based on Díaz et al. 2015)	Decision-making Power Responsibilities Formal (e.g. property rights, treaties, legislation) & informal (social norms & rules) institutions Scale (local to global) Degree of legitimacy, fairness, rights	<i>Target</i> - improvement of deliberation and policy process through recognition of stakeholder values <i>Transformative</i> - policy pathways, communication paths between actors

The SESF diagnosis highlights many components that are influential and interacting in the fishery. The fishery has characteristics of a common-pool resource system, with high rivalry and non-excludability (Partelow and Boda, 2015). The resource has a high economic value and a co-management committee was identified with diverse actors groups to deliberate sustainable policy recommendations (Table 2). The ecological system is described in its basic elements as highly productive and large in size with multiple levels of unclear system boundaries in the social and ecological system. The primary action situations affecting fishery outcomes are deliberation and information sharing in the co-management committee (Table 2). Target knowledge on actor perspectives and goals is combined with system knowledge on the functional structure of the co-management committee to aid in an analysis of transformative pathways through the action situations affecting the SES outcomes.

Table 2. A demonstrative diagnosis of the Southern California Spiny Lobster Fishery using the social-ecological systems framework. First tier subsystems from the SESF are shown (Figure 2). Data from the fishery and the knowledge types developed are indicated. This table represents a subset of data taken from the full diagnosis of the fishery from Partelow and Boda (2015). *Stakeholder groups: commercial (C), recreational (R), non-consumptive (N), environmental (E), marine science (M) and government (G).

SESF 1 st tier (Figure 2)	Southern California Spiny Lobster fishery	Knowledge types
Resource system	Southern California coastal marine zone Unclear system boundaries High productivity Large ecosystem Predictable seasonality	<i>System</i> - description of the resource system and functional processes as related to the resource unit.

Part 2: Context and concepts

Resource units	Lobsters High economic value Identifiable reproductive females High mobility during recruitment Low adult mobility Slow growth rate	<i>System</i> – description of lobsters as a resource unit.
Governance	Facilitated co-management between stakeholders Operational rules to be deliberated for fishing Constitutional choice rules exist for policy making Marine protected areas exist	System – describing the governance system characteristics and functional processes.
Actors	Six relevant actor groups (C, R, E, N, M, G)* Varied knowledge of SES between groups Established social capital in groups High actor group leadership History of conflict in policy planning for MPAs	<i>System</i> - identification of actor representatives and characteristics on the co-management committee and their larger actor groups. <i>Target</i> – actor perspectives, goals and values. Consensus on the pursuit of normative sustainability goals.
Action situations	Information sharing: Stakeholders share knowledge about SES during co-management meetings Deliberation: Stakeholders deliberate policy pathways to achieve group and collective goals	<i>System</i> - description of interactive processes as well as deliberative and knowledge sharing procedures <i>Transformative</i> – Reconciling trade-offs between different actor goals and values through deliberation and information sharing. Effective governance pathways can be identified. Education occurs through information sharing.

Interlinkages and mutual learning

In this section, we discuss the strengths and weaknesses for facilitating mutual learning and interlinkages in both approaches. The application of the case study in the Southern California Spiny Lobster Fishery is used to provide examples for our analysis. We frame five key points where interlinkages or mutual learning can be facilitated: (1) Broadening the range of value domains in the SESF, (2) Expanding the diagnosis of ecosystem functioning in the SESF, (3) Describing and analyzing social systems in ES, (4) Structuring a common language and framework in ES, and (5) Mutual challenges and improvements needed in both approaches.

Broadening the range of value domains in the SESF

A weakness of the SESF is a lack of recognition for more diverse value domains attributed to resource units, the resource system, and actors. Currently, economic value of the resource unit is the only explicitly recognized value that is diagnosed as influential. Thus, the SESF does not consider broader values of the resource system or resource unit, such as the biophysical, socio-cultural, or relational values recognized in the ES concept (Martín-López et al. 2014, Chan et al. 2016). Learning from how the ES concept recognizes multiple value domains can enhance the diagnostic capacity of the SESF. Socio-cultural values relating to the resource system can play a large role in decision-making processes for resource management as well contribute to the development of stakeholder perspectives (Ban et al. 2013). Reciprocally, neglecting biophysical values in natural resource management can degrade the functional integrity of ecosystems through lack of recognition. Adding new components to the framework requires consideration for the nested relationships within the frameworks structure (Frey and Cox 2015). We suggest that the second tier component ‘economic value’ in the SESF could be replaced with ‘values’. Subsequent third tier components could include biophysical, socio-cultural and economic values. Market and strategic values have been suggested at the third tier level (Delgado-Serrano and Andres Ramos 2015). As values can likely be attributed to the resource system and actor subsystems as well (Figure 2), there is a need to consider how and where the inclusion of value components can enhance the framework beyond the recognition of dynamics that are centered on the resource units. The facilitation of more target knowledge would likely result.

It is evident that the SESF diagnosis is missing key value domains that play an integral role in shaping stakeholder perspectives on the co-management committee of the lobster fishery. Socio-cultural and relational values influence the main action situations affecting system outcomes, deliberation, and information sharing. For commercial fisherman, decision-making may be influenced primarily by the economic value of the resource. However, the recreational, non-consumptive and environmental groups may endorse biophysical or socio-cultural values gained through benefits such as sense of place, recreational opportunity, intrinsic value and community identity. If these values are not identified in a diagnosis of the system, their inclusion in an analysis for transformative knowledge generation in the policy recommendation process will be missed.

Expanding the diagnosis of ecosystem functioning in the SESF

In addition to recognizing further values, use of the SESF from natural scientists is needed to expand diagnostic components for the resource system. Ecological drivers are not as well empirically investigated compared to social dynamics through existing applications and literature. This can be attributed to a lack of contributions from the natural sciences in development and use of the framework (Vogt et al. 2015). Ecosystem characteristics (resource systems and resource units) have underlying supporting and regulating processes that may be influential in shaping system outcomes, particularly the provisioning of resources. These components should be

included in the diagnosis and generation of knowledge that can inform sustainability. This enhances the potential to develop theory that includes ecological system drivers in SES interactions and outcomes. Learning from the ES concept, recognition for ecosystem functioning is pivotal among the common classification schemes (e.g. Millennium Ecosystem Assessment 2005, Haines-Young and Potschin 2012). In particular, the first and second operational stages of the ES cascade focus on biodiversity and ecological functions as important underlying foundations leading to ES and human well-being. Enhancing the diagnostic capacity of the SESF can be achieved by learning from how the ES concept recognizes ecosystem functioning as a core driver of SES outcomes.

The SESF diagnosis of the fishery places the resource unit (lobsters) as the focus of analyzing the ecological system. However, the ecological system consists of many species and ecological relationships that allow the system to function and lobsters to exist. Many of these ecological functions provide diverse benefits to the different stakeholder groups (Table 2). More specificity is needed for describing the resource system components beyond the 2nd tier level of the framework. In addition, recognition for physical, chemical, and biological rules in ecosystem functioning may play a key role in diagnosing a system (Epstein et al. 2013, Vogt et al. 2015). Developing theory and analytical methods that integrate social and ecological system components can only be done with in-depth component development on both sides of the SESF. Fully understanding the lobster fishery with existing theories requires this for an accurate assessment. Overall, managing natural resources will be more effective when influential social-ecological linkages can be diagnosed with a robust framework of components and can inform decision-making.

Describing and analyzing social systems in ES

There is no standardized approach to analyze the social system in ES research. The ES cascade stages are clear in the ecological system, but the social system and the governance feedback stage are less developed. There is no common set of social system components similar to the list of identified services and values. The identification of governance structures and their outcomes remain vague (Jacobs et al. 2013, Görg et al. 2015, Primmer et al. 2015). Social system analysis using ES is left to interpretation, which minimizes the benefits of using a common conceptual framework across cases, for comparisons and theory generation. Thus, research of ES governance needs to be enhanced, with thought for developing common components for analysis (Bennett et al. 2015). A review of the different social system and governance analyses using ES would be useful to consolidate efforts. With intention for mutual learning, ES researchers can draw on the development of the SESF for social system analysis. The SESF has identified many components to diagnose social systems, particularly relating to how institutions affect behavior and decision-making through empirically studied components.

Using ES, knowledge on the governance and institutional structures of the fishery remain vague, and rely on the use of other frameworks or knowledge to identify them. The main reason is the lack of explicit components for an assessment. This makes it difficult to produce system

knowledge on the underlying structural social components influencing the Southern California Spiny Lobster Fishery. There are no explicit linkages or components between governance and ecosystem functioning that can be used to identify specifics in our case. In contrast, target knowledge is more clearly facilitated through the identification of explicit values that can be associated to different stakeholders. The missing facilitation of system knowledge relating to the fishery's governance hinders an effective analysis of the management plan with the ES concept.

A common language and standardized framework for ES

Various ES classification schemes exist and are used with (e.g. MEA, TEEB, CICES) (Bull et al. 2016). For example, the MEA differentiates four ES categories (supporting, provisioning, regulating, cultural), while the CICES classification differentiates only three categories (provisioning, regulating, cultural). Regarding the ES cascade, there is no cohesive approach for how to apply the cascade as a step-by-step process. For each step, different literature builds the basis for the assessment (Table 1) because different groups of researchers (often with specific disciplines focusing on one step) focus on the specific steps with no standardization. An analysis using ES is typically not applied as a holistic conceptual framework to explain the whole SES. Consequently, findings are compartmentalized to specific steps and are hard to combine or compare. In contrast, the SESF has been suggested as a formalized structure that can build an ontology and common language for SES research including guiding literature aimed at structuring comparable data (Frey and Cox 2015, Hinkel et al. 2015). Standardizing use of the concept should not limit the ES approach, but generate knowledge that can be clearly communicated and compared across case studies (Haines-Young and Potschin 2014). Formalizing a guideline to add and interpret the relationships between nested components in the ES conceptual framework may be useful in this regard.

The general steps of the ES cascade are clear when implemented in our case study. There is a procedural flow from the Southern California coastal ecosystem and functions such as upwelling and biophysical parameters. This leads to the social system with the identification of ES, economic and socio-cultural benefits gained by each stakeholder group as well as the derived well-being. Finally, closing the feedback loop with governance through policy recommendations for the SES. However, the procedural steps or components for a more detailed analysis are not clear. As seen in Table 1, there is no clear way to compare specific components of governance in the analysis of the lobster co-management committee or governance structure as done by the SESF. As a result, conclusions or transformative knowledge cannot be generated easily, transferred or compared to other similar SES.

Challenges and improvements in both approaches

Common challenges exist in all SES research to generate knowledge for sustainability. For ES, manifold usage of the concept has led to a lack of cohesion between its multiple classification schemes, definitions and aims. Since the publication of the MEA (2005), hundreds of yearly

publications now include wide ranging interpretations of the concept for different research and policy agendas (Chaudhary et al. 2015). Larger-scale endeavors such as the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) also try to conceptualize the ES concept to bring on a common international policy agenda (Díaz et al. 2015). The ES concept has found its way to some national policy- and decision-makers such as the Obama administration who announced that ES must be considered in all federal decision-making (The White House 2015). Such broad usage has led ES to be considered a boundary object for sustainability (Abson et al. 2014). However, the different perspectives contest the possible uses of the ES concept, including monetary valuation and the role of the concept in supporting conservation initiatives (see discussion between Silvertown (2015), Schröter and van Oudenhoven (2016) and Wilson and Law (2016).

The SESF has yet to gain roots within a broader community of researchers. Most of its usage comes from researchers directly connected to its foundations. Literature on the framework has suggested many expansions to broaden its diagnostic scope, including ecologically (Vogt et al. 2015), in recognition of external political settings (Guevara et al. 2016), for application in diverse cases (Hinkel et al. 2015, Marshall 2015) and as a tool in sustainability science (Partelow 2016). While the framework is being pushed as a potential common SES language and formal SES ontology (Cox and Frey 2015, Hinkel et al. 2015), ontological consistency in current empirical applications is lacking (Thiel et al. 2015). While the framework continues to expand its use in contextual case diagnoses, it needs to reconcile broader and diverse engagement with maintaining the ontological consistency required to facilitate useful comparative analysis across cases.

Lastly, both approaches lack empirical applications that demonstrate how they can be used to generate transformative knowledge. This aspect concludes the flow of knowledge as part of a holistic research process (Figure 1). Although neither approach may have been intended for such ambitions, this has been considered an integral aspect of SES research. Nearly all SES approaches face difficulties to find appropriate methodologies that use conceptual frameworks to interlink different types of data, engage society as well as highlight and implement practical solutions. Large gaps exist between theory and practice in such research efforts, which often aim to be transdisciplinary but lack applied solutions beyond the scientific discourse (Zscheischler and Rogga 2015). Knowledge integration and mutual learning between existing scientific efforts can be a major step towards bridging the science-society gap.

Conclusion

In this article, we have analyzed and compared the ecosystem services concept (ES) and Ostrom's diagnostic social-ecological systems framework (SESF). We identified how each can generate system, target and transformative knowledge to compare their contributions and ability to mutually learn from each other in SES research. Use of the ES concept facilitates ecocentric system knowledge, this is contrasted with how the SESF is primarily used to facilitate anthropocentric system knowledge. Concerning target knowledge, the ES concept is often used as

a tool to facilitate co-production and value trade-offs with stakeholders, whereas applying the SESF is descriptive and analytical in the diagnosis of actor behavior and decision making processes. Lastly, both perspectives lack empirical applications that demonstrate how they can be used as academic tools to both generate and implement transformative knowledge in real world cases. To address these gaps, we highlight compatibilities and mutual learning possibilities between them through understanding their strengths and weaknesses as well as their history and how they are used in research. It is increasingly necessary that the SES research community further unifies through boundary work if academic contributions are to match the pace at which informed solutions are needed for real-world sustainability challenges.

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Part 3: Empirical research

Research 4: Operationalizing the social-ecological systems framework in pond aquaculture

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Abstract

This study develops and applies an interdisciplinary and mixed method approach to operationalize the social-ecological systems (SES) framework in the context of aquaculture, the fastest growing food production sector worldwide. We apply this methodology to conduct a case study of community-based pond aquaculture on the island of Lombok, West Nusa Tenggara, Indonesia. This diagnostic approach demonstrates how sustainability challenges are interrelated at multiple levels through an analysis applying common-pool resource (CPR) and collective action theories. At the community level, qualitative data show how pond aquaculture systems can have CPR dilemmas, requiring communities to work together to solve them. We show how a provision dilemma manifests from the need to maintain common canal infrastructure to distribute water to private ponds. Asymmetric incentives to contribute exist because there are up and downstream users in the pond network, similar to some irrigation systems. Second, at the level of individual ponds, we developed indicators for the Resource System, Resource Unit, Governance and Actor tiers of the SES framework. Indicator data for each pond was measured and transformed into normalized quantitative scores to examine the relationships between social and ecological outcomes within and between ponds. We combine the results of our multi-level analysis to discuss the broader social-ecological relationships which link collective action challenges in managing common canal infrastructure with pond level outcomes and current government policies for advancing community development. We emphasize the need for increased knowledge and training on effective aquaculture practice as an underlying driver of current system conditions. This study raises many methodological challenges associated with designing empirically based SES research and building SES theory. We discuss challenges with integrating diverse data types, indicator selection and making normative assumptions about sustainability.

Key words

Sustainability | collective action | interdisciplinary | mixed-methods | Indonesia | livelihoods, Lombok

Introduction

The social-ecological systems (SES) framework has been proposed and is widely cited as a tool for advancing empirical SES research, developing SES theory and progressing sustainability science (Ostrom 2009, McGinnis and Ostrom 2014, Cox et al. 2016). However, there are few studies which demonstrate its potential for facilitating interdisciplinary and mixed-method empirical examinations to advance SES theory (Thiel et al. 2015, Partelow 2016). This is in large part due to ambiguities in understanding the relationships between the many nested concepts and variables in the framework, which have different disciplinary origins. In addition, there are few attempts demonstrating how mixed-method data collection and analytical methods can be facilitated in practice. This includes defining SES concepts, developing indicators, testing field methods and integrating diverse data between multiple disciplines.

In this article, we attempt to advance interdisciplinary methods within SES research by operationalizing the SES framework in the context of pond aquaculture systems (Hinkel et al. 2015, Leslie et al. 2015, Partelow 2015). We apply our approach to a community-based pond aquaculture system located in a deforested mangrove estuary on the island of Lombok, West Nusa Tenggara, Indonesia. We focus on the communities of Bertong, Madak and Empol in the district of Sekotong on the island's southwest peninsula (Figure 1). Our research design builds on the approach demonstrated by Leslie et al., (2015) and draws on existing literature applying the framework e.g. (Schlüter & Madrigal 2012; Macneil & Cinner 2013; Cox 2014; Partelow & Boda 2015). We examine our case study at two levels, the whole community and the individual ponds as distinct units of analysis.

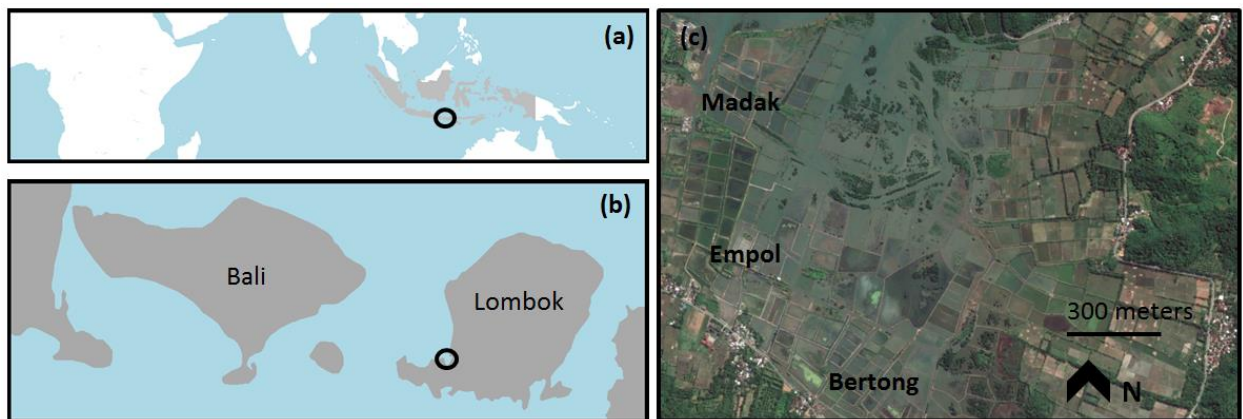


Figure 1. (a) Indonesia and location of Lombok. (b) Lombok and location of study site near the Sekotong Peninsula. (c) Satellite image over our three study sites Madak, Empol and Bertong. Top of the image is the mouth of the estuary into open water. Aquaculture ponds can be seen as square farming plots (Map data: Google, DigitalGlobe).

Aquaculture in Southeast Asia and Indonesia

Aquaculture is the fastest growing food production sector worldwide, bringing both potential solutions and new challenges for marine and coastal sustainability (Troell et al. 2014, FAO 2016). Pond aquaculture is by far the most common type of fish production in the world, accounting for 65% of global fish production between 2005-2014, having the largest implications for food security in the sector (FAO 2016). However, the sustainability of pond aquaculture remains largely unexamined compared to other food production systems and wild-catch fisheries (Partelow et al. 2018a). In Southeast Asia, aquaculture provides an additional or alternative livelihood for communities traditionally dependent on harvesting marine resources which have become severely exploited throughout the region (Halim 2001, White et al. 2005, Rimmer et al. 2013, Von Essen et al. 2013, Williams et al. 2014). Aquaculture has been considered a sector that can enhance the resilience of food systems compared to wild catch fisheries which are the last large-scale food source to make the transition from hunting and gathering to controlled production through farming (Neori et al. 2007, Klinger and Naylor 2012, FAO 2016).

In Indonesia, country level policies are driving research and development in search for new economic opportunities that can balance sustainable development trade-offs (Ferrol-Schulte et al. 2014). Securing nutrient rich food for a country of 250 million people scattered across more than 900 inhabited islands necessarily requires utilizing the vast abundance of coastal and marine resources in a sustainable way (White et al. 2005, Gurney et al. 2014). However, little is known about the challenges and impacts of transitioning livelihoods towards aquaculture, or the types of governance approaches or institutions which will be needed to secure a sustainable future for the sector (Eriksson et al. 2012, Von Essen et al. 2013).

Pond aquaculture systems

There are different types of coastal aquaculture, such as terrestrial pond-based systems and ocean-based mariculture (Swann 1992, Huong and Berkes 2011). In this study, we focus on a pond-based system which requires the maintenance of pond and canal infrastructure, typically constructed through networks of dikes and levees with earthen walls (Figure 2). Pond aquaculture systems are hybrid common-pool resource systems, with similar characteristics to irrigation systems in terrestrial farming. The production within private and ecologically semi- enclosed ponds is dependent on the sea water provided by a commonly owned and maintained system of canals. Regular seawater exchange through the common canals is essential to stabilize water levels, balance nutrients and expel waste generated by aquacultural practice in ponds. Water exchanged through the canal network is a point source to the ocean, which concentrates the waste water outflow from all ponds within a large area to a single location, which can lead to acute pollution. The mechanism of seawater transport is dependent on daily tidal fluctuations and on infrastructure maintenance. Ponds furthest away from the ocean are tail-enders when it comes to the quantity and regularity of water obtained. Sea water must travel through the network to reach each pond, and the further inland the more likely that canal infrastructure becomes a hindering

factor. In contrast to mariculture systems, terrestrial ponds have physical boundaries between them, substantially isolating ecosystem conditions such as nutrient levels and pollution within each pond. This can create variability in production between ponds related to differing social and ecological conditions (Azim et al. 2002, Islam et al. 2005).

Pond aquaculture has considerable potential to be a reliable and secure mechanism for food and livelihood security when the biophysical conditions of the ponds can be controlled through knowledge of the conditions and mechanisms needed for different species to grow i.e. through water exchange (Sumagaysay, 1998; Sumagaysay-Chavoso & San Diego-McGlone, 2003; Laapo & Howara, 2016). The conditions of the water will play a role in the rate and amount of production that is possible for different target species. The water conditions including salinity, pH, temperature, dissolved oxygen, nutrient levels (i.e. phosphorus and different forms of nitrogen) and any pollutant (i.e. heavy metals, pesticides) will affect the health and growth of the cultivated organisms (Lapointe & Ryther, 1979; Garg & Bhatnagar, 2000; Jana *et al.*, 2006). External conditions affect pond water parameters, and seasonal changes such as rainfall can lead to changes in salinity and water depth (Braaten & Flaherty, 2000). Knowledge of these dynamics is critical for making pond aquaculture a viable mechanism for food and livelihood security (Edwards, 2000). However, this knowledge can be highly specialized, and capacity building and education to disseminate this knowledge for practical use in many remote tropical coastal communities often does not exist or is costly to accumulate and disseminate.

Analytical framework

The literature on common-pool resource (CPR) systems has become closely associated with that of social-ecological systems (SES) (Ostrom 2007, Cox 2014b). In both streams of literature, resource use dilemmas have been shown to create difficulties in managing them sustainably due to combined social and ecological conditions and their multidimensional characteristics (Hardin 1968, Berkes 2008, Poteete et al. 2010). Individual use interests, often overharvesting or free riding, can conflict with the common interests of the group. Cooperation or collective action, either self-organized or externally motivated, has proven to be a key component for solving common-pool resource dilemmas (Poteete et al. 2010). However, collective action theories have not been frequently used to analyze tropical pond aquaculture systems despite the evident role they play in influencing changes in coastal commons (Huong and Berkes 2011, Bayazid 2016, Partelow et al. 2018a). Research on collective action continues to examine why some groups can solve CPR dilemmas effectively through building institutions and changing them, while others do not (Dietz et al. 2003; Heinmiller 2009; Poteete et al. 2010; Agrawal 2014). Common frameworks have played a considerable role in providing a structure to define and compare system components, interactions and outcomes across systems (Ostrom 2009; Binder et al. 2013; Cox et al. 2016).

Frameworks “provide the basic vocabulary of concepts and terms that may be used to construct the kinds of causal explanations expected of a theory,” (McGinnis and Ostrom 2014). To advance SES theory, the use of conceptual frameworks can help guide the examination of social and

ecological system components and their interactions in case study research (Partelow and Winkler 2016). The SES framework is a synthesis of concepts and variables from multiple disciplines. The framework is envisioned to be a common language of basic concepts for SES research and a diagnostic tool to help guide the identification of variables and interactions affecting system outcomes. The framework is conceptually constructed in a nested and decomposable way (Ostrom 2009, McGinnis and Ostrom 2014). The framework has multiple tiers of nested concepts, the first tiers include the Resource System (RS), Resource Units (RU), Governance System (Gov), Actors (A), Social, Economic and Political Settings (S), Interactions (I), External Ecosystems (Eco) and Outcomes (O). Second tier concepts are nested within each first tier (Table 1).

Table 1. The social-ecological systems (SES) framework (McGinnis and Ostrom 2014).

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) 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	Governance Systems (GS) 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
Resource Units (RU) 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	Actors (A) 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

Interactions (I) 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	Outcomes (O) O1- Social performance measures O2- Ecological performance measures O3- Externalities to other SESs
Related Ecosystems (ECO) ECO1- Climate patterns ECO2- Pollution patterns ECO3- Flows into and out of SES	

Research design

This study examines how social-ecological system variables interact at and between multiple levels in pond aquaculture systems. We do this through a mixed methods analysis applying common-pool resource (CPR) and collective action theories. Two levels of the system are analyzed with separate but interrelated approaches.

(1) At the community level we collect and analyze qualitative data to argue that certain social and ecological conditions are manifested from ineffective knowledge on how to maintain desirable pond conditions for aquaculture through improving water distribution infrastructure (i.e., canals). We draw on common-pool resource theory to hypothesize that the current social-ecological conditions present a supply-side provision dilemma to maintain canal infrastructure, which is related to creating, maintaining and improving the canals which the whole community depends on to regulate seawater exchange in their ponds (Ostrom 1990, Ostrom et al. 1994).

(2) At the pond level, social and ecological indicators were developed and measured for each pond unit we sampled. All pond level data was transformed and combined into quantitative normalized scores to analyze and compare social-ecological relationships. We hypothesize that the ecological conditions will vary between the ponds and will become less desirable the further into the network (away from the coast). This would be due to continuously less effective water exchange, reducing productivity and income accordingly. Additionally, we build on the research from Leslie et al., (2015) to hypothesize that there will be positive relationships between scores of the first tier variables of the SES framework, social (Governance and Actors) and ecological (Resource system and Resource units). We further hypothesize that there will be positive relationships between the Interactions tier with the Actors and Resource units tier scores. In our discussion, we qualitatively analyze the link between pond and community levels of our analysis

through examining multi-level social-ecological relationships. In addition, we attempt to discuss distinctions between proximate and underlying causes of the current conditions, combining our analysis across levels. We highlight the role of problem recognition, government investments and knowledge of the SES as key drivers.

Methods

The research design of this study is a multi-step procedure combining a community level qualitative diagnosis with the quantitative research design from Leslie et al., (2015). We expand on this approach to demonstrate how it can be applied at the local level and to conduct an intra-case comparative analysis of aquaculture pond conditions. Data collection was conducted between November - April 2016. Initial exploratory and observational phases focused on establishing contacts, meeting with local pond farmers, village leaders and community residents. Our exploratory observations and interviews were designed to gather data related to the concepts of the SES framework as well as to identify contextually relevant indicators to measure specific concepts at the pond level. Following our initial observations, we refined our focus to examine two units of analysis, recognizing two distinct levels in the SES: (1) the community level, and (2) the nested level of individual ponds, where each pond is considered its own social-ecological unit. Once we defined our two units of analysis, the next step was to identify appropriate indicators and the further methods needed to measure and analyze them at each level.

Community level

A total of 74 interviews were conducted with the help of a translator. Interviews were conducted in Indonesian (Bahasa) or the local language Sasak, depending on the interviewee. We conducted three rounds of interviews. After each round, the interview questions were revised following a diagnostic approach by asking nested sets of increasingly refined questions (Cox 2011). Snowball-sampling guided our selection of interviewees with multiple points of entry into the three communities. However, availability of individuals during field visits and working schedules mandated occasional convenience sampling after observing additional individuals to be included (n=16). The first round of interviews (n= 13) thus focused on the structure and activities of the farming group in Bertong, the Actor (A) and Governance (Gov) characteristics in the community as a whole. Bertong was targeted first, due to the location of our contacts and leaders in the area. Subsequent interviews, within the first few days, led to individual contacts in the other communities. Upon completion of the first round, interview questions were further refined to generate structured interview data on the individual farmers of specific aquaculture ponds (n=35), who provided additional data on the community. Our aim was to link the social data of farmers with the ecological data from each pond. Interviews were conducted with pond farmers from all three communities. The indicators developed for the social data collection were linked to the SES framework concepts (Appendix 1).

Ten key informant interviews were conducted with members of the three communities and government actors in the regional district, who had been selected based on their leadership positions. Questions were designed to examine the broader role of local, regional and national government, including subsidy programs and historical development in the area such as the evolution and distribution of property rights. Interview data was organized by coding with the SES framework using the software MaxQDA. Statistical analysis was conducted in Microsoft Excel, OpenOffice and R (R Core Team 2016).

Pond level

At the pond level we hypothesized that individual ponds would have spatially variable social-ecological outcomes due to their location in the pond-canal network and due to the individual characteristics of the pond farmers. This was done to offer a more in-depth examination of pond aquaculture and marine SES case studies which often generalize characteristics at the community or regional level (Leslie et al. 2015, Partelow et al. 2018a). Our approach draws on similar studies in irrigation systems, where the literature attempts to investigate the role of single individuals with distinct farming plots in a network (Janssen et al. 2011; Cox 2014). Thus we attempt to demonstrate that aquaculture ponds and social (individual) characteristics and outcomes may vary substantially within an otherwise perceived rather homogenous SES.

A sample of 62 ponds (Madak 14, Empol 11, Bertong 37) were analyzed as distinct social-ecological units, all ponds are biophysically separated by constructed mud walls (RS3) (Figure 1) and farmed by individuals (some farmers use more than one pond) (A1). We developed indicators to measure the social-ecological conditions of our sample ponds. The concepts, indicators and type of data collected are shown in Appendix 1 below. All data for the individual pond indicators were transformed and analyzed as normalized quantitative scores (Appendix 1). A higher score is associated with a more desired environmental, social or economic condition. Categorical data were expressed as either 0 or 1. Continuous data were ranked according to the 0, 10, 25, 50 and 75, 90 and 100 percentiles, which were assigned the values 0, 0.1, 0.25, 0.5 and 0.75, 0.90 and 1 respectively. The indicator values were matched to the closest percentile from the resulting ranking. In case a high value represents a less desirable condition, the inverse of the value was taken. The resulting scores are presented in Appendix 1. For the individual pond scores, data was attributed to multiple ponds if they were owned by the same user, with the exception of “pond size” and “distance along canals” which are unique to each pond. Pond area was determined using the QGIS field calculator. The distance of each pond upstream within the canal upstream was measured manually using the QGIS ruler tool (details below).

19 ponds in the community of Bertong were selected to represent a cross-section of distance from shore, spanning from the edge of the water to the most inland point near a main road. Data on physical parameters of these ponds were collected in two-week intervals from December - March 2016. Measured parameters included salinity, temperature, pH and oxygen content, which were measured using a WTW Multi 3430 multimeter (Xylem Analytics, Weilheim). Water depth was measured on two locations per pond, one in the opening of the main gate as a reference point and

another at a random location, where the pond bottom was perceived to level off. This data was used to assess temporal changes due to seasonality and to test the hypothesis that pond location (distance into the network) negatively influences the variation in pond conditions and can be used as an indicator for equilibrium properties (RS6) and location (RS9) in our analysis (Appendix 1). Spatial analysis and representation of pond parameters and indicators for each pond was done using the mapping software QGIS (projection EPSG:102029, Asia_South_Equidistant_Conic). Pond polygons were manually digitized using satellite imagery sourced through Google Earth and projected into QGIS.

Results

Community level

Resource system (RS)

Pond-based aquaculture (RS1) in Bertong, Madak and Empol is situated in a coastal mangrove estuary near the Sekotong bay (RS9). Due to the natural landscape, the ecological boundaries are clearly defined (RS2). The low lying estuary is separated from the sea by a thin strip of beach with canal and river outlets, and otherwise surrounded by hills. The estuary is dominated by human constructed canals and aquaculture ponds built from mud (RS4; Figure 2). Local mangrove habitat has been deforested due to farming and the use of mangrove wood for distilling salt from seawater is an alternative income. Most ponds contain no mangrove trees or a low density of naturally occurring trees. Seasonality plays a significant role in the production of food and perceptions of environmental change. The island experiences two main seasons, the wet season dominated by consistent rainfall from November to April and a dry season from May to September (RS6). During the wet season, freshwater creates brackish conditions with higher water levels, providing the most suitable conditions for aquaculture. During the dry season, ponds either contain water with high salinity content or no water. Tidal fluctuations bring sea water into the pond-canal network. Due to uneven water distribution in the canals, the pond conditions fluctuate based on the location. We further discuss details of the Resource units (RU) and Resource system at the pond level below.

Resource units (RU)

Pond-based aquaculture is focused on the production of milkfish (*Chanos chanos*) and seaweed (genus: *Gracilaria*) (RU4), following region wide trends. The species are typically grown together as a co-culture (RU3). Resource unit mobility (RU1) does not play a role as the ponds have clear physical boundaries between them, controlled by manual floodgates. However, it is more difficult to harvest mobile resources such as fish compared to seaweed, as many of the

ponds are large (Appendix 1). Salt is produced during the dry season, in smaller ponds, through evaporation. Naturally occurring species, including tiger prawns, wild shrimp, crabs and various other fish species are harvested periodically in small quantities as they enter the canals and ponds with the seawater (Figure 2). We further present characteristics of the Resource units (RU) below; as they differ at the individual pond level, including the economic value (RU4), number of units (RU5) and growth and replacement rate (RU2).

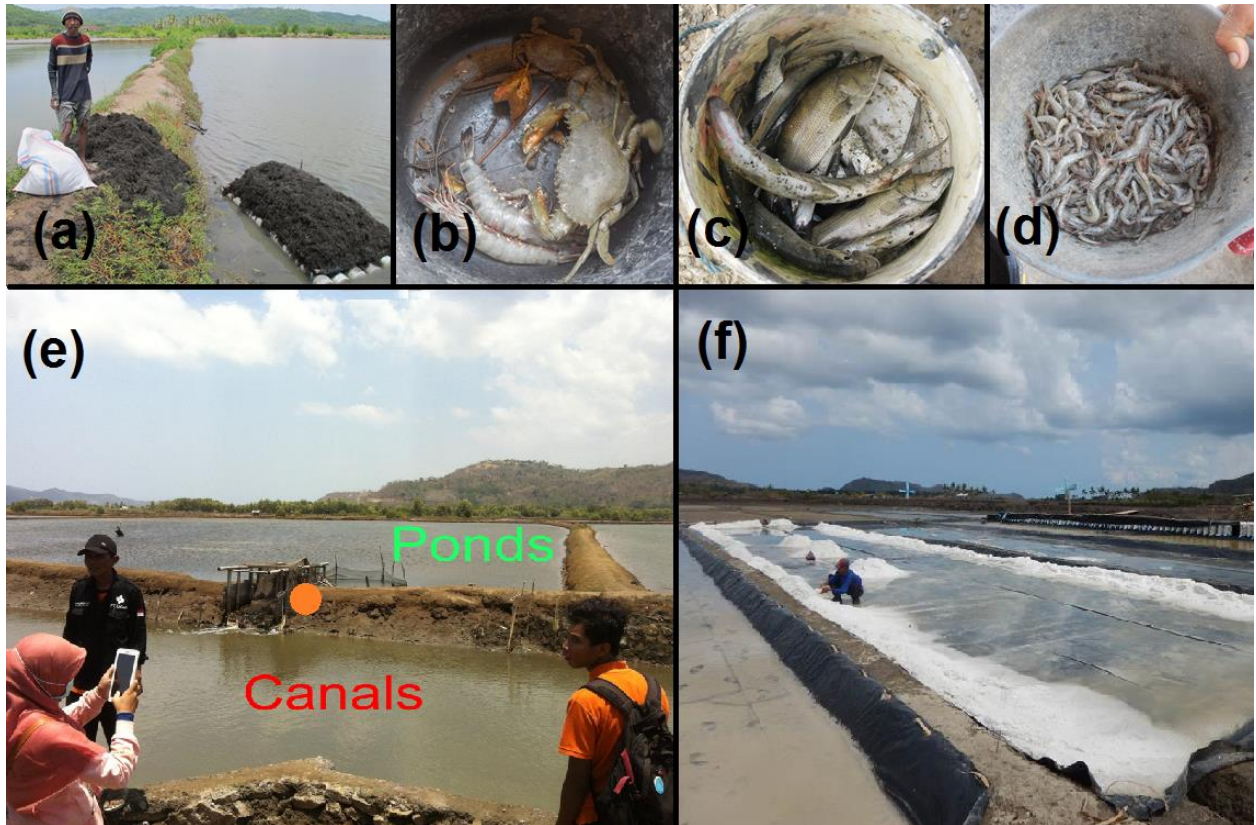


Figure 2. (a) Seaweed harvested with a float. (b) Prawns and crabs naturally occurring in pond-canal network. (c) Milkfish. (d) Shrimp, naturally occurring. (e) Pond (green), canal (red) with manual water exchange gate (orange). (f) Salt production in dry ponds. (All photos taken by authors)

Governance system (GS)

Three organizations provide funding and help to manage the area in different ways (GS1; GS2). The regional government through the Department of Fisheries and Aquaculture instituted a five year program in 2013 to support aquaculture activities in rural communities through subsidies and training. The Indonesian Institute of Sciences (*Lembaga Ilmu Pengetahuan Indonesia - LIPI*) currently conducts a pilot project to cultivate juvenile sea cucumbers (*Holothuria scabra*) in the

area with ambitions to advance the prospects for more valuable species. The Coastal Community Development program of the International Fund for Agriculture Development (IFAD) consults on the advancement of aquaculture activities. In order to receive government aid, community members need to form farming groups (I7). Groups can apply for specific projects related to group activities such as salt production, producing fish fry or receiving pumps for inland ponds. Support is never given as direct financing, but in the form of seaweed seed, fish fry, and equipment or as payment for labor to develop infrastructure (I5). The regional government officially monitors and enforces aquaculture activities in the region (GS8). They monitor the success of aquaculture groups who receive funding to assess future development aid. Farmers and community members provided mixed statements regarding the existence of formal rules for aquaculture or mangrove use. Few mentioned rules that cutting mangroves should come with a fine of 1,000,000 IDR (~75 USD) and the need to plant 100 mangroves, but cutting mangroves was interpreted more as norm that is socially stigmatized. Our observations and interviews suggest this has never been observed by locals or enforced by the regional government (GS8). It was clear through observation in the communities that the use of mangrove wood for distillation fires and construction is regular. However, small patches of mangrove restoration areas are organized by the government and IFAD (I5). The use of poison to harvest fish from ponds is understood to be prohibited (GS5), but we received mixed statements that this may only be an informal rule. Gaining access to written community or regional government documents containing written rules was not possible, as written rules likely do not exist. In addition, there is a high presence of illegal gold mining in the local hills, which is common among the communities, suggesting a general lack of enforcement of any formal rules.

The self-organization (I7) of aquaculture groups is required by the government to apply for and receive subsidies, equipment and training (I5). Groups are required to have a leader, secretary and treasurer (GS3; GS7; see Actors below), which may or may not work together in shared ponds. Groups are typically family members or friends (A6). The relevance of collective choice arrangements within groups are unclear but likely negligible. Most members farm individually, with their group playing a minimal role except to receive aid, such as a pump (GS6). Pond ownership is regulated in a number of different ways (GS4) due to the historical continuity of land ownership and shifts in use over time (GS10). In 1989, the establishment of a shrimp farm changed the property rights system of parts of the area. An investor bought ponds, but has not used them since 1994, and abandoned a plan for a shopping mall in 2015 (I5). While this investor is the proprietor of many of the ponds, they are used by local farmers who now have a mixed system of self-owned, rented, and borrowed or profit sharing arrangements. The financial security of the tenure agreements was not examined in detail, but the general lack in financial planning suggests that foreshadowing financial security plays a minimal role in daily decisions on farming practice and spending.

Actors (A)

Aquaculture groups are supposed to have a maximum membership of 10 people (A1), who select a leader, secretary and a treasurer (GS3). The leader has an organizational role, distributing tasks

among the group members (A5). In this study we interviewed members of 9 government supported groups, including most groups in the communities we were aware of, but others may exist. The average annual income per person from aquaculture, typically the main source of income, is 10,375,000 IDR (~740 USD), which averages less than two USD per day (A2), far below the Indonesian national average (World Bank 2016). However, the vast majority of respondents stated that they feel financially secure. Culturally, the community is highly homogeneous, identifying as Muslim and/ or Sasak, the local ethnic group. We observed apparent socioeconomic divides among older community members. Those who live slightly removed from the main pond areas have comparatively less desirable living conditions. These individuals also complained about inequalities of access to government resources through the group program. Overall, all three communities are remotely located in a rural setting with minimal access to public services and infrastructure (A4). This is relative to the rural development context within Indonesia as there is a basic school and hospital with a decent road to the area.

Aquaculture has been practiced for more than three generations, although largely unsuccessfully and with limited or no government support under different property rights arrangements. Many respondents consider it a part of their family history (A3). Much of the farming used to be for subsistence, however, prices for fish, seaweed and shrimp have increased and can now be sold on the market or to middlemen (A8). Illegal gold mining, roadside shops and agriculture supplement the income from aquaculture for many families. Farmers often assist each other, sharing seed and pond maintenance efforts (A6). This cooperation existed long before the aquaculture groups were formed. These groups have been formed from existing community networks among family and close friends. Theft from ponds is a problem, mostly from outside the community, as it is difficult to continuously monitor the ponds. Most individuals want to avoid conflict and police enforcement is lacking (I9).

Aquaculture is practiced in an artisanal way, using basic traditional tools and gill nets for harvesting fish, or floats to collect seaweed (A9) (Figure 2). One aquaculture group was given a motorized pump through the government support program to regulate water levels for salt production through evaporation. However, most individuals regulate pond water levels with tidal flows and manual floodgates (A9) (Figure 2). The need for pumps to clean the ponds or to keep the water levels high in the dry season was frequently stated and observed as necessary (A9). Tidal knowledge plays an important role in regulating the water levels and pond conditions, but the knowledge of farmers on how this relates to effective aquaculture practice and environmental stewardship is generally low (A7). The quality of ocean water coming into the ponds is assumed to affect all ponds similarly, and the 'external' ocean conditions were assumed to be consistent, the same across all ponds, and therefore not a determining factor. It only becomes an important variable in this analysis relative to the variance it creates between ponds in the network, which would be minimal. Environmental perceptions are largely shaped by seasonal changes, with the majority stating that the natural environment has not changed in their lifetime, but some said that they used to be able to collect more shrimp, fish and crab from the wild in the past (A7). Statements of seasonal predictability were varied along with the importance of mangrove in the estuary (A7). Individual variability is further examined at the pond level below.

Pond level

To test the hypothesis that pond conditions vary in relation to location in the network, we analyzed the standard deviations of salinity, pH and temperature in relation to distance into the canal network (from the coast) (Figure 3). The distributions of pond condition values, averaged over time, are shown in Figure 4. We observe positive relationships between pond conditions, salinity in particular, and distance into the network. This confirms our hypothesis. Salinity is the most relevant indicator of seawater infiltration. This suggests that pond conditions may become less stable and thus less desirable for aquaculture the further into the network due to continuously less effective and stable seawater distribution and exchange. As a result, the distance from the coast was used as an indicator for location (RS9) in the calculation of the social-ecological pond scores.

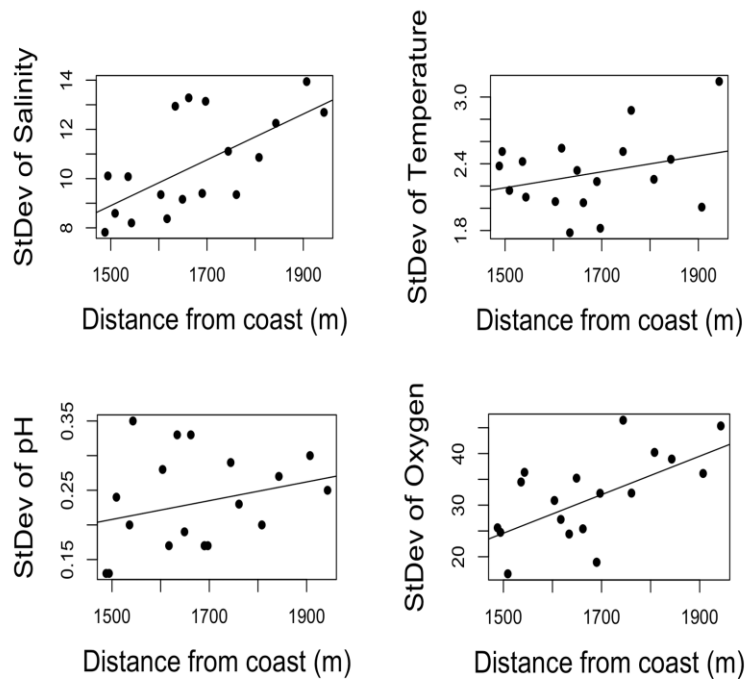


Figure 3. The standard deviation of the water parameters measured in the sampled ponds. Ponds are represented as dots. Variation is generally shown to be dependent on the distance from the coast, up the canal network. Distance was measured from the center of the pond to the coast.

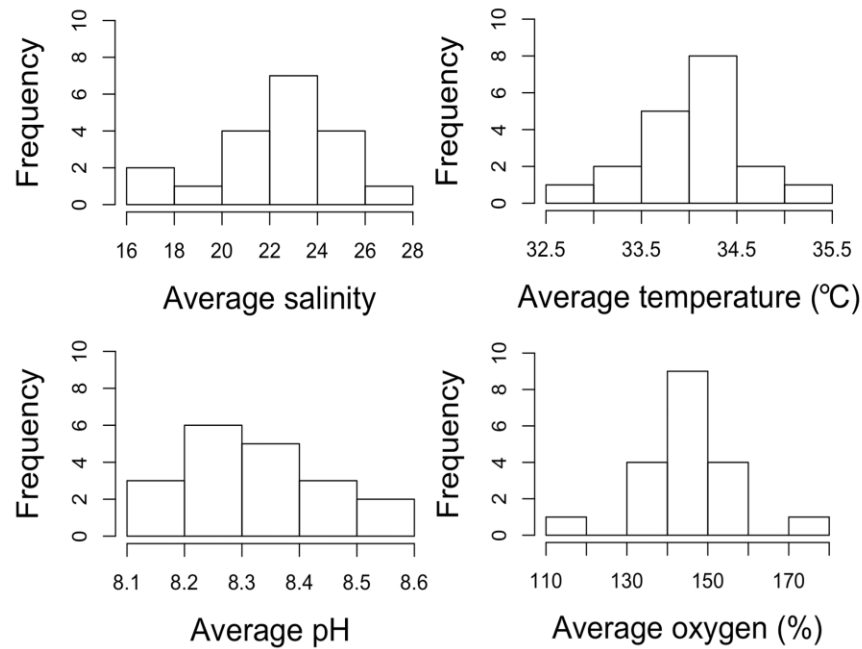


Figure 4. Histograms of the frequency distribution of the average water parameter measurements for the ponds.

Indicator values were calculated into five scores for each pond, one aggregate score for each of the measured first tier variables (RS, RU, G, A, I) of the SES framework. The indicators, data ranges and weighting system for the calculation are shown in Appendix 1. First tier pond scores were plotted in a correlation matrix to analyze their relationships (Figure 5). As hypothesized, we observe a likely positive relationship between RS and RU, suggesting ecological pond conditions may influence aquaculture production and the income derived from it. In addition we observe a likely relationship between RU and GS as well as RS and GS, suggesting that pond ownership and group membership may relate to increased production. There was no significant relationship between A and GS or between I and RU. A total social-ecological score was calculated for each pond from the first tier scores, which are mapped and plotted in Figure 6. Despite spatially dependent ecological conditions, we observe that combined scores are spatially variable due to heterogeneity in the social conditions. Despite ponds which exhibited high individual 1st tier scores or high single indicator scores, few ponds have high combined scores or high scores across multiple tiers of the SES framework (Figure 6). Scores suggest that spatial heterogeneity may be influenced by governance and actor sub-scores (Figure 6). This seems to occur despite indications that ecological conditions may be influenced by location in the pond-canal network. In general, total scores are influenced by coupled social-ecological conditions.

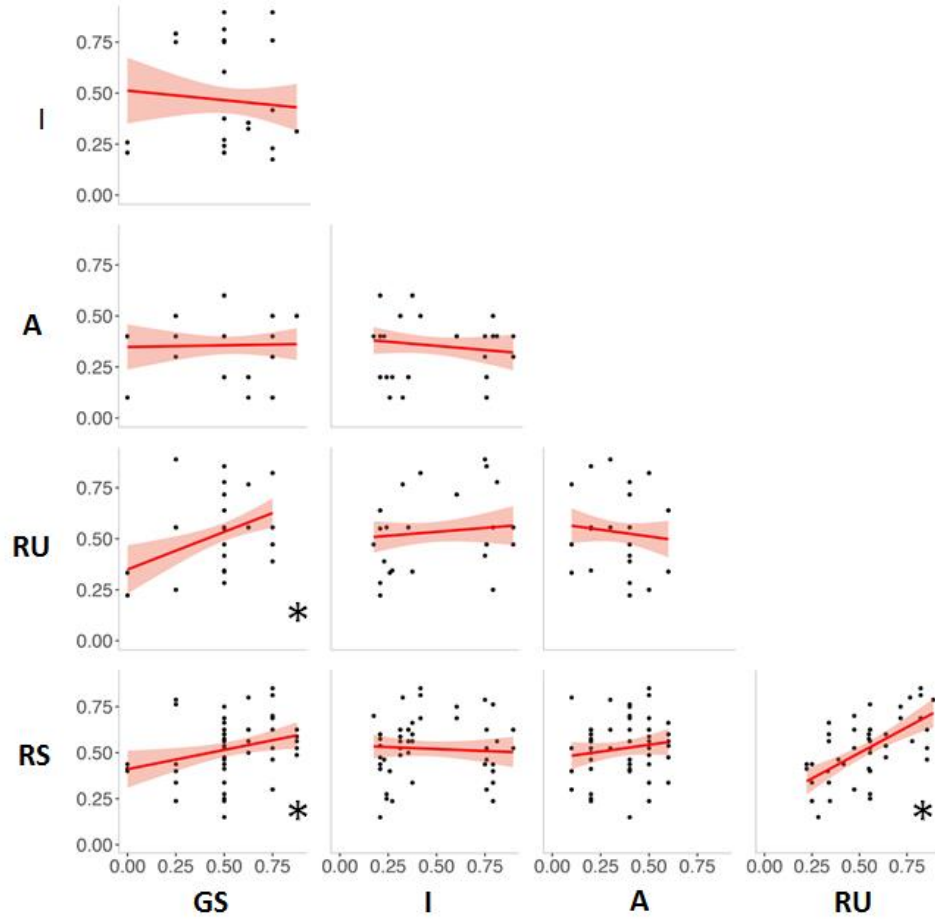


Figure 5. Correlation matrices between cumulative pond scores at the first tier level of the SES framework (every first-tier variable given the same weight). Axis labels refer to the 1st tier concepts GS (Governance System), A (Actors), RU (Resource Units), RS (Resource System) and I (Interactions). Trend lines are fitted with linear regression and the shaded area refers to the 95% confidence intervals. Models marked with an asterisk are statistically significant at $p \leq 0.05$.

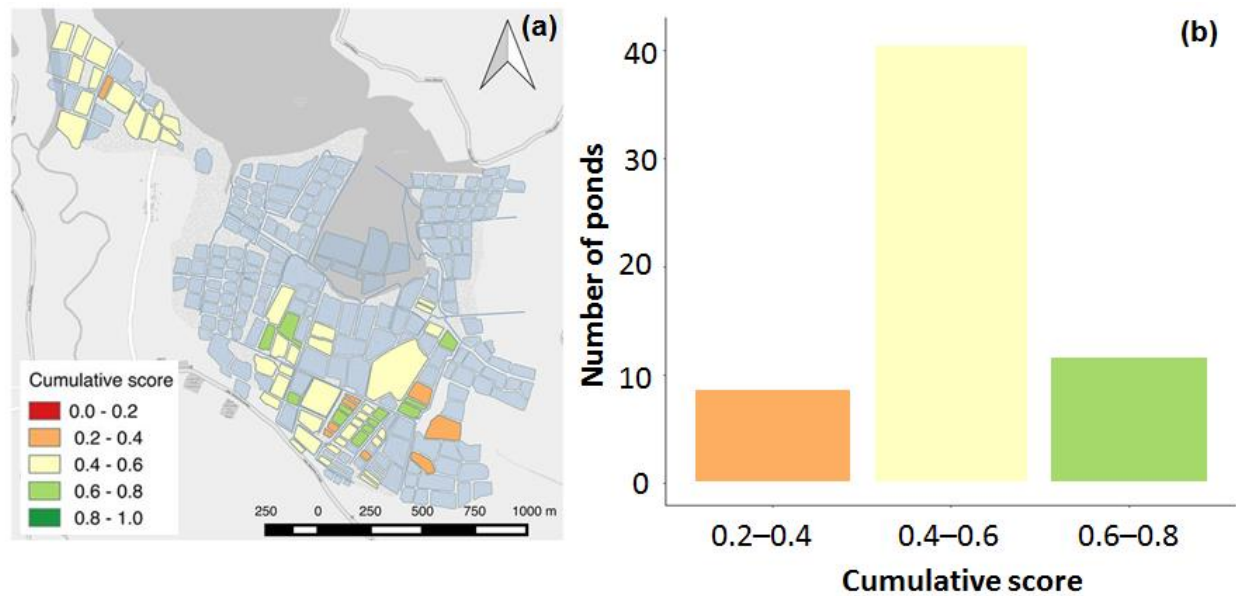


Figure 6. (a) Spatial distribution of cumulative pond scores. (b) Number of ponds in each score category.

Discussion

Pond aquaculture presents a new and largely unexplored context for defining the conditions in which CPR dilemmas can manifest and for examining how community-based institutions and governance have evolved in response. In this section we sort through our case analysis to discuss how linked social-ecological conditions present challenges for improving the desired development goals for pond aquaculture in the area. Improving aquaculture production is the primary goal for LIPI and communities as revealed by our community level and key informant interviews.

Our diagnostic approach has asked nested sets of questions, starting with more general inquiries related to concepts of the SES framework, to more nuanced and specific sets of reevaluated research questions (Cox 2011). In doing so, we have demonstrated how a mixed method approach for applying the SES framework can be done. However, this has not come without difficulties in understanding how to appropriately characterize and diagnose pond aquaculture systems, as there is sparse literature to guide indicator selection and context appropriate methods within the sector. This has allowed room for developing a new methodological application of the SES framework and testing the fit of CPR and collective action theories in a new context, and the ability to differentiate their relevance at different levels of analysis (Faysse and Mustapha 2017).

Proximate causes and collective action

This analysis suggests that variable pond conditions are likely due to poor canal infrastructure and its management. This hinders effective water distribution and exchange. Canals are a shared resource between all pond farmers, and finding ways to collectively manage them is a central factor of achieving successful social-ecological outcomes. We can interpret this canal maintenance as the proximate cause of the variable and uneven distribution of pond conditions. Canal infrastructure is the common good provided in the system and it would deserve a lot more attention in a follow up study to understand how CPR problems manifest in pond aquaculture. However, the main focus of this paper is on applying the SESF. We observe a social-ecological link that is reinforced by this dilemma. Poor pond conditions hinder production capacity and stability. This instability is then transferred to the social conditions such as income generated. This is reflected above in the significant positive correlation between the ecological tiers (RU; RS) and the governance system (GS), as well as between the resource unit (RU) and the resource system (RS) scores. This supports similar observations by Leslie et al., (2015). It is of considerable interest to understand which specific social and ecological conditions are driving these relationships, and how these may affect the ability of the community to cooperate and build institutions which can effectively respond (Ostrom 1990, Poteete et al. 2010). We explore this in detail below with CPR and collective action theories. However, the main focus of this paper is on applying the SESF, but we reiterate the importance of the detailed analysis of canal infrastructure for a follow up study.

Minimal cooperative efforts exist in Bertong, Madak and Empol to address community and government desires to improve aquaculture development. We can briefly relate the conditions we observe to existing CPR literature for potential explanations. Farming groups have been externally motivated to self-organize in order to be eligible for government subsidies, which leaves an ambiguous answer to the idea that they are able to self-organize effectively through intrinsic motivations (without external incentives) with their existing capacity or knowledge of how the system functions (Poteete and Ostrom 2004). Leaders are mandatory to establish each group (Gutiérrez et al. 2011), but otherwise play a minimal role in further organizing group activities which may be similarly explained by the fact that they are not self-actualized in their role. However, there is likely some reason why these individuals were selected as leaders which may be related to social status, age or experience.

Organized farming groups are largely composed of extended family members with close relations and frequent communication, which suggests a certain degree of trust or social capital as a barrier for entry to the group (Poteete et al. 2010). However, the communities are relatively homogeneous in regards to culture, dependence on the resource and socioeconomic attributes, which may suggest a higher potential to cooperate collectively, and group sizes are relatively small, less than 10 people (Vedeld 2000, Poteete and Ostrom 2004). The ponds, community boundaries and canal network are clearly defined, and ponds are easily assigned a system of property rights (Ostrom 1990, Schlager and Ostrom 1992). However, while ponds are easily distinguished with property rights, the canals exist as the jointly owned common infrastructure,

and there is a lack of formal or informal institutional mechanisms to deal with its provision. Similarly, there is a lack of formal and informal rules-in-use for aquaculture and the mangrove forests in general, as well as for monitoring pond or social conditions which have been shown to be important determinants of whether institutions are likely to achieve desired outcomes (Ostrom et al. 1994; Cox et al. 2010; Rahman et al. 2017). Some informal rules were mentioned but no enforcement or sanctioning has been observed or reported.

In summary, with the characteristics we observe, it is not surprising to see that the current conditions for collective action are fairly unfavorable. The prospects for improving aquaculture development will require institution building such as rules and procedures for canal maintenance as well as addressing the underlying challenges which are stagnating current conditions, which we explore below. In addition, it is important to recognize that this study cannot be considered fully exhaustive. As mentioned above, it is evident that social capital, mental models, trust and reciprocity very likely play a role, but we cannot support strong conclusions about their influence.

Underlying causes and the need for knowledge

A more underlying cause of inaction to improve pond aquaculture development is the lack of knowledge and problem recognition within government programs and among farmers. There is little awareness of pond conditions, how they fluctuate over time and how this affects ecological performance via water exchange from canals, and how this is ultimately coupled to social outcomes. Stabilizing temperature, salinity and pH levels in the appropriate combination is necessary and will differ between target species. Suitable equipment and training would be needed to monitor these parameters, but this requires targeted investments from the government or NGOs (GS8; I2; I9). Existing training programs have been well received and further requested, but these have focused on supporting current aquaculture procedures with subsidies rather than investigating what challenges exist and how to best address them. It is evident that government programs could better prioritize improving the canal network through monitoring, either themselves or by partnering with external researchers. Providing training on how and why the stabilization of pond conditions can improve aquaculture production may better incentivize collective maintenance efforts. Improved canal infrastructure could also help stabilize pond water levels during the dry season, and overall water quality throughout the year, potentially allowing year-round aquaculture or at least a prolonged growing season.

Salt production is a current solution for ponds during the dry season through a government sponsored pilot program. Salt can be stored year round and be sold when needed or when prices on the market are higher (RU6; RS8). However, income generated from salt production is considerably lower than for fish or sea cucumbers. Improved farming techniques will need to be informed through government or NGO programs. Milkfish are currently farmed due to their adaptability to high salinity ranges. If co-culture with more valuable commodities such as sea cucumbers is to be established, fluctuating pond conditions need to be considered. Sea cucumbers (*H. scabra*) are considered a robust species for pond aquaculture, but our results indicate that current pond conditions do not have suitable temperature and salinity ranges for them (Battaglione

et al. 1999), despite active government research programs to pilot the development of sea cucumber aquaculture in the area.

Under the current intensity of use, seawater in-take is not a subtractable resource in this context. However, it may be in the future due to pollution or overcrowding such as in confined space mariculture systems. At the moment there is no competition between farmers over sea water appropriation, leaving the main challenge to improving the canal network which simply allows for the sufficient delivery of water. However this requires further problem recognition to motivate a collective effort among farmers to solve it, a task which government aid and NGO support has not been able to successfully achieve so far (Fujii et al. 2005). If problem recognition increases, we can draw on common-pool resource theory to still foresee and view the case as a provision dilemma between farmers, depending on their location within the network (A4; RS9). In the ponds located closer to the coast, we measured more stable water parameters than in ponds further into the network (away from the coast), some of which even receive a high influx of freshwater during flooding and rainfall in the wet season. Thus there are different degrees of dependence on collective action to improve the network among farmers, and there are inherent asymmetric or heterogeneous preferences about the kind of joint investment needed, with incentives to free ride (Poteete and Ostrom 2004). There is greater variability of pond conditions further into the network. Even though seasonal temperature and salinity fluctuations will always occur to some degree, high variability could likely be mitigated for more predictable and stable production and income. In addition, selecting the appropriate species that can cope with fluctuating pond conditions and using seasonal species rotations may aid in maintaining productivity across seasonal changes (Wang and Lu 2015).

Here we reflect more broadly on the nature of pond aquaculture dilemmas, and how we can situate the type of dilemma we observe into the existing understanding of CPR dilemmas. The conditions for a provision dilemma exist, but the subtractability of seawater does not create a problem with appropriation. We are not aware of any literature which assesses whether cases faced with the dual dilemma of infrastructure provision and subtractable water appropriation such as irrigation systems, which is presumed to be a more difficult situation to solve institutionally, actually facilitates a more dire scenario where the joint problem is more easily recognized than cases with a single dilemma. Facing a dual dilemma increases the necessity of collective action due to more drastic consequences of inaction. However evidence that the severity of a dilemma leads to higher or lower cooperation is mixed (Osés-Eraso and Viladrich-Grau 2007, Cox et al. 2012, Blanco et al. 2015). In our case it is apparent that the single provision problem is not recognized or too subtle and indirect to generate sufficient collective efforts. It is worth considering the role of problem severity and persistence over temporal and spatial scales, such as the role of seasonality across aquaculture farming plots, when framing the conditions under which CPR dilemmas (particularly in diverse cases like aquaculture) effectively motivate collective action or effective institutional responses.

Assessing sustainability

Assessing the drivers of outcomes between multiple levels of a social-ecological system is a complex task. We have attempted an empirical analysis which may suggest that we are assessing the sustainability of Bertong, Madak and Empol, which we caution as being abstracted. We suggest a more nuanced discussion on the methodological process of attempting to understand how complex and context dependent systems function. This analysis evaluates the current pond level conditions with normalized indicator values, calculated to provide a pond score for each first tier variable of the SES framework (i.e. RS, RU, Gov, A, I). Justification for what constitutes a higher or lower value for any indicator was contextually grounded at the community level. However it is difficult to directly associate higher or lower pond scores to conditions which are sustainable for any given pond. The preferential condition for any individual may vary, or not align practically, with what we interpret as the more desirable conditions at the community level, or theoretically with normative values of sustainability in the literature or with the global agenda for sustainable development. Heterogeneous preferences for sustainable development likely exist within communities and across multi-level governance systems, and this has methodological implications for how we can measure and draw conclusions about sustainable outcomes in our research design.

For example, we assume in the community level analysis that a farmer who rents a pond would rather own his pond, and thus receives a lower score for the indicator of property rights because renting is less desirable due to the risks associated with decreased autonomy, regular costs and less economic certainty due to dependence on another owner (Feder and Onchan 1987, Acheson 2006). However, there may be other reasons that may explain why a farmer is renting a pond, which are more desirable for his particular situation, and this may change over time. Simultaneously, government subsidy programs may incentivize lending programs which favor the transfer of private property to state control to better enforce regulations. Many scales on which indicators are measured can be associated with normative value preferences which may differ from what is generalized as more desirable when creating the measurement scale at the group or community level. The variability in what contributes to a sustainable outcome for specific ponds is not reflected when preferential values are assumed to be homogenous and weighted equally in the calculation between all ponds. This is a methodological problem associated with comparing quantitative values on a fixed and generalized scale, and implicates the need for further research to understand dynamic value preferences and decision-making processes relative to normative goals at multiple levels, and how this may differ between individuals, groups and communities.

Methodology and theory for diagnosing aquaculture systems

The SES framework has been frequently applied in coastal and marine settings (Schlüter and Madrigal 2012, Basurto et al. 2013, Partelow 2015, Guevara et al. 2016). However, we are not aware of existing literature applying the framework to pond based aquaculture systems. We have found the framework well suited for examining aquaculture systems, in contrast to literature

suggesting the need for adaptations to improve the detailed analysis of other sectors e.g. (Epstein et al. 2013, Basurto et al. 2013, Marshall 2015, Partelow and Boda 2015, Vogt et al. 2015, Guevara et al. 2016). In addition we are unaware of existing studies which apply this methodology (Leslie et al. 2015) in a community-based setting, or to compare units of analysis within a single case. This has revealed numerous methodological challenges, some of which confirm existing literature, and some being more nuanced in relation to our methodology and specifically to aquaculture systems.

A brief discussion is warranted on the implications of indicator selection and the use of mixed methods for comparative research. Indicators are often selected to measure the 2nd tier variables and concepts of the SES framework, and these selections as well as the methods to measure them are typically driven by a combination of the research questions and context. Our variable indicators may be suitable for application to other cases within this sector, but unlikely for cases with different settings (McGinnis and Ostrom 2014, Guevara et al. 2016, Partelow 2016) or different research questions. Comparing results with other applications of the framework outside the sector must proceed with caution. Identifying system conditions linked to outcomes becomes abstracted without considering the indicators used or context relevant definition of the concept it measures. Further meta-analysis work using the SES framework and within commons scholarship will need to find ways to address concept-indicator gaps to enhance the accuracy and transparency of synthesis work which contributes to theory building.

More specifically, this analysis provides numerous examples of the role that indicator selection and measurement play in determining results. For example, individual pond scores are influenced by the weight that each indicator is attributed. Multiple indicators may represent a single 2nd tier variable, and many second tier variables contribute to the aggregate score of each first tier. The relative influence that any indicator has on system conditions is difficult to assess empirically which makes it difficult to justify specific weighting calculations. In this case study, we gave all second-tier variables equal weights within the first tier. The influence that each indicator has on the final score or the first tier variable score thus depends on the number of indicators used. This raises the possibility of over- or under-representation. A possible way to address this issue would be to statistically investigate the influence of variables on fixed and measurable outcomes such as known ecological pond conditions which are viable for selected aquaculture species or income levels relative to meeting basic needs. However, as we discussed above in relation to sustainability, fixed scales for measuring outcomes or the more desirable conditions for any indicator will likely vary between pond units and individuals. Modelling may be a viable method to explore how changes in weighting affect outcomes across pond units. Modelling different scenarios based on different weightings of the importance of each variable in the system, or scenarios based on different normative assumptions (i.e. the preferences guiding the scale of each measured indicator such as preference for pond ownership vs renting, or preferences for being highly dependent on aquaculture as the only income source vs having multiple employments and income sources) is a viable direction for future work.

It is difficult to theoretically position or empirically analyze the influence of any single independent variable without considering interactive effects with others. This remains a challenge

for interdisciplinary research on complex systems, and this analysis. This can be addressed by using mixed method approaches. At the community level we attempt to do so by qualitatively discussing distinctions between proximate and underlying causes. At the pond level, quantitative relationships can be examined between single indicators or aggregate second and first tier scores. However, there are many shortcomings in making claims about causal links in complex systems, particularly when relying on theory which is not fully developed to assess complex system dynamics or within the context of study, such as pond aquaculture. There are many potentially important interactive effects between variables in our analysis, between the first tier levels the framework (i.e. RS, RU, GS, A, I) and the two levels of the system we analyze (i.e. pond and community), which are not accounted for directly in this analysis. This study has aimed to provide a methodological guide post for SES research in pond aquaculture systems by using the best available knowledge and theory, which has made evident new potential hypotheses to guide future research.

For example, the relationship between resource unit production and resource system conditions may be oversimplified without considering how knowledge sharing among group members takes place or the role of theft on trust and reciprocity. Appropriate definitions of these variables are needed in the context to accurately assess them. This would require more extensive qualitative, observational and/ or behavioral economics data. Both aspects are very difficult to empirically measure. In addition, property rights allocations and group leader selection is likely influenced by historically evolved social networks or community relationships which have developed power asymmetries between individuals in group decision making processes (Dasgupta and Beard 2007). Similarly, interest and cultural homogeneity may not play a significant role in influencing community level cooperation when we observe high dependence on government subsidy programs which prioritize group membership and group competition in the same communities for subsidy aid. This occurs despite apparent collective interests in developing the whole area and common canal network. This may change at the individual or family unit level, where working together to maximize income can only be done by distributing labor and time efficiently between the few family members involved. 'Dependence on the resource' is an important factor stressed by collective action theory, which needs to and can be very well explored in the pond aquaculture context. High dependence can be presumed to be an enabling condition for collective action that motivates users, however, it also increases vulnerability due to changing ecological conditions which may limit fish production or economic conditions, e.g. fluctuating prices. Pond farmers repeatedly stated that they would prefer to only do aquaculture if it were possible, selecting to increase their dependence and vulnerability for specialization. The interactive mechanisms which influence the role of 'dependence on a resource' in collective action may be many, including the legality of other income sources, preferences for habit formation, predictability of labor and self-identity, as well as the role of specialization on fish production and general farmer well-being.

There are not yet many studies examining pond aquaculture from a collective action theory perspective. However, it becomes clear that canal infrastructure has clear commons characteristics. It is evident through this study that there is a crucial need to understand the ecological and social peculiarities of the system to effectively develop commons theory in the pond aquaculture context.

Policy outlook

This analysis suggests that numerous policy changes may assist in better achieving desired outcomes in Bertong, Empol and Madak. Participatory adaptive management to provide retentive capacity building and education efforts (Fujitani et al. 2017) to assist farmers in understanding how and why infrastructure improvements may improve pond conditions for production would likely be a fruitful step forward. Raising awareness among farmers that they face a collective action problem in the provision of common canal infrastructure would create additional knowledge to address maintenance problems. Capacity building and training programs will likely add more value to the current direct aid programs, which provide materials and seed. Communities will likely remain dependent on these programs until the overall social-ecological conditions improve through increased production and income. Farmers will likely be more motivated to work collectively on improving their common canal infrastructure when they have knowledge on how it helps their pond conditions, their production and ultimately their income. Recognizing the enabling conditions for collective action and mitigating the occurrence of a provision dilemma between head and tail-enders in the canal network will likely be necessary to improve the outcomes in all the communities. Leadership training, increasing knowledge of the system and subsidizing the appropriate species to be grown in the current pond conditions are evident improvements which could be made.

Conclusion

This study has built on previous research attempting to operationalize the SES framework through a mixed method research approach that integrates quantitative and qualitative data at multiple levels of analysis. We have adapted the methodology from Leslie et al., (2015) for application to community-based pond aquaculture systems. We have shown that pond aquaculture systems have potential to be effectively analyzed with common-pool resource theory, to be characterized as SES and diagnosed with the SES framework. This has allowed us to better understand the system dynamics which facilitate the current conditions, showing that relationships are suggested to exist between social and ecological variables on outcomes. We have shown that ecological pond conditions are likely to fluctuate based on location within the canal network, and argued that this is likely due to a lack of problem recognition to motivate collective efforts to improve infrastructure maintenance. Drawing on common-pool resource theory, we observe the conditions of a provision dilemma which may hinder efforts for farmers to cooperate and address existing challenges. In addition we have shown that relationships between first tier SES framework scores (conditions) of individual ponds can be tested with our methodology when indicators and measurement techniques are justified within the context. We observe relationships between the following pond scores: RS - RU, RU - GS and RS - GS, building the empirical understanding that finding sustainable pathways for aquaculture requires examining them as social-ecological systems. However, the approach we present can be critiqued and improved as a methodological foundation for further research. We highlight the role of

context in indicator selection and measurement for data comparability. We have discussed the challenges with drawing conclusions on system sustainability when value preferences are likely to vary between individuals, groups, communities and the researchers involved.

Acknowledgements

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Appendix 1. Indicators, normalized data ranges and weights used to calculate pond level scores. Each indicator is categorized by its relationship to the 1st and 2nd tier concepts of the SES framework. Theoretical importance of each indicator in the case context is shown.

First Tier	Second Tier	Indicator	Theoretical importance	Normalized data (transformed) * Original data	Weight Second tier
RS	Size (RS3)	Pond size	Pond size reflects production capacity.	1.00 – 54876 m ² 0.90 – 10696.8 m ² 0.75 – 6970.5 m ² 0.50 – 4073.5 m ² 0.25 – 3072 m ² 0.10 – 1822.5 m ² 0.99 - 667 m ²	1/4
RS	Productivity (RS5)	Kg of milkfish	Higher productivity indicates suitable pond conditions and leads to higher income.	1.00 – 1125 kg year-1 0.90 – 785 kg year-1 0.75 – 450 kg year-1 0.50 – 258 kg year-1 0.25 – 136.5 kg year-1 0.10 – 100 kg year-1 0.00 - 0 kg year-1	1/4
RS	Predictability of system dynamics (RS7)	Flooding	Floods damage ponds and growing conditions. Economic and labor losses incurred.	1.00 – Never floods. 0.00 – Floods at least once a year.	1/8
		Drying out	Drying out prevents aquaculture.	1.00 –Never dry. 0.00 – Dry at least once a year.	1/8
RS	Location (RS9)	Distance from coast	Shorter distance along the canals leads to better water supply and more stable water parameters	1.00 - 25 m 0.90 - 259 m 0.75 - 1000 m 0.50 - 1489 m 0.25 - 1835 m 0.10 - 2027 m 0.00 - 2164 m	1/4
GS	Network structure (GS3)	Group member	Membership provides access to subsidies and training.	1.00 – Member of a group. 0.00 – Not a group member	1/2

Part 3: Empirical research

GS	Property rights (GS4)	Ownership	Investment and conservation is more likely with owners (Acheson, 2006). Greater autonomy and are more likely pass it to future generations.	1.00 – Owner of pond property 0.00 – Does not own.	1/4
		Cost	Rent or profit sharing is an economic cost and implies a lack of autonomy.	1.00 – Does not have to pay for pond use. 0.00 – Has to pay to use the pond.	1/4
RU	Resource units (RU)	Species grown	Multiple commodities increases earnings and resilience to prices and pond conditions.	1.00 – milkfish, seaweed, salt and shrimp/crab. 0.50 – milkfish + 0.17 for each additional.	1/3
RU	Growth/ replacement rate (RU2)	Number of harvests	Indicates productivity and the potential earnings.	1.00 – 4.5 harvests year-1 0.90 – 3 harvests year-1 0.75 – 2.5 harvests year-1 0.50 – 2 harvests year-1 0.25 – 2 harvests year-1 0.10 – 1.6 harvests year-1 0.00 - 0 harvests year-1	1/3
RU	Economic value (RU4)	Income	Higher earnings indicate higher economic security. Higher earnings from aquaculture also make the continued use of this livelihood more likely.	1.00 – 72,000,000 IDR year-1 0.90 – 19,600,000 IDR year-1 0.75 – 10,000,000 IDR year-1 0.50 – 6,250,000 IDR year-1 0.25 – 3,000,000 IDR year-1 0.10 – 1,000,000 IDR year-1 0.00 - 0 IDR year-1	1/3
A	Leadership/Entrepreneurship (A5)	Leader	Group leadership indicates a certain level of social standing competence, influence or motivation.	1.00 – Individual is a group leader. 0.00 – Individual is not a leader.	1/10
		Entrepreneurship	The openness to sea cucumber cultivation indicates an interest in new aquaculture activities	1.00 - Interest in sea cucumber cultivation 0.00 - No interest in sea cucumber cultivation	1/10
A	Social capital (A6)	Theft	Theft reduces harvest potential, predictability and trust (Agrawal, 2003).	1.00 – Theft does not occur. 0.00 – Theft does occur.	1/5
A	Knowledge of SES (A7)	Perception of mangrove	The perception indicates knowledge of condition and importance for flood and erosion mitigation.	1.00 – Mangroves are important. 0.50 – Important elsewhere. 0.00 – Not important.	1/5
A	Dependence (A8)	Number of livelihoods	High dependence on a livelihood higher likelihood to invest and cooperate with others.	1.00 – High dependence, only livelihood. 0.50 – Medium, multiple livelihoods. 0.00 – Low, less important for livelihood.	1/5

Part 3: Empirical research

A	Technologies available (A9)	Access to a pump	A pump can be used to regulate water levels in the pond in order to avoid drought or flood and the associated harvests losses and infrastructure damages	1.00 - Access to a pump 0.00 - No access to a pump	1/5
I	Information sharing (I2)	Teaching aquaculture to next generation in the family	Teaching aquaculture to the next generation increases the likelihood that it will be practiced in the future	1.00 - Teaches aquaculture as livelihood to children 0.00 - Does not teach aquaculture to children	1/2
	Investment activities (I5) Investment activities (I5)	Hours spent working at pond per day	The more hours can be spent working at the pond, the better it can be maintained. More time investment also shows a willingness to invest in the livelihood	1.00 - 7 hour day-1 0.90 - 6 hours day -1 0.75 - 5 hours day -1 0.5 - 3 hours day -1 0.25 - 1.5 hours day-1 0.10 - 0.75 hours day-1 0.00 - 0 hours day-1	1/12
I		Purchasing of fertilizer	Purchasing of fish feed, fish fry and seaweed seed show ability and willingness to invest in aquaculture practices aimed at increasing production	1.00 - does purchase fertilizer 0.00 - does not purchase fertilizer	1/12
I		Purchasing of fish feed		1.00 - does purchase fish feed 0.00 - does not purchase fish feed	1/12
I		Purchasing of fish fry		1.00 - does purchase fish fry 0.00 - does not purchase fish fry	1/12
I		Purchasing of seaweed seed		1.00 - does purchase seaweed seed 0.00 - does not purchase seaweed seed	1/12
I		Receives government subsidies	Reception of government subsidies (mostly in the form of fish fry or seaweed seed) means that less personal investment needs to be made	1.00 - does receive subsidies 0.00 - does not receive subsidies	1/12

Research 5: Mangroves, fishers and the struggle for adaptive co-management: Applying the social-ecological systems framework to a Marine Extractive Reserve (RESEX) in Brazil

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Abstract

Brazil has a network of Marine Extractive Reserves (RESEX), a form of Marine Protected Area (MPA) using co-management. The RESEX program aims to bring traditionally marginalized populations with natural resource dependent livelihoods into national development processes by empowering them to participate in governance and steward biodiversity conservation. In this article we apply the social-ecological systems framework (SESF) and collective action theories to diagnose challenges for co-management in the Caete-Teperacu marine RESEX near Bragança, Brazil; a multi-use mangrove estuary supporting a small-scale crab fishery. We conducted key informant interviews and build on over 20 years of research in the region to provide an overarching analysis of the challenges facing co-management. We describe the variables from the SESF in the case context and find that many social and ecological variables interact in clusters over time, and these clusters can be identified as themes, including (1) social and political momentum supporting the RESEX, (2) shifting perceptions of local residents and fishers, (3) patron-client relationships and social-ecological traps, (4) challenges with institutional fit and (5) the interactions between harvesting closures, compensation and dependence on local natural resources. Furthermore, we use collective action theories to help explain the role that each variable plays in either hindering or enabling successful governance. Our findings suggest that institutional resilience is needed to make RESEX adaptive to shifting social and political momentum. It could do this by providing more platforms for communication, deliberation and knowledge exchange among the relevant actors. We believe our findings reflect broader challenges facing RESEX implementation throughout Brazil and lessons can be learned for MPAs facing difficulties with the implementation of co-management worldwide.

Key words

Social-ecological system | adaptive co-management | collective action | coastal | collaborative governance | marine protected area | small-scale fisheries | conservation | crabs

Introduction

Up until quite recently, social and political momentum continued to build in Brazil for the establishment of Marine Extractive Reserves (RESEX), a form of Marine Protected Area (MPA) aimed at democratizing access to natural resources through participatory co-management with both social and environmental goals (ICMBio 2012, Santos and Brannstrom 2015). The RESEX program aims to bring marginalized traditional populations who depend on local natural resources into national development processes by empowering them to participate in governance. RESEX goals include the sustainable management of resources to maintain local livelihoods while simultaneously stewarding biodiversity conservation (e.g. Simonian and Glaser 2002).

In Brazil, RESEX co-management is a major advance since it legitimizes nature-dependent and largely marginalized natural resource users in a formal legal framework to replace widespread illegality in harvesting practice and to motivate collective action for sustainable resource use (Glaser et al. 2003, Di Ciommo 2007). RESEX and other types of conservation units are facilitated by the Chico Mendes Institute for Biodiversity Conservation (ICMBio) throughout Brazil. Founded in 2009, ICMBio is part of the Federal Ministry of the Environment (MMA), and, in collaboration with the Institute of the Environment & Renewable Natural Resources (IBAMA), also tasked with monitoring environmental laws.

Of Brazil's currently 88 RESEX, 24 are marine and 12 of these are located on the coast of the state of Para, including our case study. Marine RESEX programs have struggled for success (da Silva 2004, Santos and Schiavetti 2014), facing a variety of challenges including social conflicts between fishers and other actors (Santos and Schiavetti 2014), low social and cultural preparedness for formal governance (da Silva 2004, Di Ciommo 2007), low socioeconomic welfare and few alternative livelihood opportunities (Glaser and da Silva Oliveira 2004, Santos and Brannstrom 2015) and deficient monitoring and compliance with rules (Erler et al. 2015, Nobre et al. 2017). Recognition for the historical dynamics of local management and adjusting co-management to local norms has shown to be difficult, and failure can hinder progress (Tebet et al. 2018). Most studies see the RESEX program as a move in the right direction, but argue that implementation is afflicted by a multitude of institutional challenges.

The Brazilian RESEX program expresses a shift in the political discourse on environmental management towards a collaborative "people and nature" conservation model (Mace 2014, Bennett et al. 2017), reflecting a worldwide conceptual move towards collaborative governance through co-management (Armitage et al. 2009, Bodin 2017). Co-management brings multiple state and non-state actors together to cooperate, typically including local resource users (e.g. fishers) and other civil society groups (e.g. NGOs, private sector) (Carlsson and Berkes 2005).

All marine RESEX apply a generic co-management model. However, this is not a panacea for success. In order to improve the likelihood of sustainable human-nature relations, co-management requires adaptation to changing social-ecological system (SES) conditions and other contextual factors (Jentoft 2000, Bene 2004, Folke et al. 2005, Ostrom and Cox 2010, Basurto and

Nenadovic 2012). Adaptive co-management has been reported as more successful when the involved actors can create institutions for collaboration that facilitate mutual learning and knowledge integration. Recognizing the unique social-ecological conditions of rural coastal Brazil, and making policies like RESEX adaptive to them, is critical for success (Borges et al. 2017, da Rocha et al. 2017).

Collective action is a necessary part of co-management (Noble 2000, Folke et al. 2005, Bodin 2017). Actors need to cooperate to develop mutually agreed rules, institutions and goals. Collective action theories provide a useful lens to unpack the reasons why establishing institutions for cooperation is difficult. Many social and ecological characteristics have been shown to hinder or enable collective action over time (Ostrom 2009, Poteete et al. 2010, Bodin 2017). Much of the literature on MPA governance emphasizes the need to recognize how complex social-ecological interactions influence governance. Synergies between commons, collective action and SES research are improving our understanding of the enabling conditions for successful collaborative governance (Ostrom 2009, Bodin 2017).

At the land-sea interface, coastal SES research has helped unpack the complexity of spatially overlapping characteristics and interactions between marine and terrestrial systems, and how these influence sustainability (Alexander et al. 2016, Pittman and Armitage 2016, Partelow et al. 2018a). Coastal zones often have multiple spatially proximate ecosystem types, resource uses and actors, often with divergent interests, creating challenges for collective management (Schlüter et al. forthcoming, Glaser and Glaeser 2012, Glaser et al. 2012). They face a double squeeze from both terrestrial and marine drivers of change. This emphasizes the need for knowledge integration across those systems and between those actors who use them to increase the adaptive capacity of governance (Álvarez-Romero et al. 2011, Whitney et al. 2017). Mangrove and estuarine systems demonstrate this complexity, as they are often subject to policies designed for land management and conservation which do not take account of the fluid dynamics of aquatic species or the specific resource use behavior in small-scale fisheries.

In this article we apply the social-ecological systems framework (SESF) using qualitative data (Ostrom 2009, McGinnis and Ostrom 2014) to diagnose the challenges facing co-management in response to social-ecological change in the Caeté-Taperaçu (CT) RESEX. The CT RESEX is located near the city of Bragança, State of Pará, Brazil, 215 kilometers southeast along the coast from its state capital Belém, on the mouth of the Amazon River delta (Figure 1) (Saint-Paul and Schneider 2010). Bragança supports 113,000 inhabitants, with more than 40,000 living in rural and largely undeveloped areas. The CT RESEX is a large coastal estuary forming a peninsula with numerous rivers and tributaries, and it is embedded in the world's second largest continuous mangrove ecosystem spanning ~23,000 square kilometers.

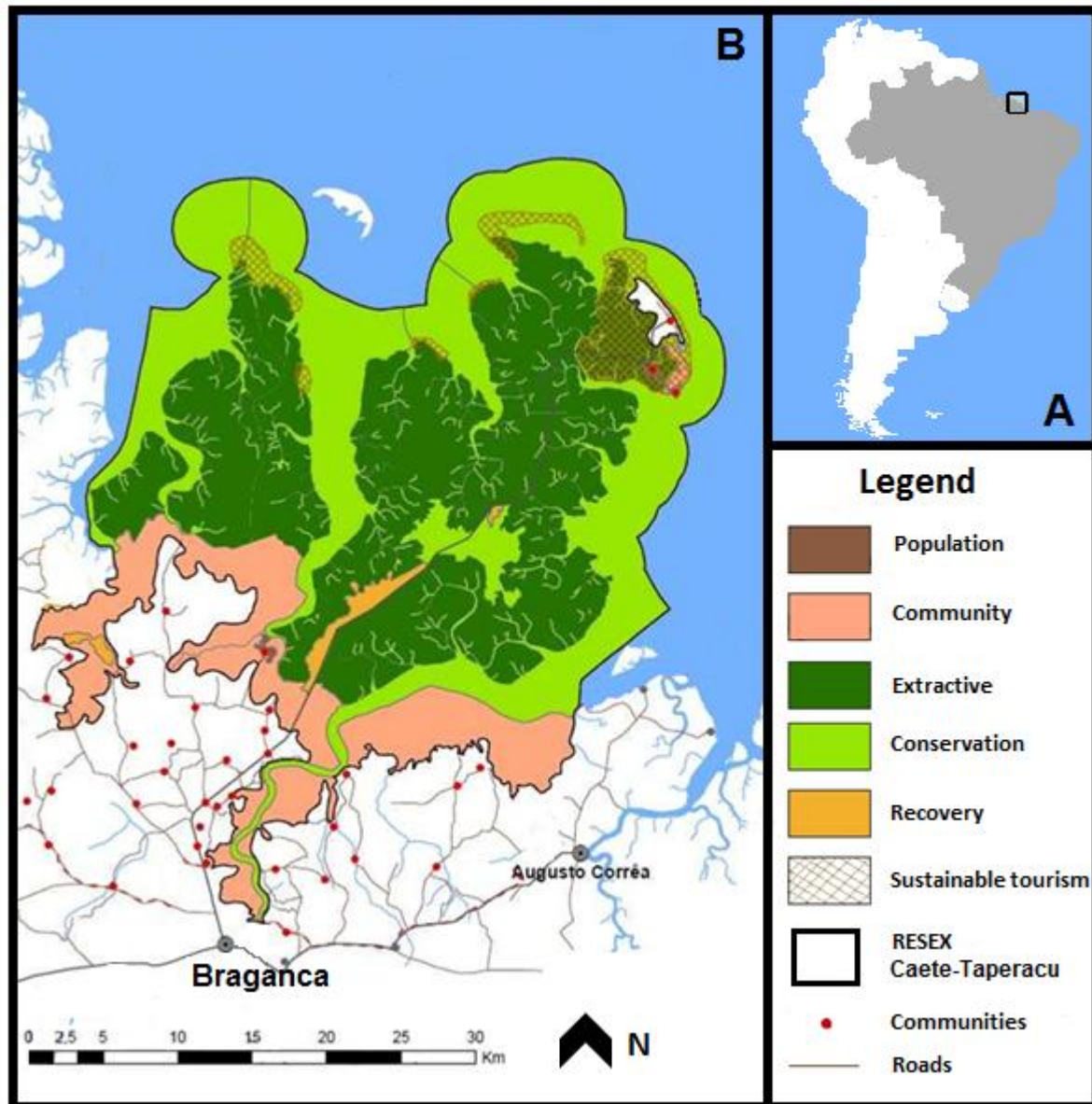


Figure 1. (A) Location of the Caeté-Taperacú RESEX in Brazil. (B) Bragança area and the RESEX boundaries and zones within the RESEX according to the management plan. Source: (ICMBio 2012).

A number of studies have analyzed RESEX areas using Ostrom's (1990) design principles (da Silva 2004, Le Tourneau and Beaufort 2017, Nobre et al. 2017, Tebet et al. 2018), but to our knowledge this study is the first to apply the SESF. The framework is well suited for the study of small-scale fisheries (Basurto et al. 2013, Partelow 2015) with numerous case study applications in the literature (Schlüter and Madrigal 2012, Ernst et al. 2013, Leslie et al. 2015, Partelow and Boda 2015, Guevara et al. 2016). Few studies have demonstrated the value of the SESF as a tool for qualitative research as a coding framework for the organization and analysis of qualitative data e.g. (Ban et al. 2015, Hoogesteger 2015), particularly in small-scale fisheries e.g. (Lozano

and Heinen 2015, Partelow and Boda 2015, London et al. 2017). Qualitative data analysis is an integral part of environmental social science research as it allows for thick descriptions of complex variables and the evolution of narratives and interactions over time (Bryman 2012, Cox 2015). This study uses the SESF in two novel ways. We examine groups of interacting second-tier variables and their interactive effects as ‘key interactions’ influencing overall outcomes. We also consider these interactions over time (two decades) in our analysis, which has only been explored by a few articles (Epstein et al. 2014a, Ban et al. 2015).

Methods

This study conducts qualitative research (Silverman 2005, Flick 2014) using a diagnostic approach guided by the SESF (Ostrom 2007, Cox 2011, Hinkel et al. 2015, Partelow 2016). The SESF is a diagnostic tool structured into tiers of nested and related concepts (Appendix 1). The unit of analysis in this study, the focal SES, is the biophysical area within the political borders of the CT RESEX (Figure 1) and the associated actors and registered residents, with focus on fishers harvesting mangrove crab (*Ucides cordatus*) the most economically important natural resource in the area (Glaser et al. 2010b). This study is guided by the following research questions (RQ):

- What SESF variables are present and potentially influence outcomes in the CT RESEX?
- What are the key interactions between variables in the CT RESEX?
- With many separate research projects in the CT RESEX, how can an analysis of the SESF provide a synthesis and overview to inform more effective co-management?

Primary data

Semi-structured key informant interviews (n=31) were conducted between March and July 2016 (Table 1). Recorded interviews lasted between 45 minutes and 2 hours. Individuals were selected for their direct experience with the formation and/ or implementation of the RESEX. Snowball sampling allowed for finding other relevant individuals to interview. Multiple ‘entry points’ into the social network of key informants were employed. Most interviewees had been involved with the RESEX for more than 10 years including researchers, board directors of the community associations, RESEX deliberative council members, ICMBio employees, Bragança municipality employees, community leaders, associated NGOs and actors from the private sector. Interviews were conducted and recorded in Portuguese, then translated, transcribed and analyzed by the authors.

Table 1. List of interviewees by stakeholder group, the specific actor within that group and number of interviews.

Actor group	Who	Number of interviews
Government	ICMBio local manager ICMBio local employees Mayor of Bragança Municipal environmental office Municipal fisheries department	2 3 1 2 1
RESEX Deliberative Council	Deliberative council members	6
RESEX community members	Current RESEX president Ex-RESEX president Community leaders (also representatives) Community representatives (only)	1 1 6 3
Association of RESEX Users	Board of directors (ASSUREMACATA)	6
Academic	Federal University of Para Federal Institute of Para	4 1
NGO	Pastoral Council of Fishermen (CPP)	4
Private sector	Crab processing businesses	2

Secondary data

Most of the data that supports this article comes from primary sources, but academic literature provided useful secondary data. This included local research that had resulted in Portuguese language publications from the Federal University of Para (UFPA) in Bragança. Bragança was the location of a ten year international research cooperation (the MADAM project) from 1995-2005 co-funded by the Brazilian and German research ministries, with a comprehensive book published on the many social and biophysical dimensions of the area pre-RESEX (Saint-Paul and Schneider 2010). Many chapters of this book provided data for this article as well as six published theses from UFPA, four post-RESEX evaluation reports and the official RESEX management plan documents. Additional background literature was included as cited.

Data analysis

Interviews followed a diagnostic process, first developing and asking general questions related to the first-tier variables of the SESF. Based on the answers to these, and after each interview, the

two authors of this article who did the fieldwork (SP and SS) discussed and briefly analyzed responses. This allowed for refining and developing more nuanced questions related to specific second-tier variables for following interviews. The length of the interviews varied substantially, as some informants had extensive knowledge on specific topics, provided detailed information in relation to only a few or a series of related questions. Others provided general information on many questions. A structure of starting questions was tailored to each individual based on who they were and what they were likely to know about. Interview data was cross-checked with multiple interviewees. Once a point of saturation in responses to a question occurred (similar responses to a question from numerous individuals) the data on that variable was considered validated (Fusch and Ness 2015). Varied responses prompted further questions and cross-checking. Answers in the early stages of the research typically allowed for a descriptive understanding of variables, supporting RQ1. Later in the diagnostic process, responses to further refined questions provided data on interactions between variables and more complex system dynamics, supporting RQ2. The final synthesized description of each relevant SESF variable and its interactions in the SES are presented below.

Primary qualitative data from interviews were transcribed and secondary data (i.e. articles, book chapters, theses) were entered into the qualitative data analysis software MaxQDA (MaxQDA 2016). In a first step, all data were coded using the SESF variables as a coding framework (i.e. qualitative text segments were linked to the second-tier variables they provide data on). Next, one of three actions was taken. Either the data represented a consensus on the description and role of that variable, or conflicting accounts were identified or further third-tier variables were developed to make a more nuanced description and analysis, following an ontological logic (Frey and Cox 2015). The two authors who conducted the fieldwork agreed on how the data was coded through consensus coding. After final coding, each second-tier variable was described in the context of the CT RESEX and analyzed with MaxQDA for its relation to other variables through jointly coded segments and interpretive analysis. Using the description of each second-tier variable in the case, collective action theories were used to analyze the role of each variable. This provided an additional explanatory lens to view the role each variable plays in relation to current outcomes related to cooperation and co-management.

Results

Social, economic and political settings (S)

With the end of the military era and the new Brazilian constitution in 1988, an era of political stability ensued from 1998 to 2015 with continuous investments into social and economic sectors, eradicating extreme poverty and expanding Brazil's lower middle class (S1). Recently, increasing political instability saw the impeachment of the last elected president while cuts in educational, environmental and public service expenses have had negative implications for the incomes and livelihood chances of the poor (Pinheiro et al. 2015) (S3). Exclusionary and often elitist

transformations in agrarian, environmental and indigenous policies have been shaping the current sociopolitical scenario, threatening the integrity of conservation initiatives and the people dependent on local natural resources.

North Brazilian economic development has been consistently well below national averages for many decades. Regional inequalities between North and South Brazil persist despite some recent successes in poverty eradication. A particular problem is the lack of access to higher education and to income options that are not based on traditional natural resource extraction such as fishing (S2). Expanding seafood markets in Brazil have turned the Bragança region into a national seafood supply center (S5) and even on international markets for certain species (*Lutjanus purpureus* – red snapper; *Cynoscion acoupa*¹ - acoupa weakfish)) (Bentes et al. 2012). This is in part due to changes in technology (S7) for the processing of crabs (*Ucides cordatus*). However, this has led to the first signs of crab overexploitation, a key species of the ecosystem and regional economy (Glaser and Diele 2004, Koch and Nordhaus 2010). Global market processes are thus threatening the ability of local natural resource dependent communities to achieve conservation and sustainability goals (Sant’ana-Júnior 2014).

Resource system (RS)

The CT RESEX coastal mangrove estuary has clear biophysical boundaries surrounding the small-scale mangrove crab fishery (RS1) between the Caeté and Taperaçú rivers on the Bragança Peninsula (RS2) covering over 420 km² (RS3). Accessing the mangrove is challenging; it requires taking a public bus or bicycle along a public road or a boat into small estuarine canals which are only accessible at high tide. However, actual crab collection is always done on foot, walking and wading through the mangrove area to find crab burrows located around tree roots. The mangrove forest is a swamp with entangled roots in deep thick mud, and requires considerable physical endurance and local knowledge to navigate for fishing (Figure 2) (RS4). Due to the difficulties with carrying large sacks of crabs, fishers don’t go far into the forest or stray off known routes (RS9) (Thies-Albrecht 2016). Seasonality affects cycles of ecosystem functioning (RS7). The rainy season, from January to May, is more difficult and dangerous for fishing activities than the dry season from June to December.

¹ The swim bladder is sun dried and sold to emulsifier industries and has a high value in export markets (Bentes et al. 2012).



Figure 2. (A) A fisher harvesting mangrove crabs (*U. Cordatus*) by hand. (B) Women processing cooked crabs in a privately owned facility. (C) Live mangrove crabs for sale in Bragança city market. (D) Fishing boats during low tide in the mangrove estuary. (All photos by authors).

Resource units (RU)

Multiple resource units are harvested in the CT RESEX, more than 20 have been identified including mixed finfish species, crabs and mangrove wood (Glaser et al. 2010b). This study focuses on the small-scale mangrove crab fishery for *Ucides cordatus*, the economically most important species. Second-tier variables can be applied to each resource unit (McGinnis and Ostrom 2014), but this reaches beyond the scope of this study.

Mangrove crabs (*Ucides cordatus*) are hardly mobile in their adult lives, typically foraging within a 1 meter radius of their burrow (RU1) (Diele and Koch 2010). Crabs seem to only venture further out during the annual 3-4 days of the “andança” reproduction period. Mangrove crabs have a slow growth rate and reproduce during the rainy season peaking in January and February (RU2). Females carry eggs for 3-4 weeks before releasing them during spring tides after which they spread across the estuary as juveniles (RU1; RU7) (Diele and Koch 2010). Fishers

distinguish male and female crabs by differences in body shape, reproductive organs, “hairiness” and distinct tracks in the burrow (RU6). There is a positive feedback loop between mangrove production, beneficial soil bacteria and crab foraging, where increases in one create direct or indirect increases in the other two (RU3; RS6) (Koch and Nordhaus 2010). Crab density in Northern Brazil is high, estimated at 1,650,000 individual crabs per square kilometer in a healthy forest (RU5; RS5) (Diele and Koch 2010). The number of crabs caught per fisher per day may be up to 300, with average catch per person per day (CPUE) around 150 crabs (RU5) (Nascimento et al. 2015). Mangrove crabs are sold live or as cooked and processed meat. Live crabs are sold to patrons for 2-5.00 Reals per crab (~0.6-1.60 USD); processed meat is sold for 7-25.00 Reals (~2.25-8.00 USD) per kilo locally depending on the season and quality (RU4), and 60-80 Reals in the state capital Belém.

Actors (A)

Multiple actor groups exist in the CT RESEX (Glaser and da Silva Oliveira 2004) and the second-tier variables could be applied to each separately (McGinnis and Ostrom 2014). We focus on fishers and RESEX residents as a combined actor group whose livelihoods are directly affected by the RESEX program.

There are ~4200 families distributed across 50 communities (A1) who are considered residents with the rights to use the CT RESEX. Communities are connected to each other and Bragança town by a main asphalt road and secondary dirt roads; the latter are difficult to access during the rainy season (A4). A majority of fishers and residents are highly livelihood dependent on extracting local natural resources, are either self-employed or contracted to extract crabs or wood for processing companies. Financial hardships can be directly related to seasonal and other changes in the local availability of crabs, and seasonal fishing closures during crab reproduction periods (A8). The socioeconomic conditions of rural dwellers in the CT RESEX are low-income and subsistence-based, with little access to many public services and infrastructure for many, but not all communities (A2).

Due to the scattered nature of village locations and difficulties in accessing the mangrove, many fishers harvest in the areas surrounding their places of residence or close to the coastline with boat access (A3) (Thies-Albrecht 2016). Accessing mangrove crab resources requires local knowledge on tidal flows, estuary navigation and the ability to identify crab burrows, size and the sex of the animals (A7). Fishers with boats have greater access to distant mangrove areas, but also incur higher time and monetary costs. Collecting crabs is only legal by hand, but poles with large fixed hooks are increasingly used to get crabs out of burrows deeper than an arm's length (A9). Hooks can injure undersized or female crabs, which should not be harvested. After about 2005, some fishers in the region have started to use plastic snare-like traps (*redinhas*) positioned at the top of a crab burrow. Snares are picked up on return trips, but some are forgotten, leaving plastic and dead crabs behind. Crabs are sold live to patrons (middlemen) or cooked and processed by women in the household for sale, or most recently processed by employees in a nascent artisanal processing industry. Entrepreneurship and leadership in the CT RESEX are weak (A5). In a few

villages, private businesses for crab collection and processing are being established, but this is being initiated by outsiders (non-residents of RESEX). Most fishers are beholden to patron-client systems which are often exploitative, but their only market access option (A4; A6; I4). Much in contrast to the period between 1996-2005 (Glaser and da Silva Oliveira 2004, Glaser et al. 2010b), today there is a general lack of capable individuals willing to invest time and effort to participate in RESEX politics or to take community leadership roles. This can be related to the fact that no compensation for lost income is paid to small-scale producers who engage with the RESEX, disagreements between leaders due to disputes over institutional power in management, a lack of leadership continuity, along with the minimal participation of young people. Many community leaders are older and no longer fish, many of our interviewees reported initial participation but dropped out over time due to a lack of financial incentives or perceived benefits. Fishing is perceived as a better use of time, resulting in direct income (A6). Recent programs to build leadership capacity organized by UNESCO and Rare (NGO) have attempted to address this challenge.

Governance systems (GS)

The Caeté-Taperaçú RESEX was created in 2005 as a co-managed Marine Extractive Reserve; where the rights to extract resources are given to an association of users to collectively develop rules (GS1; GS4). A timeline of key political events from 1990 to 2017 are shown in Appendix 2. The co-management rights apply exclusively within the RESEX boundaries (GS2) (Figure 1). In order to address identified user conflicts relating to the local mangroves, local village residents were offered co-management rights to address conflicts under the RESEX legal framework, then administered by the Conselho Nacional de Populações Tradicionais (CNPT), the predecessor of ICMBio. Since 1998, extensive diagnostic assessments were conducted in the area by the local university, the rural farmers union and CNPT/IBAMA. These contributed to the initiation of the RESEX in 2005. Despite these earlier efforts, the initial ‘diagnostic phase’ to assess the status of the area or the current management plan is stated in the official document as not having begun until 2009 (GS10). The final management plan was only published in 2012, stating the goal of “...conservation, preservation and sustainable use of natural resources...to improve the living conditions and enhancement of traditional culture for people...residing in and/ or around [the RESEX], (ICMBio 2012).”

The core co-management board of the CT RESEX is the Deliberative Council (DC). The DC is facilitated by ICMBio and comprised of local, regional and national actors. The DC contributes to “actions aimed at the implementation of the Management Plan,” (ICMBio 2012), deciding on rules or changes to rules (GS6). DC member organizations are considered as the rule-makers of the RESEX (GS5). The 50 communities are divided into 8 representative groups (*polos*). Table 2 shows member organizations of the DC. The management plan was generated and approved by ICMBio and the DC. Appendix 3 shows its current rules-in-use (GS6). The operational rules for crab fishing focus on user rights, similar to those in other benthic and crustacean fisheries (Basurto et al. 2013, Partelow and Boda 2015). A Monitoring Program (Program of Voluntary Environmental Agents) was created by IBAMA in which some residents received training in

environmental education, protection, preservation and conservation of natural resources in the RESEX area (Brazil 2005). However, the program was largely unsuccessful due to conflicts with monitoring and rule compliance involving relatives and friends of volunteer agents (Amaral et al. 2008) and was thus discontinued in 2013 (Brazil 2013a). Therefore, although graduated sanctions exist, they are no longer enforced by registered users themselves or by external authorities (Ostrom 1990). However, registered users are obliged to pay a tax to the DC for monitoring and enforcement. A 50 year concession is given to the association of users (ASSUREMACATA) with rights to grant access, resource extraction, management and exclude others, but the alienation rights and the actual land title are held by the Brazilian state (GS7) (Schlager and Ostrom 1992). Table 2 shows the multi-level network structure for co-management (GS9).

Table 2. Stakeholder groups with one seat on the Deliberative Council each.

Organization type (GS5)	Stakeholder group	Role/ mission	Level of jurisdiction
Public sector GS5.1	Chico Mendes Institute for Biodiversity Conservation (ICMBio)	Direct management, implementation and oversight of RESEX areas	Local Regional National
	Camara Municipal of Vereadores	Legislative body of the municipal administration promulgates organic law and legislative inspection.	Local
	City Council of Bragança	Seat of executive power, enforces laws.	Local
	National Institute of Colonization & Agrarian Reform (INCRA)	Advanced agrarian reform through formalizing land tenure for economic development.	National
	The Port Authority of Eastern Amazonia (CPAOR)	Maritime authority responsible for compliance with maritime and port laws and regulations.	Regional
	Secretary of State for the Environment of Pará (SEMA)	Regional office of national environment secretary.	Regional
	Institute of the Environment & Renewable Natural Resources (IBAMA)*	Oversees ICMBio, provides social and environmental research and research permits for resource management and manages constitutional framework for the RESEX areas (e.g. licensing, user registration, law)	National
Private sector GS5.2	Enterprise Technical Assistance & Rural Extension Pará (EMATER)	Official organization that promotes Technical Assistance and Rural Extension	Local Regional
NGO GS5.3	Federal University of Pará (UFPA)	University, provides scientific support and consultation.	Local Regional
	Women Movement Paraense Northeast	Social feminist movement that has been implementing a network to avoid violations of women's human rights.	Regional

Part 3: Empirical research

Community-based GS5.4	Polo Tamatateua Polo Center Polo Caratateua Polo Acarajó Polo Treme Polo Bacuriteua Polo Ajuruteua Polo Campos	Represent communities (in separate groups) in the CT RESEX.	Local
	Association of Users CT RESEX (ASSUREMACATA)	Represents registered users of the CT RESEX as a whole. Holds land title to CT RESEX. Responsible for implementing rules of the management plan.	Local
	Union of Artisanal Fishers of Bragança PA	Represents the rights of artisanal fishers in a local context.	Local
	Breeders and Bragança Beekeepers Association	Local NGO	Local
Hybrid GS5.5	National Council of Extractive Populations (CNS)	Represents the rights of agro-extractivist workers in a national context.	National
*IBAMA is not on the Deliberative Council, but oversees RESEX and protected areas throughout Brazil, and is tasked with the formal approval and implementation of legislation proposed by the Deliberative Council, through ICMBio.			

The RESEX program was subsidized with development aid through the Bolsa Verde program, targeting households directly dependent on resource harvesting. To qualify for Bolsa Verde, families must be registered residents of the RESEX with the ICMBio office and earn less than 70 Brazilian Reals (~22 USD) per family member per month. The program provides 300 Brazilian Reals (~95 USD) every two months with the aim to reduce over harvesting due to financial needs. Approximately 3,700 families are part of the program increasing their income significantly. However, criticism for the Bolsa Verde program is that it only focuses on terrestrial resources, which may result in greater pressure on marine resources, due to the displacement of terrestrial harvesting (Kasanoski 2016).

Related ecosystems (ECO)

Low lying mangrove estuaries are vulnerable to sea-level rise (ECO1). Landward shifts of the mangrove/marsh in the Bragança region to higher ground have been observed since 1972 and have been linked to increases in mean sea level (Lara et al. 2010). Mangroves are moderately resilient to sea level rise, but this can be compromised by human activities which disturb sedimentation processes (Krauss et al. 2014, Woodroffe et al. 2016). In Bragança, disturbances include the removal of crabs, altering river flows around settlements, forest degradation due to wood harvesting (Glaser et al. 2003) and infrastructure development such as the road construction through the middle of the Caeté peninsula causing considerable erosion.

Interactions (I)

Key interactions 1: Altered social and political momentum

In 2005, co-management was new for coastal populations who were keen to assume some control over decision-making on the natural environment their livelihoods depended on (Glaser and da Silva Oliveira 2004, Diele et al. 2010). The CT RESEX was officially declared in 2005 (A3) after four years of preparatory meetings, networking, collaborative analyses and capacitation work with local residents, NGOs, unions and a further two years of legislative processing by the responsible agencies at the national level (IBAMA/CNPT). In the first decade, the incentive to influence and implement the rules most central for local livelihoods was a key driver behind local participation to support the RESEX (GS10) (Glaser and da Silva Oliveira 2004). However, this momentum changed. Administrative delays, altered livelihood options and political favoritism all played a role. Previous leadership and momentum dissipated as numerous key individuals from the earlier period were no longer involved, while leadership of political movements without much local knowledge took over. This hindered local participation and representation for continued action. When the RESEX was finally created with a formal management plan, nearly 10 years after its inception, changing leadership and shifting perceptions of its purpose had reduced local motivations for continued effort and involvement.

Key interactions 2: Shifting perceptions, communication and location

In the late 1990s and early 2000s, there was a high level of social energy that initiated and sustained collective efforts to establish co-management. However, local perceptions of the purpose and benefits RESEX co-management would bring began to change. In its initial period, the RESEX rationale focused on empowering local communities to be semi-autonomous in how they regulate the use, management and conservation of local natural resources. As the program took shape however, the significant social benefits such as free houses, “green” scholarships and a range of durable consumer goods (e.g. fridges and stoves) led the local residents to start perceiving the RESEX as a government social aid program. This was in full accord with the RESEX objective “to include traditional populations into the national development process” (Allegretti 1987, 1994). During this social development process, achieved in a period of socialist government, RESEX was associated with multiple social development forces (Movimento sem Terra; Bolsa Verde). The impressive range of material benefits associated with this shifted local perceptions and expectations away from the collective efforts for natural resource co-management. With material gains, livelihoods depended less on the mangroves. Outside families were also motivated to move into the RESEX area where help with their substantial development needs such as housing, education and consumer goods, was available. Fishers also migrated to the region as it became a commercial hub. As a result, the number of registered RESEX users increased substantially and before long subsidized housing was no longer available for everyone who needed it.

Skepticism of the social development programs came to relate to the whole RESEX, grounded on the newly emerged idea that the RESEX purpose was to distribute subsidized social development aid. These developments undermined the local incentives to work together through co-management, in order to take and implement collective decisions for the area and its future. Success in establishing sustainable human-nature relations through collective action was thus displaced by falling dependence on local mangrove resources, by dysfunctional leadership and by multiple social subsidies, which were perceived as failing to deliver evenly distributed benefits. This social and political momentum for RESEX thus stagnated along with the trust and confidence of those working to achieve its original goals.

Unclear communication about the purpose of RESEX and other development programs contributed substantially to why perceptions shifted. Information flow between all actors was minimal and influenced by competitions for political influence. Many residents tried to capitalize on development programs for short-term gains. For the average mangrove user, it became easier to improve their socioeconomic situation through development aid than by investing in the co-management of resource harvesting. Those in leadership positions are reported to have competed for power and influence rather than investing in long-term efforts to establish collective governance through co-management.

Three information flow bottlenecks can be identified as influential. First, only a few key individuals were well informed about the purpose and motivations for the RESEX, and the number of actively engaged individuals has decreased over time. Second, ICMBio lacked monetary and human resources to develop communication channels, disseminate official information and train community leaders, leaving information about RESEX to be overshadowed by rumors, discontent, and politically motivated misinformation. Third, with 50 geographically isolated communities, official information did not reach many actual mangrove resource users. Communities have been historically separated, in part due to the characteristics (RS9) of the resource system (mangrove) and resource units (mangrove crabs). Mangrove crabs live rather stationary and non-migratory adult lives, and fishing areas seem to have emerged according to the local ecological knowledge about crab distributions, with certain productive fishing areas being more easily accessible than others. Communities have likely been established around these areas due to patterns in resource harvesting, benefiting from known routes through the difficult-to-navigate mangroves (Thies-Albrecht 2016). Although there is no formal property rights system for fishing, informal fishing areas are recognized and implemented by local fishers. Rights to access fishing areas are often temporally delimited, relating more to when you fish than where (Oliveira and Maneschy 2014). Difficulties in communication and market access can be seen as a geographical consequence of how local communities have co-developed informal fishing areas with local ecological knowledge of the mangrove and crab populations. The still very close link between mangrove-adjacent villages and their surrounding resources still suggests a great need for a sustainable local extractivism that resolves difficult and spatially reinforced social-ecological linkages.

Key interactions 3: Patron-client relationships and social-ecological traps

The price of mangrove crabs has increased over time, driven by increasing demand from markets for seafood throughout Brazil. The State of Para is a top provider of seafood nationally. However, prices received by local fishers remain low due to exploitative patron-client relationships. Patrons control market access for most fishers who reside remotely and cannot transport crabs to market independently. Profits do not trickle down to local fishers beholden to patrons who offer low prices, increasing their own gains. Fishers often cannot select alternative patrons, as there are few to choose from.

Exploitative patron-client systems can lead to overharvesting since increased extraction is the only way to make a better living when receiving low prices. Overharvesting is also motivated by high crab mortality during transportation (25-55%) (Legat et al. 2006). A ventilated plastic box with a water-soaked lining is mandated but unlikely to be used by many or enforced (Brazil 2013b). Similar situations have been described in the literature as social-ecological traps (Boonstra et al. 2016). Overharvesting pressures in combination with difficulties in accessing new mangrove areas due to informal fishing areas, have forced fishers to begin harvesting smaller (illegal) crabs locally, which have lower market value. Harvesting greater quantities of smaller crabs is necessary to earn a stable income. Fishers often become indebted to patrons, and loans are difficult to pay back due to limited crab availability and tidally limited fishing time, and by the lack of alternative livelihood opportunities. This self-reinforcing negative feedback loop, where low prices lead to overharvesting in order to maintain a stable income, slowly degrading ecological productivity and economic value of the resource over time, termed “a vicious circle” (Glaser et al. 2010, p.329) which undermines the integrity of the mangrove forests as a mechanism of social insurance for the poor who rely on local natural resources when other economic and food options are not available.

Key interactions 4: Institutional fit and equitable participation in co-management

Transitioning from no formal governance to co-management is an institutional novelty for most residents. Traditional populations are being challenged to reconfigure their institutional space, the social structures within which they interact, engage with the concept of governance and use local knowledge to make beneficial changes to their own resource use behavior (Esterci 2002, Teisserenc 2014, DiPaolo 2017). While the informal institutions of the early 1990s are now formalized in the RESEX rules, informal institutions have continued to change. Formal RESEX rules are not conceptualized to follow but such adaptiveness is needed to make the RESEX work. Many fishers find participation in RESEX-related meetings confusing and ineffective, despite the goal of creating a more equitable deliberative environment. Equitable participation is a practical challenge, as some actors have more knowledge about the RESEX and are more familiar with participating in formal political meetings, such as members from local universities, ICMBio and the municipality. This can reinforce existing narratives of disempowerment and mistrust through formalizing governance and procedural approaches which favor the participation of the actor groups who designed them. Although residents have the largest number of seats on the

Deliberative Council, their influence is disproportionately small (Silva-Junior 2013, Narahara 2014).

Key interactions 5: Harvesting closures and compensation

A temporary ban on crab harvesting (I1) occurs during key reproductive periods called *andanças*, mass mate-searching events which take place 4-5 times per year for up to 4 days each (Diele and Koch 2010, Brazil 2017) (GS6). During reproduction, crabs spend longer periods outside their burrows, leaving them exposed to harvesting (RU2). Fishers are not compensated for lost income during seasonal closures, and there is little rule enforcement relating to the collection of crabs by hobby and leisure collectors during the *andanças*. Fishers requested closures themselves, with the condition that they can receive compensation (“seguro defeso”) for not fishing from January to April during crab reproduction and from June to September when crabs change their carapace, (Bragança 2009, Nascimento et al. 2015). However, communication about official rules and seasonal closures² is minimal in some areas, many fishers simply do not know about them. The lack of compensation for lost income during closed periods with few alternative income sources and low knowledge of rules means that fishing during seasonal closures largely continues even when it is well known as bad practice. When income is low, the mangrove acts as a form of insurance for many families who harvest local resources for subsistence (such as crabs and wood) when they cannot purchase additional food or supplies (A2). Overharvesting undermines the resilience of the ecosystem and crab populations, which in turn undermines the ability of ecosystems to act as a reliable source of food security and insurance that can support social welfare.

Outcomes (O)

Our results engage with recognizing complexity, in an attempt to avoid overly simplified models of SES outcomes and their drivers. Trends in recent progress towards CT RESEX goals can be briefly synthesized from our analysis. Resource dependent livelihoods remain vulnerable to ecological and social changes. Co-management has not motivated sufficient collective action to continue the momentum for the substantial changes needed to pull fishers out of social-ecological traps, or to bring diversified economic opportunities and decrease the fragile dependence on local natural resources. Social development programs attached to RESEX have made progress on reducing local resource dependence, but this is not due to successful co-management. Collective action is a foundation for co-management success but collective efforts have not occurred to a sufficient degree to suggest co-management has been successful in achieving RESEX goals (O1). Significant barriers have appeared. There are many different social and ecological reasons why

² Santos and Schiavetti (2017) alert that there is a lack of clarity in Brazilian environmental legislation regarding the concept of the right to use the coastal environment and contradictions between Brazilian environmental legislation and some rules in marine RESEX areas.

collective action and co-management have stagnated. The SES conditions influencing collective action from the SESF are shown in Table 3. Viewed in combination, we can see how current theories help explain hindered progress. Beyond needed collective action on the Deliberative Council and among residents to motivate political will, there remains a need to improve livelihoods and social outcomes. Many social performance measures have remained the same since pre-RESEX. Ecologically, crab population data and harvesting rates suggests stability, although evidence for increased mangrove degradation, gradual increases in catch-per-unit effort and the number of fishers suggests that this will likely degrade ecological health if continued at current rates (O2). Any substantial ecological degradation or changes to resource abundance and distribution would certainly bring reciprocal social impacts. Sea level rise, human migration into the area, the development of industry and political instability are likely to bring increasing pressures and challenges for effective governance, but their precise impacts are difficult to assess (O3).

Table 3. SESF second-tier variables and their case value in the CT RESEX associated with hypotheses of collective action theory (Ostrom 1990, Poteete et al. 2010, SESMAD 2014). A general trend is shown for cases values current and a brief contextual explanation.

SESF	Hypothesis/ theoretical claim for collective action (CA)	Case value	Case trend	Case explanation
A5	Accountable leadership increases likelihood of CA.	Low	Unclear	Shifting social momentum and lack of capacity minimizes motivation to participate.
A6; I2; GS3	Communication increases likelihood of CA.	Low	Unclear	Geographical isolation and lack of effective mechanisms for communication.
GS6; I4	Conflict resolution mechanisms increase likelihood of CA	Low	Unclear	Lack of regular Deliberative Council meetings. Lack of monitoring and rule enforcement.
GS6	External sanctions can override pro-social motivations, decreasing likelihood of CA.	Low	Unclear	Minimal self-monitoring or external sanctioning occurs.
A2	Cultural heterogeneity decreases likelihood of CA.	Medium	Stable	Informal social and cultural institutions differ between actor groups on Deliberative Council.
A2	Economic heterogeneity of actors increases likelihood of CA.	High	Stable	Most residents have very low income, external actors are wealthier and can invest more.
A1	Smaller groups increase likelihood of CA, reducing transaction costs.	High	Increasing	4200 registered families. Many other actors are involved (e.g. NGOs, political, academics, state).
A2; A8	If actors have a common interest, CA is more likely.	Medium	Unclear	Undermined by shifting perceptions and motivations to participate in RESEX.
A8	High dependence on local natural resources can motivate CA.	High	Stable	Residents are highly and directly dependent on local resources, but other RESEX actors less so.

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A6	Past collaborations increase likelihood of social capital and therefore CA.	Medium	Decreasing	Early social-political momentum initiated collective efforts, but this diminished, past leaders are no longer involved.
A2; A6	If costs bring proportional distribution of benefit, CA is more likely.	Medium	Unclear	Short-term benefits are few; long-term benefits are difficult to prioritize and incentivize.
I2; I7, I8	If transaction costs of CA are high, it is more difficult.	High	Unclear	Participation difficult with institutional differences. Long-term character of benefits reduces short-term incentives.
A1	If user group boundaries are clear, CA is more likely.	High	Stable	RESEX has clear user group boundaries. Users need to register to receive benefits.
GS6; GS8	Graduated sanctions increase compliance and trust in institutions for CA.	Medium	Unclear	First verbal or written warning, then 30-90 day suspension of extraction rights, then permanent exclusion. However, no cases of enforcement.
GS6.2	Collective choice rules for decision making increases likelihood of CA.	Medium	Unclear	RESEX ensures collective choice arrangements through the DC. A legal framework exists, but this does not work well in practice.
GS6.3	Rules fit (e.g. accepted by) outside authorities increases likelihood of CA.	High	Stable	Constitutionally mandated
GS4; GS8	Governance fit to local needs and institutions increases likelihood of continued CA.	Medium	Unclear	RESEX is a step in the right direction. Co-management aims to fit and evolve from local informal institutions. Initial social energy has declined, leaving an unclear path forward.
GS9	Nested levels of governance increases likelihood of continued CA.	High	Stable	See Table 5
RS2	Clear biophysical boundaries increase likelihood of CA.	Low	Stable	Boundaries are difficult in practice, and the mangrove ecosystem is continuous.
RS3	Moderate biophysical size is more conducive to CA.	Medium	Stable	Communities are scattered with isolated fishing areas, but social interactions are possible.
RS5; RU2	Productivity is curvilinear for CA, too high or low decrease likelihood.	High	Decreasing	Crab production is very high, which may be giving a false impression of stability and need for CA among fishers.
RS7; RU7	System predictability increases likelihood of CA.	Medium	Unclear	Crab reproduction is highly predictable, closure rules potentially effective if followed. Other factors like sea level rise decrease predictability.
RU6; I1	Resources with distinctive markings can be harvested or managed more selectively,	High	Stable	Easy distinction of crab gender increases ability to harvest selectively, reducing the extraction of reproductive females.

	increasing likelihood of CA.			
RU4	Low value produce may not incentivize CA, but high value produce can lead to overexploitation that is too fast for institutions to respond.	Medium	Increasing	Fishers receive low value from patrons, which does motivate CA as they need to spend more time fishing. Overall crab prices are going up. However, institutional responses are slow, taking decades to establish RESEX in practice.

Discussion and conclusions

Marine RESEX programs exist throughout Brazil and their unique institutional arrangements have motivated numerous studies (da Silva 2004, Diegues 2008, Santos and Schiavetti 2014, Nobre et al. 2017) examining the inclusive approach to MPA governance, which combines human well-being objectives and conservation goals (Bennett et al. 2017). However, marine RESEX have struggled to achieve success in mangrove conservation (Santos and Schiavetti 2014, Borges et al. 2017) in line with MPAs globally (Halpern 2014, Bennett and Dearden 2014). The institutional complexity of MPA governance continues to challenge scholars and practitioners (Jones et al. 2013, Alexander et al. 2016).

Some general lessons can be drawn from this analysis allowing for some general conclusions about the wider Brazilian and MPA context. Regional and local ICMBio offices have few resources for implementation and outreach, mirroring findings showing that a lack human and financial resources are a considerable barrier for MPA success worldwide (Pomeroy et al. 2005). The benefits of RESEX co-management have not always been clear to remote resource users who would benefit most from its implementation; and decision-making has not always represented the diversity of actors' socioeconomic conditions and livelihoods (Santos and Brannstrom 2015). This supports the shift towards making MPA governance more inclusive and participatory with local people to enhance success (Glaser et al. 2010a, Tam 2015). Social and institutional differences as well as the historical marginalization of rural fishing communities in national policy have created challenges with communication about the purpose of RESEX. The perceived legitimacy of and trust in the RESEX as an institution, to collectively invest in, was therefore never fully established. Local and regional politicians have used the RESEX and associated social development programs to leverage their own political agendas, often misaligned with the original co-management goals.

While collective action of resource users is a necessary pillar of co-management success, so is strong and continued state commitment. Resilience to shifting social and political momentum requires mechanisms and platforms where deliberation, knowledge exchange and social learning among actors can inform decision-making (Armitage et al. 2008, Reed et al. 2010, Plummer and Hashimoto 2011, Tengö et al. 2014). Facilitating iterative deliberation and capacity building were initially recognized as necessary, but implementation is difficult without well-supported and well

intentioned leadership, and without substantial institutional transformation to render the deliberation process itself more inclusive. Continued investments to maintain communication and capacity building efforts would certainly be beneficial to address shifting perceptions and political discontent among local actors.

Ostrom's Design Principles provide a theoretical framework for evaluating enabling conditions for community-based governance, and studies of other marine RESEX show that co-management has provided many of these conditions in concept, but that they have been difficult to establish in practice (da Silva 2004, Nobre et al. 2017, Tebet et al. 2018). This study draws similar conclusions, expanding on the Design Principles by applying broader theories of collective action. Finding effective conflict resolution mechanisms through the Deliberative Council, although envisioned, has been difficult since the active and regular participation of local actors was not successfully facilitated. Leadership accountability and consensus-building among fishers and RESEX members have suffered in the context of other social development programs, not least due to a lack of communication and well-established collective-choice rules for regular meetings and decision-making. As of 2016, we observe a misfit between formal co-management rules and local informal institutions; many residents are not familiar with self-organizing activities or regular participation in local governance. This study aligns with similar reflections and concerns in other RESEX areas (da Silva 2004, Di Ciommo 2007, Vadjunec and Rocheleau 2009, Santos and Schiavetti 2014, Erler et al. 2015, Santos and Brannstrom 2015, Le Tourneau and Beaufort 2017, Nobre et al. 2017). Setting up co-management is not enough, continued efforts to create more user engagement and stronger institutions that can establish harvesting rules congruent with local livelihood sufficiency and ways to control adherence to them are needed. Despite these challenges, there remains political momentum to establish new reserves in other areas; coastal governance in the RESEX format still symbolizes empowerment and the inclusion of marginalized rural populations into national governance (Santos and Schiavetti 2014, Santos et al. 2017).

From the perspective of resource users, high dependence on local natural resources with low market values due to sub-optimal patron-client relations makes developing incentive structures for participation in co-management difficult when time, money and motivations are scarce and volatile. Patron-client systems in small-scale fisheries might in some cases evolve to provide mutual benefits (Ferrol-Schulte et al. 2014), but the remote locations, high dependence on few patrons and increasing external market prices in the CT RESEX make this, as many other patron-client relations (Glaser et al. 2015) strongly asymmetric. Small-scale fisheries have been facing these challenges for decades, often driven by the integration of fish products into global markets with complex supply chains that do not bring proportional economic gains back to rural fishers (Berkes et al. 2006, Eriksson et al. 2015, Bennett and Basurto 2018). Long-term sustainable exploitation is difficult to adhere to when short-term gains are needed, often driving overexploitation to meet basic needs or pay back debts (Glaser et al. 2010b). Incentives to change harvesting behavior and support governance reform are low when promised reform to establish the RESEX has taken more than a decade.

Co-management may only work when the intended beneficiaries are motivated to act collectively to support. Motivations for self-organization among residents are affected by multiple factors, but this analysis has focused on how and why user perceptions form in relation to the legitimacy and usefulness of governance models. However, even if some or many residents do view co-management as beneficial, further consideration for how formal models of governance interact with existing local social and cultural institutions is necessary (Glaser et al. 2010a, Rahman et al. 2017) to achieve an adequate level of institutional fit to the social-ecological context (Olsson et al. 2007, Epstein et al. 2015).

A growing body of literature, including this study, suggests the need to consider social-ecological complexity in the design and successful long-term implementation of co-management (Armitage et al. 2009, Bodin 2017). Outcomes that are collectively accepted as beneficial are more likely to be achieved when governance institutions are adaptable, i.e. can evolve to a changing social-ecological context (Plummer and Hashimoto 2011, DeCaro et al. 2017, Whitney et al. 2017). Limited knowledge on SES complexity and the integration of such knowledge into policy practice obstruct the CT RESEX and other MPAs (Poltnac et al. 2010, López-Angarita et al. 2014). This relates to recognizing local traditional (Tengö et al. 2014), system, target and transformative knowledge (Partelow and Winkler 2016).

The SESF has proven to be a useful research tool for advancing this knowledge, helping to describe the complexity of variables and identifying knowledge gaps. The SESF is useful as an organizational and coding framework for analyzing large amounts of qualitative data. However, it is not obvious how the SESF can facilitate an analysis of the interactions between variables methodologically without better linking to theory. Theory such as collective action helps to unpack the potential explanations why certain variables influence outcomes. However, understanding the interactive effects between variables; i.e. how clusters of independent variables interact to shape outcomes, is more difficult to measure empirically, hindering the development of theory to better understand complex SES. Further applications of the framework should focus on developing methods for analyzing the interactions between variables (Hinkel et al. 2015, Leslie et al. 2015, Partelow 2015). This study frames ‘key interactions’ as the clusters of variables shaping important outcomes with thick qualitative descriptions. This is a different conceptualization of the ‘Interactions (I)’ variables as originally envisioned in the SESF, as the variables representing the spaces where actors deliberate and make choices influencing the SES. Perhaps another way to view interactions between variables in the SESF, as done in this study, is to identify which variables interact to build on existing theories (e.g. social-ecological traps), or to generate new hypotheses of how variables interact in a SES.

Co-management is as much about gaining the acceptance of local people through fostering an environment of social and political momentum as it is about establishing the appropriate formal governance arrangements (Bennett 2016, DeCaro et al. 2017). Further linking collective action and institutional change theories with MPA co-management literature may provide a better understanding of these underlying social processes and how they can influence whether formal governance will work in practice (Schlüter et al. 2013, Weber de Moraes et al. 2015). These processes are constantly fluctuating over time, thus co-management requires persistent and

regular efforts to maintain collective efforts. An understanding of how the CT RESEX evolved over time was useful to unravel the changing political narrative in the course of its establishment. Historical evidence and qualitative time-series data can provide useful insights, and further research can explore how the SESF can be applied to sort through the social-ecological complexity of changing political narratives and how this relates to collective action over different time periods (McGinnis and Ostrom 2014).

To conclude, we focus on some specific aspects of our case study and policy reflections for marine RESEX throughout Brazil. The CT RESEX would benefit from numerous actions and policy changes that will move it more towards adaptive co-management. Capacity building through increased communication and outreach to local residents seems necessary to regain trust and social energy to support RESEX by emphasizing the opportunities that can come from collective empowerment. As there are many inherent system characteristics reducing the likelihood of collective action, developing the right incentives to participate for all actors needs to be acted on, by addressing known barriers. If communities are isolated, disseminating information and communicating through local organizations, media publications and radio may help to connect them. If local cultural institutions do not fit well with the formalities of governance, adapting meeting locations to community time preferences and locations may be useful. New formats for Deliberation Council meetings may create more space for equitable participation, building up social capital among actors and creating knowledge exchange (Brewer 2012, Nenadovic and Epstein 2016). Programs supporting alternative livelihoods and recognizing the role of women in the emerging crab processing industry may help break the “vicious circle” of social-ecological traps and motivate renewed social energy for change among women who are typically not included (Santos 2015, Koralagama et al. 2017). Developing incentives to motivate young residents into leadership roles and into education opportunities outside the area could advance social development goals (Zurba and Trimble 2014). These changes are, of course, easier stated than done. It is also apparent that many motivated individuals continue to invest time and effort into RESEX progress. Overall, the CT RESEX in the context of Brazilian policy progress can be viewed as a positive development. However, broader critical reflection on the contemporary marine RESEX program is in order. RESEX was established to support communities with strong pre-existing self-organizational capacity; such was the case with the rubber harvesters in the era when Chico Mendes and many others struggled for it. Formal co-management was the last piece in their struggle for empowerment. In many RESEX now, formal co-management is instead the starting point. Even if social and political momentum to establish a RESEX area was initially there, collective action must be continuously built up under conditions where it might face considerable difficulties. This does not suggest that co-management cannot work, but considerable adaptations are likely to be needed for success.

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Appendix 1. The SES framework with alternative structure for Governance Systems (GS) proposed by McGinnis & Ostrom (2014).

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) 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	Governance Systems (GS) GS1- Policy area GS2- Geographic scale of governance GS3- Population GS4- Regime type GS5- Rule-making organizations GS5.1- Public sector GS5.2- Private sector (for profit) GS5.3- Non-governmental (non-profit) GS5.4- Community-based GS5.5- Hybrid GS6- Rules-in-use GS6.1- Operational choice rules GS6.2- Collective choice rules GS6.3- Constitutional rules GS7- Property-rights systems GS8- Repertoire of norms and strategies GS9- Network structure GS10- Historical continuity
Resource Units (RU) 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	Actors (A) 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
Interactions (I) 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	Outcomes (O) O1- Social performance measures O2- Ecological performance measures O3- Externalities to other SESs
Related Ecosystems (ECO) ECO1- Climate patterns ECO2- Pollution patterns ECO3- Flows into and out of SES	

Appendix 2. Timeline of key events.

Date	Event
1990	First RESEX created in Brazil
1960 to 90's	Drought related immigration waves from the State of Ceará to Bragança, and from the logged and cattle farmed Amazonian rainforests, both expanding the fishing sector.
Late 1990's	First social movements advocating for RESEX establishment in Bragança.
1995	"Mangrove Dynamics and Management" (MADAM) research program was initiated to research the dynamics of mangrove ecosystems and to support the formulation of management recommendations based on this knowledge.
2000	First concerted initiative at RESEX creation in Bragança with required preliminary studies.
May 2005	Creation of the Caeté-Taperaçu RESEX. "Plano de Utilização".
August 2005	Association of RESEX Users (ASSUREMACATA) is established.
2006	Benefits come to RESEX members (houses, scholarships, compensation payments for foregone use of nature, consumer goods such as refrigerators, cookers).
2007	Constitution for the RESEX Deliberative Council established.
2008	Dispute between community leaders for the institutional political space in RESEX management (legislative election- "vereador").
2009	Chico Mendes Institute for Biodiversity Conservation (ICMBio) established.
	Arrival of the first manager of the RESEX
	Start of process to develop management plan.
	The meeting "I Forum paraense do caranguejo-uça" with 500 crab collectors representing 21 municipalities from State of Pará discussed the crab fishery management.
2011	The "Contrato de Concessão de Direito Real de Uso" (Land concession to the association of users) of the RESEX was established for 50 years
	Publication of who is eligible to receive benefits from governmental programs in the CT RESEX, decided by the Deliberative Council.
2012	Publication of Management plan for the Caeté-Taperaçu RESEX.
2013	Judicial suspension of user association (ASSUREMACATA)
2014	IDATAM (Institute of Development and Technical Assistance of the Amazon), civil association that provided services of technical assistance and rural extension to RESEX communities.
	Creation of CONFREM ("Comissão Nacional para o Fortalecimento das Reservas Extrativistas e dos Povos Extrativistas Costeiros Marinhos"): Representation of Traditional Populations from marine RESEX areas.
2015	Evaluation workshop with 40 communities represented.
	Meetings to update the operational use rules of the RESEX (Work Groups: crab, fisheries, currais and monitoring).

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	“Acordos de Gestão” (Updating of “Plano de Utilização”)
2017	Training of young people in sustainability by UNESCO Cooperation Program and Vale Foundation (Sustainable Fishing Project on the Amazon Coast – “PeSCA”)
	Training program for leadership and biological monitoring of fisheries- crab, <i>Ucides cordatus</i> , and king weakfish, <i>Macrodon ancylodon</i> - was initiated by the NGO Rare (Fish Forever Program).

Appendix 3. Rules-in-use.

Rules-in-use (GS6)	Rules
Operational rules* (GS6.1)	<ul style="list-style-type: none"> - The RESEX is divided into six use zones: Population, Extraction, Recovery, Community Reserve, Priority Conservation, Priority Sustainable Tourism - Access to natural resources is restricted to registered CT RESEX users - Welfare subsidies only given to individuals or families meeting certain conditions - Fishing gear limited to traditional and small-scale techniques - Seasonal closure for crab reproduction, but no compensation - No harvesting of female crabs, minimum male crab size of 6 cm carapace - Enforcement should include community participation - Basic infrastructure for harvesting can be built (e.g., paths, roads, piers) - Tax paid by registered users to Deliberative Council - Graduated sanctions
Collective choice rules* (GS6.2)	<ul style="list-style-type: none"> - Deliberative Council (DC) develops management plan and its implementation - All complaints about the RESEX are dealt with in the DC - DC collects user tax funds to develop monitoring programs - Can enforce graduated sanctions - DC is supposed to meet every 3 months, but receive no financial support - Decision making is done by voting by the different stakeholders on the council - Consensus is needed when voting, but when it is not reached, a vote is taken - Which stakeholders are on the council is constitutionally mandated - Management plan valid for at least one year from the date of its approval by IBAMA. Proposals for changes can only be made after this period
Constitutional rules* (GS6.3)	<ul style="list-style-type: none"> - Formal management plan given to IBAMA to approve - RESEX must have a Deliberative Council with specific stakeholders involved - 50 year land use concession granted to users - Management plan needs to be updated every 5 years - Any significant social or environmental intervention in the RESEX must be approved by the respective supervisory agencies - Changes in the rules may neither conflict with the objectives of the reserve nor with current national environmental legislation
* Rules are not a fully exhaustive list	

Research 6: Collective action, co-management and small-scale fisheries: Applying the social-ecological systems framework to compare three Responsible Fishing Areas (AMPRs) in Costa Rica

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Abstract

Costa Rica is supporting Marine Areas of Responsible Fishing (AMPRs) to enable small-scale fishing communities to apply for exclusive harvesting and management rights within spatially delimited areas under a co-management policy framework. Communities need to self-organize their own fishing association and develop a fishing management plan to apply for an AMPR. In this article we apply the social-ecological systems framework (SESF) to diagnose and compare the multitude of challenges facing the establishment of three AMPRs in the Gulf of Nicoya. Collective action is needed to establish an AMPR and to make continued implementation work, but all three cases struggle for success. We identify the social and ecological conditions influencing collective action in each AMPR and compare the similarities and differences between them. Empirically, we conducted 126 interviews with government officials, civil society organizations, community leaders and fishers to conduct a qualitative comparative analysis of the drivers influencing collective action and co-management success with the SESF. Our results show initial success but all face continuing difficulties for different reasons. Nonetheless, some commonalities exist. Common drivers of collective action to initially establish the AMPRs include the desire to restrict certain types of fishing gear due to perceptions of resource scarcity, high dependence on local resources, and the necessity to improve and develop alternative livelihoods. A few variables continue to enable collective action, but these variables differ between cases, particularly in their interactions with other variables and degree of influence, such as the effectiveness in monitoring and sanctioning mechanisms, the presence of effective leadership and the economic heterogeneity of actors. However, in all three cases, there are more variables hindering collective action. A primary challenge is the difficulty with governing fishing areas that have heterogeneous gear types because fishers tend to perceive the challenges for governance, perceive resource scarcity, form social groups and adhere to rule compliance based on the gear type they use. In addition, mistrust among actors, internal conflicts, non-rule compliance, lack of governmental support and resource unit mobility all hinder collective action. Our findings suggest that AMPRs are a promising and potentially effective governance strategy for empowering and integrating often marginalized small-scale fishing communities into national development processes. However, more investment from the state and local communities is

needed to make governance strategies more deliberative through capacity building. This will increase the likelihood that AMPRs are viewed as an acceptable and legitimate governance approach and help to ensure that governance institutions are adapted to fit the social-ecological context of each AMPR.

Key words

Social-ecological system | common-pool resources | small-scale fisheries | Marine Protected Area (MPA) | co-management | cooperation | responsible fishing

Introduction

Small-scale fisheries (SSF) provide 90% of the livelihoods and account for 50% of the total fish capture in the global fisheries sector (FAO 2015). In many tropical countries, SSF are a central pillar of wellbeing for rural coastal communities, providing a primary source of food, shaping cultural identity and maintaining an artisanal way of life dependent on local natural resources (FAO 2014a, Biswal et al. 2017). However, SSF face a myriad of critical challenges for sustainability. Overexploitation due to their characteristics as Common-Pool Resources (CPR) (Schlager 2004, Acheson 2006), and the manifestation of social dilemmas for management (Schlager 2004), are often combined with weak or ineffective top-down state governance (Holling and Meffett 1996, Biswal et al. 2017). In cases where fishing communities are able to govern themselves, it is often due to self-organized community-based governance, where fishers have taken responsibility for management through developing and maintaining strong institutions (Noble 2000, Jentoft 2004, Chuenpagdee and Song 2012). However, many SSF are not able to self-organize or adapt institutions to changing conditions. In other cases, community-based management may not be sufficient to address external influences such as incoming migration (Binet et al. 2012, Cripps and Gardner 2016, Wanyonyi et al. 2016), local or global roving banditry (Berkes et al. 2006, Cox et al. 2017), regional pollution (Richmond et al. 2007, Partelow et al. 2015) or fluctuating market prices from globalization (Eriksson et al. 2015, Bennett and Basurto 2018). A shift towards collaborative SSF governance is being adopted by many state governments in an effort to find joint solutions for management (Jentoft and McCay 1995, Armitage et al. 2009, Bodin 2017).

Co-management is a form of collaborative governance shifting the environmental management paradigm towards a participatory and polycentric model (Armitage et al. 2009, Bodin 2017), typically involving multiple actors from the state, civil society and local communities who make joint decisions for management (Carlsson and Berkes 2005). Co-management has been extensively studied in SSF with mixed results, but is generally thought to increase the legitimacy of governance and increase compliance with rules by including fishers in decision-making processes (Jentoft 2005, Cinner et al. 2012). It is also seen as a way to shift some of the management costs from the state to local communities, relieving the state and empowering

communities (Jentoft et al. 1998, Sutinen 1999). Furthermore, it may be a more adaptable approach, better enabling the fit of governance to the local context when it can facilitate knowledge integration and social learning among actors involved (Armitage et al. 2008, Tengö et al. 2014). However, it can also increase incentives for overexploitation or reinforce existing inequalities and conflict (Jentoft 2000, Béné et al. 2009).

Collaborative fisheries governance approaches reflect an institutional rebound away from generalized panacea policies that were largely unsuccessful because they failed to adapt to context or include local actors in decision-making (Jentoft et al. 1998). On the other hand, successful collaborative governance is often dependent on self-organization of local actors and knowledge exchange between different organizations and institutions to develop mutually agreed upon goals and rules (Armitage et al. 2008, Berkes 2009). Many variables influence whether local actors can self-organize and work together, which often requires establishing local leadership, reconciling conflicts and building consensus that participation and deliberation is a beneficial direction forward (Acheson 2003, Ostrom 2005). These processes have shown to be influenced by a wide range of social and ecological factors, largely recognized by a fusion of research on collective action, common-pool resources, SSF and social-ecological systems (SES) (Basurto and Nenadovic 2012, Kittinger et al. 2013). Numerous studies have shown that while a large variety of variables interact to shape collaborative governance outcomes, the specific influence of any single variable is likely to be context specific and vary between cases (Gutiérrez et al. 2011, Cinner et al. 2012). SES research has helped to sort out the complexity of interactions in SSF (Basurto et al. 2013, Partelow and Boda 2015), and expand recognition for the increasing number of variables and how they interact to influence collective action and collaborative governance (Ostrom 2007, 2009).

Despite complexity, collective action research on SSF has been able to identify trends in the enabling conditions for success. Within communities of fishers, the existence of strong leadership, social capital and trust has shown to be beneficial (Acheson 2003, Gutiérrez et al. 2011, Basurto et al. 2016). Governance that includes mutually accepted operational rules, collective choice arrangements and mechanisms for decentralized enforcement have been more likely to succeed (Schlager 2004) than if lacking (Trimble and Berkes 2015). Ecologically, small to medium-sized predictable ecosystems with non-mobile species have shown to be more manageable than large unpredictable systems with highly mobile species (Schlager et al. 1994, Epstein et al. 2014a, Trimble and Berkes 2015). In relation to markets, patron-client relationships can be mutually beneficial (Ferrol-Schulte et al. 2014), but they can become asymmetric when market prices increase through the integration of local products into global markets (Bennett and Basurto 2018) or when patron selection is not a competitive market for fishers. Social-ecological traps, and gilded traps, can occur when market prices increase quickly without sufficient institutional mechanisms to manage the increased rates of harvesting and access, leading to ecological collapse with negative consequences for social wellbeing (Acheson 2006, Steneck et al. 2011, Kittinger et al. 2013). Overall, collective action can be an effective driver of governance under certain conditions, especially when they facilitate the development of institutions that are adaptive to fit local social-ecological conditions through participation and deliberation among local actors (Armitage et al. 2009).

In Costa Rica, Marine Areas of Responsible Fishing (AMPRs) have been established as a form of Marine Protected Area (MPA) with a co-management model for governance (Fargier et al. 2014, Lozano and Heinen 2016). The AMPR model was proposed and implemented by INCOPESCA, the Costa Rican government organization regulating fisheries and aquaculture. AMPRs are promoted as a form of community-based common property management, to give rights back to traditional resource dependent communities who want more control in local resource management with legal support from the state. The significance of AMPRs in Costa Rica can be seen as shift towards legitimizing the artisanal fisheries sector, in an attempt to move towards marine and fisheries governance that includes the goals and participation of local communities for sustainability, rather than a model of exclusion which has largely failed (Mascia and Claus 2009, Lozano and Heinen 2015). The first AMPR was established on Isla de Chira in 2009. INCOPESCA has since allowed other communities in the Gulf of Nicoya, Golfo Dulce and San Juanillo to apply for AMPRs with the aim to make artisanal fisheries more sustainable by reducing overexploitation and conflicts among fishers through promoting alternative livelihoods and conservation (Salas et al. 2012, Ayales Cruz et al. 2013).

The Gulf of Nicoya is located on the Pacific coast of Costa Rica and is the largest tropical estuary in Central America, containing highly productive fisheries due to numerous large river systems and upwelling that bring freshwater and nutrients to support a variety of fish populations (Murasé et al. 2014, Kappelle 2016). The gulf supports about 11,000 artisanal small-scale fishers with minimal alternative livelihood opportunities (FAO 2014c). Small-scale aquaculture and tourism sectors are developing in a few places, but most locations around the gulf remain rural and undeveloped. Fisheries in the Gulf of Nicoya have been threatened by overexploitation for decades due to a rapidly expanding fishing sector including an industrial shrimp fishery using bottom-trawls (Araya 2013, Fernandez Carvajal 2013). Conflicts between industrial and small-scale fishers have in some part motivated government commitment for AMPRs which give property rights to small-scale fishers to exclusively manage and fish in certain waters (Lozano and Heinen 2016). However, illegal fishing, low compliance and enforcement (Pacheco Urpi et al. 2012) and increasing migration of fishers from Nicaragua and other parts of Costa Rica (Araya 2013) have put critical pressure on the gulf's resources.

AMPRs require communities to have a formal fishing association and fishing management plan to apply. They need to self-organize the creation of this association and build social momentum to select representatives into leadership positions. The management plan should outline the geographical extent of the AMPR, argue the ecological and social significance of the marine area and propose harvesting rules that align with national fisheries legislation and the FAO ethics for responsible fishing (FAO 1995, N°35502-MAG 2009, Lozano and Heinen 2015). Associations have to request financing for area maintenance. Also, to coordinate with INCOPESCA and to report progress through the management committee. Moreover, in an effort to maintain rule compliance and report infractions, an additional surveillance committee should be created to coordinate with the National Coastguard Service (SNG) (N°35502-MAG 2009), who is tasked with government enforcement of fisheries but also drug trafficking. Participation and support from other organizations is possible (N°35502-MAG 2009), such as universities and

environmental NGOs like MarViva (Weber de Morais 2016). Appendix 1 summarizes the role of each entity responsible in AMPR activities.

Seven AMPRs have been established in the Gulf of Nicoya since 2009 (Lozano and Heinen 2016) and collective action among local fishers has been a pre-condition for their initiation and establishment. Also, it has led to continued success in many communities but not in others, in part motivating the research in this article. While the AMPR model is based on legitimizing small-scale fishers in management, not all fishers and community members have been included or are motivated to participate. The large heterogeneity in the different types of fishers and gear types often creates conflicts for developing mutually accepted fishing regulations, rule compliance and enforcement mechanisms. Shifting perceptions over who should take more responsibility, INCOPECA or fishers themselves, has hindered progress.

In this article we conduct a qualitative comparative analysis of three AMPRs by applying the social-ecological systems framework (SESF) (McGinnis and Ostrom 2014). Our results are divided into three sections. (1) We identify the unique social and ecological characteristics of each AMPR and the common characteristics they have within the Gulf of Nicoya. (2) We examine the drivers of collective action that led to the establishment of each AMPR. (3) Despite perceived success in the establishment of each AMPR, we identify how current challenges for co-management can be identified using collective action theories and compare the similarities and differences between cases. We discuss the local relevance of our findings for improving AMPR management in Costa Rica and situate these lessons learned within the broader small-scale fisheries literature to contribute to more general insights on SSF governance and collective action.



Figure 1. (A) Location of AMPRs examined in the Gulf of Nicoya. (B) Location of Costa Rica in Central America.

Methods

Three out of the seven total AMPRs in the Gulf of Nicoya were selected as case studies. The process of case selection was guided by exploratory research in all seven sites. Each site was visited and assessed with an observation schedule to systematically observe and compare the broad social and ecological similarities and differences between them (Creswell and Clark 2011, Newing 2011). Open-ended interviews were conducted in each site through largely opportunistic random sampling encounters with local fishers and community leaders. Existing literature on fishing and AMPRs in the region was used. We selected the AMPRs of Palito-Montero on Isla Chira, Isla Caballo and Paquera-Tambor on the mainland peninsula (Figure 1). These cases were selected because they represent the AMPRs with the largest differences between them. The ‘largest difference’ case selection method (Seawright and Gerring 2008) was guided by our research questions and interest in examining if the AMPRs face similar or different challenges for

collective action and co-management, despite their initially perceived homogeneity in most characteristics.

This study conducted qualitative diagnostic research guided by the SESF. Broad semi-structured questionnaires were developed for various key informants and fishers. The same questionnaires were the starting point in each case, but the diagnostic process led to the development of questions that were specific to each case over time. Starting questions were initially broad and structured around the first-tier variables of the SESF, standardized across all cases. Initial interview responses led to a continual refinement of our research questions. Subsequent interviews were guided by the second-tier variables of the SESF. This process of continued refinement of research questions continued over multiple phases of interviews as more detailed information was collected within each case on the different variables. Questions became more specific to each case and we relied on the variables of the SESF as the common set of variables to ensure that the information between cases was comparable during analysis.

Data collection

All primary data was collected between November 2016 and May 2017. We conducted 126 semi-structured interviews with a wide variety of actors specific to each case (Table 1). Key informants were selected specifically in each AMPR, but many provided general information to all AMPRs, including government officials, researchers and non-governmental organizations (NGOs). Key informants specific to each AMPR were selected due to their direct experience or position in the fishing associations, leadership and historical involvement with fishing and the development of the AMPR (Table 1). These interviews followed the diagnostic process described above. In addition to key informants, fisheries and community members were also interviewed to assess general perceptions on and involvement with the AMPR. Snow-ball sampling was used to target fishers and community members, considering multiple entry points into the social network of individuals (Newing 2011, Soares, Denise; Gutierrez 2011). Information received from interviews with fishers was cross-checked with numerous other individuals until saturation or consensus in relation to a particular variable was reached. Consent was given by all individuals before each interview (Newing 2011). Participant observations also provided a means of data collection through community meetings, fishing activities, patron-client interactions, coast guard enforcement events, alternative livelihood activities such as aquaculture and eco-tourism as well as living in each community with local families for numerous weeks has informed this research. Official documents relating to each AMPR were obtained when available, including management plans, lists of association members, legal documents as well as articles and reports from local universities in relation to ecological monitoring and health. This information was used to support the development of more detailed questions and to corroborate information obtained from interviews.

Table 1. Semi- structured interviews conducted during research in field. The affiliation and actor group of each interviewee is shown in relation to each AMPR case. The gender of each individual is shown i.e. (M) Male; (F) Female.

Case	Informants	Actor group	Semi-structured interviews
Isla Caballo	Association leaders	Community	2 (M), 1(F)
	Fishers	Community	15 (M), 1 (F)
	Development association	Civil society/ NGO	1 (M)
	EBAIS (mobile staff in Venado, Chira, Caballo)	Public sector	1 (M)
	High school director	Public sector	1 (M)
	Collection center (private)	Private sector	1 (M), 1 (F)
Palito-Montero	Association leaders and ex-leaders	Community	12 (M), 3 (F)
	Fishers	Community	16 (M), 3(F)
	Development association	Civil society/ NGO	1 (M)
	Island syndic	Civil society/ NGO	1 (M)
	Collection center (private)	Private sector	2 (M)
Paquera - Tambor	Association leaders	Community	12 (M), 1 (F)
	Fishers	Community	29 (M), 2 (F)
	CAPATUR (governance committee)	Community/ private sector?	1 (F)
	Cobano municipality (governance committee)	Community/public sector?	1 (M)
	Collection center (association)	Community	2 (F)
	Fishery and Aquaculture Costa Rican Institute (INCOPECA)	Government	3 (M)
	National Coastguard Service (SNG)	Government	2 (M)
	National Institute of Rural Development (INDER)	Government	1 (M)
	Joint Institute of Social Assistance (IMAS)	Government	1 (M)
	National Learning Institute (INA)	Public sector	1 (M)
	National University of Costa Rica (UNA)	Civil society/ NGO	1 (M), 1 (F)
	CoopeSoliDar	Civil society/ NGO	1 (F)
	MarViva	Civil society/ NGO	1 (M)
	Asociación de Pescadores Pangueros Artesanales de Puntarenas (ASOPAPU)	Civil society/ NGO	1 (M)
	Collection centers (Puntarenas)	Private	3 (M)
Total			126

Data analysis

All interviews were conducted in Spanish and then translated and transcribed into English for coding and analysis. Qualitative interview data from each AMPR was coded according to the first and second-tier variables of the SESF to organize the data; we follow similar qualitative methods in SSF studies (Lozano and Heinen 2015, Partelow and Boda 2015). After completion of coding, the data relating to each second-tier variable in could be further analyzed and sorted. Data sets for each of the three case studies were made. If necessary, third-tier variables were developed to sort data into more nuanced categories, following an ontological logic for expanding the SESF suggested by Frey and Cox (2015). Added third-tier variables specific to this analysis are shown in Appendix 2.

The data coded to each variable was analyzed in relation to current theories of collective action to identify the role it may play in influencing collective action in each AMPR. Multiple sources were used as references to understand current collective action research in SSF, including general literature on collective action (Ostrom 1990, Poteete and Ostrom 2004, Poteete et al. 2010), the Social-Ecological Systems Meta-Analysis Database (SES MAD) (Cox 2014a) and specific studies in SSF (Gutiérrez et al. 2011, Cinner et al. 2012, Basurto et al. 2013, Guevara et al. 2016).

To conduct our comparative analysis, indicators were developed to determine the value of the variables from the SESF and their influence on collective action. This was done after coding the data to each variable, allowing the analysis of all interview data related to each variable to assess the appropriate values (e.g. high, medium, low) and indicators for comparative analysis between cases (Basurto et al. 2013, Epstein et al. 2014a, Partelow et al. 2018b). These values are relative to our study. However, the values to determine collective action were contrasted with measurements suggested in different case studies examining collective action (Ostrom 1990, 2009, Basurto et al. 2013, Cox 2014b, Trimble and Berkes 2015, London et al. 2017). In comparison of cases in Table 4, the most influential variables in each case are presented and matched to second-tier variables codes from the SESF. Comparing the values between cases should be interpreted with consideration that the value is relative to how influential each variable is within each case, not relative to the other cases. Moreover, a value of positive, negative or minimal influence on collective action was determined based on our analysis of interviews.

Results

Small-scale fisheries in the Gulf of Nicoya: A social-ecological system

Each AMPR has its own unique social and ecological characteristics; however, they also share many commonalities as they are all embedded within the Gulf of Nicoya. In this section, we

describe the Gulf of Nicoya as a social-ecological system, highlighting some of common settings that the AMPRs are embedded within.

Highly productive fisheries in the gulf (RS5) supported by nutrient rich upwelling and large freshwater river inputs (RS7) (Kappelle 2016) have led to the establishment of more than 20 small-scale fishing communities (Pacheco Urpi et al. 2013) (S1) and a culture of coastal resource dependent livelihoods (A8). The city of Puntarenas has grown from a small fishing village in the 1970's into the regional hub for seafood markets (S5). Most of the fish caught in the region goes through Puntarenas for local sale or transport to the Costa Rican capital of San Jose, where an expanding middle-class is driving increased demand and prices for seafood products. Networks of patron-client systems have been established locally to transport fish caught around the gulf to the city, as most fishers do not have sufficient means to transport fish themselves.

The fishing sector has expanded due to a growing coastal population (S2a), unemployment or the displacement of communities from land to develop large-scale tourism and agriculture (Salazar Araya 2012). Competition and overcrowding have created conflicts between small-scale and industrial fishers (I4) (Lozano and Heinen 2015) where historical policies for fisheries commercialization have largely favored the industrial sector, marginalizing artisanal communities (Araya 2013).

Overall, economic development in the gulf is linked to the sea. In recent years, a tourism industry has flourished for surfing, beachgoers and nature enthusiasts (Almeyda et al. 2010, Krause 2013), bringing new opportunities to transition local economies from a strong dependence on local extractivism. Some communities have explored aquaculture and rural tourism as a viable alternative, but many projects remain small-scale and exploratory. In response to growth in the region, human migration to the area has increased substantially from neighboring regions and countries like Nicaragua, with many entering the fisheries sector (Araya 2013). As a result of increasing human activities like fishing (I1) and pollution (ECO2), many consider fisheries in the gulf to be severely overexploited and on the verge of collapse (O2) (Fonseca and Solis 2005, Fernandez Carvajal 2013), threatening local livelihoods (O1).

Fisheries governance in the Gulf of Nicoya is polycentric and multi-level (GS3). Cooperativism has been part of the social and political discourse in Costa Rica since the 1970's, supported by tax exemptions and education policy that have spread roots into the artisanal fisheries sector (Lozano and Heinen 2015). SSF cooperatives (GS2) can help establish fair prices, collectively fund community projects, provide micro loans to fishers and sell their own products independently. Not all communities have well established cooperatives, but those that do have played a large role in managing daily fishery activities. From the state, AMPRs and fisheries are overseen by INCOPESCA, but enforcement responsibilities were transferred to the National Coast Guard in 2000 (Law N° 8000 2000, Pacheco Urpi et al. 2012) (GS1). However, the Coast Guard does not prioritize fisheries enforcement over drug trafficking and other national security issues, creating the perception of insufficiency and lack of responsibility in the eyes of many fishers trying to follow the rules, worsened by a lack of financing and human resources.

INCOPESCA is guided by a national policy framework (GS7) with regulations for all fisheries (GS5). Fishers are required to obtain a license, which is no longer being provided by INCOPESCA. A license is also necessary to receive subsidy benefits during fishery closures. Fishers are also required to have life insurance, to take a ‘survivor course’, purchase boat safety equipment, and to acquire a navigation certificate authorized by port authorities after periodic boat and equipment inspections. These requirements are often difficult to afford for small-scale fishers due to low wages and generally poor socioeconomic conditions. In addition, numerous gear restrictions apply to all AMPRs such as a minimum size for mesh nets and hooks. These restrictions are difficult for hand-line and long-line fishers who have to catch smaller fish for live bait, typically sardines or shrimp with purse-seine nets, an activity which is no longer allowed. General consensus among small-scale fishers is that operational rule changes have negatively impacted traditional fishing practices over time, hindering the development of small-scale fishing communities compared to the industrial sector, which has benefited substantially from national development policies. Conditions are worse for fishers who are hired as employees for other fishers, as they often do not have their own fishing permits, life insurance or subsidy benefits.

Although the gulf is spatially large, many fishers have small 3-4 meter boats with outboard motors that can easily reach any part of the gulf for a day of fishing. Many hand-line fishers harvest in their local waters, but a large percentage of fishers who use artisanal gillnets, seine nets and long-lines are highly mobile throughout the gulf. This is in part due to target species that are mobile (RU1) with varying spatial and temporal distributions (RU7), related to changes in water temperature, reproduction cycles, tidal cycles or stages of biological development. Furthermore, open-access rights to fish throughout much of the gulf has created local roving banditry, where fishers move around to ‘follow the fish’, delaying the need to establish effective local management due to overexploitation by fishing elsewhere in the meantime. These are typically the areas of other fishing communities where enforcement is lower.

Drivers leading to the establishment of three AMPRs

Within the broader settings of the Gulf of Nicoya described above, we continue to present the results of a comparative analysis of three AMPRs located in the Gulf of Nicoya, examined as distinct units of analysis with their own social and ecological characteristics. The three selected represent those with the observed most difference among the seven AMPRs that exist in the gulf. Table 2 shows the key characteristics describing each AMPR with emphasis on their differences.

Part 3: Empirical research

Table 2. The unique social and ecological characteristics of the three AMPRs examined, organized by the second-tier variables of the SESF (McGinnis and Ostrom 2014). Variables similar in all AMPRs are not shown, commonalities are briefly explained in the text.

SESF	Indicator	Isla Caballo	Palito-Montero	Paquera-Tambor
RS1- Sector	Environmental characteristics	Rocky beach, sandy beach	Rocky reefs, mangroves mudflats	Coral reefs, mangroves, estuaries, islets/bays, rocky shore, mudflats, sandy beach
RS2- Clarity of system boundaries	Buoys to mark area	Few buoys remain	Some buoys remain	Some buoys remain
RS3- Size	AMPR size (km ²)	1.48	6.12	200
RS4- Human constructed facilities	Boat access	Beach only	Beach only	Pier, beach
RS9- Location	Location of AMPR in Gulf	Small island; middle gulf	Large island; inner gulf	Mainland; outer gulf
RU - Species	main target species in each AMPR	Small size species: Croaker species, sea bass, catfish	Large species: Croaker, snapper, catfish, grouper, sea bass. Mollusks	Mixed sizes: Croaker, snapper, grouper, sea bass, catfish. Mollusks, lobster, shrimp
GS1- Government organizations	Number and type with more presence	IMAS, INAMU	INDER, INA, IMAS	INCOPESCA, SNG, INDER, IMAS, SINAC-MINAE, INA, INFOCOOP
GS2- NGOs	Fisher associations	ASCOLOPES (fisher association)	ASOPECUPACHI (hand-liners Palito) Save the Gulf (non-hand-liners) ASOMM (hand-liners Montero)	ABUZPA (divers in Paquera) ASOTAMBOR (fishers in Tambor) Asopesplayablanca (fishers in Playa Blanca) APEP (fishers in Paquera) ASPARMAR (AMPR association)
	Other user associations	No	No	CATUCO (Cobano Tourism) CAPATUR (Paquera Tourism)
	Cooperative	No	No	COOPEPROMAR (AMPR cooperative)
	Other	Development association (AD)	Development association (AD)	MarViva, Pretoma
GS4- Property rights	Number of sectors	1 unique sector – all rules apply	2 sector – almost all rules apply	14 zones – different rules (i.e. gear and use restrictions) in each, within 3 sectors
GS5- Operational rules	AMPR rules	Hand-lines only	Hand-line only	Gear restrictions depending on zone
A1- Number of actors	Actors groups	Fishers	Fishers, community, researchers	Fishers, divers, tourism, community, researchers
	Estimated community population	350 (on island)	3000 (on island)	Undetermined but more than others.
	Number of local fishers	70-90 (on island)	120 (In AMPR zone)	More than 150 (in AMPR zone)
A2- Socioeconomic attributes	Level of heterogeneity between actors/ groups	Social and economic homogeneity between fishers	Social and economic homogeneity between fishers	Economic and social heterogeneity between fishers and tourism actors

Part 3: Empirical research

	Access to basic services	Absence of most services including electricity, freshwater and waste disposal.	Presence of basic services, including freshwater, electricity, education. Absence of waste disposal.	Presence of basic services including freshwater, electricity and education.
A3- History	Year established	Initial conservation efforts in 2007; created 2012	Efforts since 1995. First AMPR legally created in 2009; extended 2012.	Efforts began in Paquera sector. Initial proposal in 2011. Created 2014
A5- Leadership/ Entrepreneurship	Leadership in local associations	Weak local leadership	Weak local leadership	Strong local leaders, self-creation of a governance committee
	Own cooperative/ collection centers	No	not functional collection centers	Yes, own cooperative functional collection centers
A8- Dependence	Alternative livelihood options	None	Aquaculture (in AMPR) Livestock Rural tourism Familiar stores	Tourism Agriculture Construction Recreational fishing Aquaculture
A9- Technology	Fishing gear in use	Gillnets Artisanal seine nets few longline and hand-line	Manly Hand-line Gillnets Few long-line	Bottom longline Gillnet

Palito-Montero AMPR

Palito's handline fishers started to organize in 1995, with the goal to protect the area and assure harvests over time (Babeu et al. 2012) as the area is important for local livelihoods (A8a). Early efforts were made to exclude gillnet fishers from inside and outside the community, who were perceived as local roving bandits (I10), and who were blamed for decreasing fish populations (RS5, A7b). Self-organized surveillance during nights (I7) and informal sanctioning mechanisms such as gear confiscation and/or destruction were developed for this purpose, which remain today (GS8c). In 2004, the Handline Fishers Association of Palito (ASOPECUPACHI) was formed by 32 fishers (I7) (Ayales Cruz et al. 2013). The association requested government support to establish a local conservation area and applied for funding (I5) from the United Nations Small Grant Program (SGP-UNDP-GEF) to mark the area with buoys and acquire surveillance equipment. Another fisher association was created a few years later called "Let's save the gulf" (Salvemos al Golfo) by non-handline fishers (I7), who were not included in the AMPR creation process and disagreed with its non-inclusionary process for banning other gear types. Violent conflicts (I4a) between gillnet and handline fishers occurred in Palito early on, but diminished over time as rules became increasingly accepted (A7; I9) and when majority of local fishers adopted hand-lines as their main gear (A9a). This process increased recognition for the AMPR as an (A7)important governance approach to maintain their livelihoods and for family subsistence (A8).

Palito was the first AMPR created in Costa Rica in 2009 (A3), and was extended to include Montero in 2012. The previous informal rules (GS4; GS5) of the area were now legally

recognized (Lozano and Heinen 2015). A fishing association from Montero (ASOMM) was also created in 2009 with around 40 fishers and community members (I7), as a requirement to create the Palito area extension with few different rules. The extension was suggested by INCOPESCA to hasten creation procedures. Collection centers were requested by both associations (I5) to directly trade their own products to markets in Puntarenas (S5b), promoted by MarViva with BID funding. Aquaculture projects have also been promoted by the National University of Costa Rica (UNA), as alternative livelihoods and to reduce dependence on fishing (A8). Both ASOPECUPACHI and ASOMM agreed to manage the area together (A6; I3) and share funding. Each association agreed to establish a surveillance system, consisting of patrolling the area in pairs every night (GS8a) and reporting the presence of illegal activity to SNG and INCOPESCA (GS3). The majority of fishers in both sectors have expressed an increase in fish abundance (RS5, A7b) (Fargier et al. 2014) relating it to surveillance measures taken (GS8a,c).

Collective action to establish the Palito-Montero AMPR was driven by strong support from government and NGOs, who provided financing and capacity building to support the local associations (I5). INCOPESCA provided support to hasten creation procedures initially (GS1c). Training to develop aquaculture projects and fish handling was provided by other governmental organizations, including the National Learning Institute (INA) (GS1b). Different NGOs (GS2a) initially supported training, funding for equipment and payment for fishers conducting surveillance during night shifts, and to build collection centers (GS2a). Biological monitoring from UNA on fish productivity in the AMPR is often done (GS8b).

Isla Caballo AMPR

Prior to the AMPR on Isla Caballo, fishers were previously organized (I7) into a Committee of Local Fishers (COLOPES). These committees were historically (A3) promoted in the country to facilitate communication between INCOPESCA and fishers (Fernandez Carvajal 2013). On the island, COLOPES was transformed into a formal association (ASCOLOPES) to comply with AMPR requirements. Initial efforts to protect the fishing grounds near the island began in 2007, motivated by fisher perceptions (A7) of decreasing fish populations (RS5). Isla Caballo followed the experience of Palito-Montero (I8) to increase conservation efforts and assure fishing areas. The initiative was adopted by the main local leader (A5) within ASCOLOPES.

The association organized the establishment of a fish collection center (I7) to create direct access to markets and improve incomes. The collection center was promoted by the NGO MarViva through funding from BID (I5). The AMPR was expected to generate alternative incomes through the development of aquaculture and tourism projects (A2a), ultimately reducing dependence on fishing as a livelihood (A8). The application was pushed forward by a few strong leaders (A5; I7), supported by UNA and INCOPESCA to design the area boundaries (GS4). Local fishers were really only involved in the approval process, requesting a signature if they agreed. This helped get the AMPR established when a majority of them agreed, but also left some fishers in disagreement. Fishers in ASCOLOPES also agreed to self-organize surveillance during nights (I7; I9) and apply their own informal sanctioning mechanisms (GS8), such as taking out illegal gear (i.e. gillnets) and destroying them, similar to Palito. However, many difficulties for

management have been expressed by different informants. The Isla Caballo AMPR was approved in 2012, but the area has faced major challenges for successful implementation. The process was referred to by leaders as delayed with spatial boundaries different than the initial proposal. This discouraged further participation from many interested local fishers from the start, decreasing the acceptability of the area as a legitimate form of governance (A3; A6).

Paquera-Tambor AMPR

The process to establish the Paquera-Tambor AMPR began in 2011, and was legally approved in 2014. The Paquera-Tambor AMPR has a diversity of actor groups (A1) involved including fishers, free divers association, non-fisher communities, tourism chambers, industrial fishers, governmental and NGOs. The purpose of initial participatory meetings was to discuss the types of gear restrictions, organized by zones within the AMPR, and the types of activities allowed within each zone (GS4) (i.e. which actor group could conduct activities in each zone). The AMPR was divided in three sectors: Tambor, Paquera and Playa Blanca, with 14 zones distributed among them (GS4). Local actors agreed to manage and look after their own sectors (I3). Similar to other AMPRs, local motivations to establish the AMPR were driven by perceptions (A7) that it would increase fish populations (RS5), leading to improved livelihood opportunities and promoting alternative sources of income (A2, A8). Moreover, plans were included to build collection centers in each of the three sectors through MarViva and BID funds (I5). In addition to the collection centers, a processing plant was planned to be built and managed by the AMPR cooperative created, to process their own fish and seafood products from the area with additional value (RU4a). The cooperative was also created to manage a common fund to be given as a form of loan to fishers periodically or in case of emergency as a form of social insurance (I5), or to sell equipment to fishers at lower prices.

Different factors have motivated fishers to participate in different AMPR management activities. The creation of the AMPR and its management has been facilitated by two non-fisher leaders (A5) in the tourism sector with professional skills in biology and administration (A2). The tourism sector has been participating in management due to the importance of the AMPR for recreational fishing, free diving and boat cruises (A8a). These leaders have organized the different actor groups together and requesting government support (A5; I6). Different governmental organizations and NGOs have supported the development of the AMPR through capacity building (GS2b; I5) and financing (GS2a; I5). Research centers have also supported biological monitoring (GS8b; I9). Investment from the fishing associations, cooperatives and the tourism sector has been provided to organize activities related to AMPR like meetings (I5). A governance committee was created (I7) integrated by different local representatives of tourism chambers, fishers, divers and the municipality. The governance committee was proposed as a participative strategy to take decisions (I3) related to AMPR functioning and inform the results to INCOPESCA (I7; GS6). INCOPESCA has since adopted the approach of developing a governance committee for other AMPRs (I10).

Common drivers of AMPR establishment across cases

Each AMPR has the requirement to develop a specific fishing management plan (Plan de Ordenamiento Pesquero, POP) with their own operational and collective choice rules. Our results show that the motivations for fishers and other actors to initiate the process of establishing the AMPR, i.e. to take collective action, was driven by some common factors across cases (Table 3). Fishers in all cases wanted to have exclusion and management rights (Schlager and Ostrom 1992) to restrict and control access of certain types of fishing gears (GS4). This was driven by a common mental model (A7) that certain gear types were destructive or enabled overharvesting, which was perceived as a threat to their livelihood due to their high dependence on fishing (A8). Moreover, fishers in all cases wanted to improve the market prices they received through the creation and self-organized management of a collection center owned by the association (A5) to facilitate direct trade to markets (S5b) by avoiding private patron-client systems (RU4a). A final common motivation to establish the AMPR in all cases was the expectation that it could lead to the development of alternative livelihoods through aquaculture or tourism, ultimately reducing dependence on fishing (A8a).

Table 3. Main Common drivers motivating the establishment of all three AMPRs.

Common drivers to establish AMPRs across cases	Desired outcome
Want to restrict fishing gears and activities (GS4; GS5) with negative impact	Protect fishing grounds to increase fish population (RS5), to secure income and sustain their livelihoods over time (A8)
Want to improve livelihoods (A2)	Trade fish /other products with an additional value (RU4a) Reduce intermediaries, increase access to markets (S5b)
Want to develop alternative livelihoods (A8)	Generate alternative source of incomes (A2a) Reduce dependence on fishery (A8a)

Have the AMPRs been successful? Comparing hindering and enabling conditions for continued collective action

Self-organized collective action has played a substantial role in the establishment of all three AMPRs, but initial efforts are not enough for continued success. Thus, continued collective action is a necessary foundation to make the AMPRs successful over time. This section presents a brief overview of the current outcomes (O1; O2; O3), the degree of success (or lack of success) in each AMPR, and then compares the hindering and enabling conditions influencing continued



collective action. Table 4 shows the key variables from the SESF, their analyzed case values and indicates how each variable is influencing collective action for each case.

Table 4. Key variables influencing collective action in each AMPR. The value of each variable is shown along with its influence on collective action in each case. Green ‘up’ arrows indicate a positive influence on collective action, and red ‘down’ arrows indicate a negative influence. A horizontal line indicates no observed or minimal direct influence on collective action. An star (*) indicate an influence on collective action contradicting a theory/hypothesis.

SESF variable	Collective action (CA) hypothesis of variable influence	Isla Caballo		Palito-Montero		Paquera-Tambor	
		Value	Influence on CA	Value	Influence on CA	Value	Influence on CA
Resource unit mobility (RU1)	CA is more difficult with highly mobile resources, which reduces the information about the stocks and flows of the resource, it can also increase transaction costs of monitoring.	High	↓	Medium	↑	High	↓
Economic value (RU4)	High value of target species within the AMPR increases likelihood of CA.	Medium	↑	High	↑	Medium	↑
Clarity of system boundaries (RS2)	Clear spatial boundaries increase likelihood of CA. Easier to tell who is in or out, and to monitor.	Unclear	↓	Partially	↓	Partially	↓
Size of resource system (RS3)	Very small areas do not generate enough incentives when resource availability is low, decreasing the likelihood of CA	Small	↓	Small	↑*	Large	↑
	Smaller areas are easier to monitor as transaction costs decrease, increasing the likelihood of CA	Small	↓*	Small	↓*	Large	↓
Operational rules (GS5)	Formal rules taken by local actors are implemented, increasing the likelihood of CA.	Absent	↓	Present	↑	Present	↑
	congruence between rules and local gears in use increase the likelihood of CA.	Low	↓	Medium	↑	Medium	↑
Collective-choice rules (GS6)	Allowance of local actors (i.e. fishers using multiple gear types) to participate in designing or modifying rules increase the likelihood of CA.	Low	↓	Low	↓	Medium	↑

Part 3: Empirical research

Monitoring & sanctioning (GS8)	Effectiveness of monitoring and graduated sanctioning help rule compliances and increases the likelihood of CA.	Low	↓	High	↑	Low	↓
Number of actors (A1)	As the number of actor groups increases, it is more likely that they have heterogeneous interests, making it more likely to create disagreements, conflict and increased transaction costs for management. This decreases the likelihood of CA.	Small	---	Small	↑	Large	↓
	The more users in group, the higher the transactions costs for management (i.e. monitoring, communication and coordination is more difficult). This decreases the likelihood of CA.	Low	---	High	↓	High	↓
Socioeconomic attributes (A2)	Economic heterogeneity increase the likelihood of CA (i.e.. Wealthy actors can afford transaction costs or invest).	Low	↓	Medium	↑	High	↑
	Sociocultural heterogeneity (i.e. traditions, activities, practices) decreases the likelihood of CA.	Low	---	Low	↑	High	↓
History & past experiences (A3)	Negative experiences with management decrease the likelihood of CA.	High	↓	High	↓	Medium	↓
Location (A4)	Actors located far apart increases transaction costs of CA.	Close	---	Close	↑	Far	↓
Leadership (A5)	Strong leadership and entrepreneurial skills increases the likelihood of CA.	Weak	↓	Weak	↓	Strong	↑
Trust/ social capital (A6)	High to moderate levels of confidence and close relationship among local actors is likely to increase CA.	Low	↓	Low	↓	Medium	↑
Knowledge of SES/ mental models (A7)	Actors who perceive that AMPR governance is successful (e.g. in reducing resource scarcity) is likely to increase CA.	Negative	↓	Positive	↑	Positive	↑
Dependence (A8)	High dependence on AMPR resources to obtain incomes and sustain livelihoods increases the likelihood of CA.	Low	↓	High	↑	Medium	↑

Technology (A9)	Technology heterogeneity (i.e. equipment, gears) hinder coordination among actors, decreasing the likelihood of CA.	Low	---	Low		High	
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Palito-Montero: Initial success followed by challenges

The Palito-Montero AMPR can be considered a governance success in the sense that it was the first AMPR in Costa Rica, providing the example that the AMPR model was possible through community-based collective action. However, it faces numerous challenges for continued success. Currently, lack of coordination and a contentious relationship with INCOPESCA is perceived by fishers (I4) (Babeu et al. 2012). Collection centers are not functioning due to a lack of operational permits (S4a) and the existence of patron-client relationships with private collection centers that pay slightly higher prices. Some fishers stopped doing night surveillance when compensation payment was no longer provided by NGOs. Although support in funding was over, private collection centers and associations have been investing in surveillance materials (I5), but obtaining enough funding to repair buoys is difficult (Figure 2). Marking the AMPR boundaries is still a challenge after nearly 10 years.

The AMPR is perceived by many fishers (A6) as overharvested (O2) due to presence of high numbers of fishers within the area, who often do not follow the rules, exacerbated by difficulties with excludability and high subtractability. The costs of establishing management and of following the rules are being assumed by a small minority of fishers (Lozano and Heinen 2015). Mistrust among fishers (A6) has been related past experiences with conflict (A3) between fishers using different gear types, leading to the expulsion of fishers from the Palito association (GS8c) or their exclusion in management processes. Moreover, fishers have complained and disagreed (I3) with current leadership, motivating some fishers to leave the association (A5). Difficulties in coordination and disagreements between both communities are frequent. This has led many fishers to be discouraged from participating in management, and few fishers remain organized to take care of AMPR management tasks (Salas et al. 2012). Furthermore, an oyster culture was developed by women in Palito as part of AMPR alternative projects (Figure 2), but some women stop participating when shared benefits were low due to the large group size or due to feeling excluded by women's association leaders and their families, who remain in the project with institutional support (UNA). Some ecotourism activities within the AMPR have been developed but are infrequent. It seems clear that alternative livelihood opportunities have not yet materialized as hoped.



Figure 2. Buoys damaged in Palito-Montero AMPR (left); oyster aquaculture developed by women in Palito (right).

Isla Caballo: Minimal success and continuous difficulties

Collective action on Isla Caballo and the establishment of the AMPR has largely been a failure. The management plan restricted all fishing gears except hand-lines. The lack of inclusion of local fishers who use illegal gears (illegal in the whole gulf) created tension between the few local leaders and everyone else (I4a). The rules for the AMPR did not include some fishers in the decision-making processes, but the majority of fishers signed the agreement to exclude gillnets. However, many of them did not respect the boundaries of the AMPR or its rules (GS4,GS5), and this was mainly due to perceived increases in fish populations around the AMPR. Some local and external fishers damaged the buoys, which were perceived as obstacles for gillnets, contributing to the challenge of marking clear boundaries (RS2). A lack of monitoring and sanctioning (GS8), coupled with the perceived illegitimacy of rules by gillnet users led to business as usual. Enforcement from the coast guard was perceived as inconsistent and largely ineffective (GS8a). The few fishers and leaders who initiated self-organized surveillance and enforcement (GS8c) were threatened by other fishers using illegal gear (I4a). Leaders have been criticized for not imposing sanctions on family members known to be fishing illegally. Overall, conflictive relationships between local and external fishers have stagnated motivation to work together and find mutually accepted rules among fishers using different gear types (A5).

The spatial size of the AMPR on Isla Caballo is too small (RS3), it does not fit the ecological distribution of target species or fishing behavior on the island (RU7). Despite targeted fish species on Caballo having a high value (RU4), these species are highly mobile throughout the Gulf (RU1) (Figure 3). Thus, most fishers are not directly dependent on resources from within the small spatial area of the AMPR (A8). Moreover, most fishers in the community use other gear types than those allowed in the AMPR and many young fishers use illegal gillnets with the potential to harvest up to 400kg per day valued around 1700 USD. These fishers have little

interest in fishing with hand-lines when there is opportunity to gain more profit with illegal gear outside the area. Funding from MarViva and BID was not given to build a collection center. Poor socioeconomic conditions and a lack of basic development infrastructure inhibited needed investments to build a working collection center (A2), hindered by state control of the property (GS4) that forbids construction on the island (S4a). The small island is the least developed in the Gulf and lacks basic services needed to build the center, such as water and electricity (A2). Freshwater is imported by boat from Puntarenas (Figure 3) and electricity is provided by solar panels or own private gasoline generators. Collective action such as meetings and self-organized surveillance for the AMPR are no longer being done (I7). Only the maintenance of buoys is continued as a requirement during seasonal closures during mandatory community work to receive closure compensation (a form of subsidy) from the government, but this has not increased rule compliance.



Figure 3. Fishermen from Isla Caballo displaced and harvested *Cynoscion albus* specie (‘queen croaker’) with hand-line gear (left) in AMPR Distrito Paquera-Tambor. Water distribution from Puntarenas to the island (right).

Paquera-Tambor: Many challenges but moving towards success

Despite the overall success in establishing the Paquera-Tambor AMPR, difficulties remain for continued success. Rivalry among fishers, leaders and/ or communities (I4a) has led to disagreements, often creating fear among fishers to participate in meetings who do not have a fishing license (A6) or for those who disagree with the AMPR proposal (GS6). Fishing regulations are often not respected during the night or during seasonal closures (GS5). This has led to perceptions (A6) of inadequate surveillance by the coast guard. Self-organized surveillance has also been inconsistent due to threats from illegal fishers during patrolling (I4a), or for being afraid to be caught by the authorities because many fishers do not have a license (GS5). Nonetheless, local informants have perceived an overall decrease in the presence of illegal fishing and unsustainable practices like shrimp trawlers in the AMPR, which was also related to

perceptions of increasing fish populations (RS5, A7). In addition, fishers and other actors are physically located in communities that are far apart from each other compared to other AMPRs (A4a), making it difficult to meet in person and coordinate due to increased transaction costs. Also, surveillance has been limited to areas close to communities due to the ease of access, limiting surveillance in other areas because of its large size (200 sqkm) (RS3). Fishers do not depend only on fish within the AMPR for their livelihoods (A8a), they often travel by boat outside the area or to the open sea for more highly mobile pelagic species like ‘dorado’ (*Coryphaena hyppurus*) (RU1; RU7).

Despite these challenges, Paquera-Tambor is making slow progress, arguably the most successful of the three cases. Strong leadership (A5) from two non-fishers (A1; A2), one in the tourism and one in the research sector has brought needed capital from the government and NGOs, facilitated formal administrative organization and provided continuous motivation to keep management moving forward. Research and monitoring is active in the area to support decisions and progress. This suggests that heterogeneity among actors, both economic and in relation to business skills, can enable collective action because it can bring needed knowledge about how to formally organize management processes and can bring needed capital that fishers would otherwise not have. This capital led the establishment of their own collection centers and cooperative, although they still depend on external markets to set prices and trade (S5a) (Figure 4), it provides incentives and direct trade of seafood to local tourism restaurants and hotels. Formal organization of meetings which are held every 1-2 months for decision making (I7, GS6), has helped bring actors located throughout the area together (Figure 4) and to evaluate progress of the AMPR and nested projects (I10). Coordination among different working groups from associations, committees and the cooperative has been aided by the use of mobile phones and online communication platforms like WhatsApp (A9). Moreover, fishing is not the only livelihood opportunity in Paquera-Tambor. Tourism had provided opportunities in the service sector (A8a), and other alternative livelihoods are available because it is connected to the mainland.



Figure 4. Collection center in Playa Blanca sector delivering fish to Puntarenas (left). Meetings for decision making in assembly, led by cooperative president (standing right).

Discussion

AMPRs are a new and institutionally unique form of small-scale fisheries governance in Costa Rica. They follow a global shift towards collaborative environmental governance that aims to better include local people in decision-making processes. AMPRs have evolved in response to largely failed ‘nature without people’ conservation models (Folke 2006, Mace 2014) in many coastal areas, many of which are exclusionary or designed after terrestrial conservation models that are not adapted to coastal social-ecological contexts (Weber de Moraes 2016). Exclusionary and misfit governance models can marginalize small-scale fishers who are highly dependent on local natural resources with few alternative livelihood opportunities. It is evident that momentum to support AMPRs reflects Costa Rica’s effort to try to avoid marginalization and to develop the coastal economy away from a high dependence on extractivism towards tourism and aquaculture.

The AMPR concept was inspired by the self-organized efforts of fishers in Palito on Isla de Chirra. The initially successful model in Palito has been largely adopted as the generic co-management approach now used for all AMPRs. However, replication of the Palito model is problematic because rural fishing communities in the Gulf of Nicoya may seem to have similar challenges and goals, but our findings show that they are substantially different in a variety of ways important for management. Key differences include target species and gear types used. These seem to have cascading effects on institutional development and change relating to who makes the rules (i.e. fishers from certain gear types), what rules get developed (i.e. what gears are banned) and the formation of perceptions on resource scarcity and the legitimacy of AMPR governance between different gear users. All of the above are causing common difficulties for cooperation and even conflict between different gear types due to it is a primary driver of informal socio-political group formation and alliances among fishers throughout the gulf. Trust and social capital within gear groups is higher, however this is often reciprocated by skepticism and contempt of other gear groups. Finding cooperative and non-exclusionary ways to establish AMPR governance that can mitigate conflicts by reconciling differences between groups of fishers using different gears is a core challenge. However, our findings also show that there are no simple governance solutions to these problems, and recognizing the complexity of interacting variables in each case is a reasonable starting point.

Recognizing complexity and interacting variables

This study analyzes collective action within three social-ecological systems, and we apply the SESF to sort and describe the complexity of variables, their interactions and their influence on collective action outcomes. However, the results presented above, and the results of many studies tend to first emphasize the role of single variables on SES outcomes and collective action. Less focus is given to analyzing the interdependent interactions between variables or their relationships to each other (Leslie et al. 2015, Partelow et al. 2018b). A core tenant of social-ecological system analysis is systems thinking, recognizing that many variables interact, often in complex, nonlinear and unpredictable ways (Liu et al. 2007a). Our study first describes the role of single variables

(e.g. Table 4), and provides qualitative descriptions for some variable interactions and relationship in section 3. We view this as a necessary first step in the analysis of a complex system, but we also recognize that more focus can be given to examining interactive effects between variables, which are critical for unpacking SES dynamics and a key next step for future research to focus on. Below we discuss some key variable interactions more explicitly.

Paquera-Tambor is the only AMPR from this study trying to find a formal solution for integrating different gear types and user groups into the AMPR management process. It has the largest AMPR, which has led to the development of zones where different types of gears can be used. However, this has increased their transaction costs because they have the diverse actor groups and the highest number of overall actors. Actor groups and individuals within groups have heterogeneous perceptions on what the challenges are for the AMPR and what the solutions should be. This has required strong leadership to keep organized and maintain constructive deliberative processes that avoid conflict. Furthermore, the large size of the AMPR, the distances between actors on land and the diversity of uses and activities has created difficulties for monitoring and enforcement. All these variables are interacting with each other, including the number of actors, the economic heterogeneity of actors, actors' location, the gear types used, leadership, operational rules, mental models (i.e. perceptions), the clarity of boundaries, monitoring and sanctioning, transaction costs and deliberative processes for management are all highly interrelated. These variable interactions make the Paquera-Tambor AMPR unique and complex. There is not one variable which explains why Paquera-Tambor is more successful than the others, it is the unique interactions between all variables.

On Isla Caballo, the development and implementation of rules restricting gear usage failed. Even though the majority of fishers agreed to establish the AMPR, many using gillnets do not respect rules, including leaders' family members, ultimately reducing rule acceptance. This was triggered by the AMPR boundaries being established differently than they were proposed, undermining compliance and the willingness to participate in further management. Strong leadership existed, but those few individuals did not aim to include all actors in decision-making. On Isla Caballo we also observed groups of interacting variables, many are the same as those in Paquera-Tambor, but they interact in different ways. Strong links exist between deliberative processes for management, fishing gears in use, dependence on AMPR resources, leadership, trust and past experiences, monitoring and sanctioning, mental models, the size of the AMPR and the clarity of boundaries.

Lastly, Palito-Montero shows that despite the initial conflicts due to excluding all gears except hand-lines, many fishers have now switched gears and started respecting the AMPR boundaries. This is the only AMPR where fishers have changed behavior according to rules. However, monitoring efforts have decreased due to negative experiences and conflicts, and it has become difficult to monitor the high number of fishers. Despite initial success and observed changes in fishing behavior, most fishers are not willing to contribute to ongoing management efforts, undermining efforts. In Palito-Montero, there appears to be strong links between perceptions of the problem and perceptions of whose responsibility it should be to provide solutions. These perceptions are associated with user groups and increased transaction costs that reinforce

skepticism towards leadership and negative experiences with existing local management processes or with state organizations tasked with monitoring and enforcement.

Collective action and small-scale fisheries

Below we discuss the congruence of our findings in relation to existing literature on collective action in SSF. Overall, most of our findings support our hypotheses (Table 4) and existing literature. Some influential enabling conditions were similar between the AMPRs, and similar to other SSF and SESF studies. Enabling conditions include strong leadership (Gutiérrez et al. 2011, Basurto et al. 2013), high dependence on resources (Lozano and Heinen 2015) and effective monitoring and sanctioning mechanisms (Pomeroy et al. 2001, Gutiérrez et al. 2011, London et al. 2017). Hindering conditions were also similar across AMPRs and with the existing literature, including the lack of external support for enforcement (Pacheco Urpí et al. 2013, Guevara et al. 2016), mistrust and negative past experiences among actors (Cinner et al. 2012, Trimble and Berkes 2015) and unclear spatial boundaries (Guevara et al. 2016). Few variables in our analysis were found to be contradicting expected hypotheses and theory. Instead, we find that some variables seem to have no effect despite the expectation that they would certainly have an observable negative or positive influence. One such exception is that we would expect transaction costs for monitoring to decrease on Isla Caballo and in Palito-Montero due to their small size and close proximity of actors, but a minimal effect was observed. This is most likely explained by interactive effects with other variables which reiterates the need for the continued analysis of collective action that considers complexity and interactive effects beyond the examination of single variable influences.

It is clear that many variables interact simultaneously to influence outcomes. Many of the relevant variables are the same in the three AMPRs, but they tend to have different values and interact in different ways. This supports the need to understand each AMPR as unique, and that each will require contextually appropriate governance within the co-management model. Many variable interactions are combinations of enabling and hindering conditions that in some ways counterbalance each other. One could assume that more hindering conditions would likely undermine success in the long term, and more enabling conditions would suggest eventual successful collective action. However, this is not such a simple equation in reality. Some enabling conditions are able to compensate for hindering conditions and some are not. The identification of variables that can compensate or counterbalance others is difficult to generalize. Nonetheless our findings present some examples.

Isla Caballo and Palito-Montero have more hindering conditions, which generally helps to explain why they struggle to work together and why solutions seem complex and out of reach. Paquera-Tambor has a delicate balance of equal hindering and enabling conditions, which is seemingly enough to slowly move things forward without overwhelming barriers. For example, the Paquera-Tambor AMPR has high transaction costs due its large size and high numbers of actors with heterogeneous interests, among many other hindering conditions described above. However, these transaction costs seem to be mitigated by very strong leadership and actors with

sufficient economic capital and capacity to invest in management and collection centers. These few variables seem to overcome many other hindering conditions in a positive but asymmetric way, suggesting that the balance between hindering and enabling conditions is relative to the importance of particular variables in a context. In Palito-Montero, the balance of hindering and enabling conditions is less asymmetric, and more balanced. A group of hindering conditions (e.g. mistrust and negative past experiences) are in some ways counterbalanced by a group of enabling conditions (i.e. private collection centers and user-based enforcement).

In all three AMPRs, increasing transaction costs are hindering collective action, and although they are sometimes balanced by enabling conditions, they are difficult to deal with institutionally. Many fishers and community members simply do not have the institutional capacity to deal with the challenges they face. This is a familiar challenge for many SSF. Many realize the necessity for AMPRs and how they could bring potential benefits. However, there is minimal capacity and experience in self-organization, communicating effectively, resolving conflicts and capacity building that can help shift the perception of what AMPR management is designed to be, i.e. a collective and empowering process built on the contributions of all individuals, rather than the perception that solutions for management should come from the outside. Resolving these issues requires institution building, and institution building takes time and investments from supporting organizations like INCOPESCA and the Coast Guard. Responsibility for dealing with transaction costs and investments can't be entirely assumed or expected to be resolved by local actors, many of whom are living in low socioeconomic conditions. However, it is also evident that government agencies also lack of financing and capacity. In the next section we briefly discuss policies which may be able to enhance the success of AMPRs as a governance model, considering the above discussion.

Are AMPRs an effective governance strategy?

AMPRs are an institutionally novel model for small-scale fisheries governance in Costa Rica, and while promising in their move towards inclusivity and collaboration, they face many challenges for success. Positive ecological conservation outcomes are more likely when local fishers, regardless of gear type, are included in decision making and empowered through capacity building to develop their own institutions for governance (Castello et al. 2009, Fargier et al. 2014), increasing the likelihood that mutually accepted rules are developed and followed (Sutinen 1999, Bennett 2016). Alternative livelihood opportunities in aquaculture and tourism can help this transition by mitigating fishing pressure and the dependence of social wellbeing on local resource extraction. Inclusionary processes and alternative livelihood opportunities are key ambitions of the AMPR governance model. However, this model faces several challenges to make what looks good on paper, work in practice.

First, all AMPRs are relatively recent, and it must be recognized that institution building, particularly issues of trust and shifting perceptions may take time to evolve. Continuous investment is needed from all actors, but especially from government agencies for capacity building to support local efforts as much as possible. More specifically, it is evident that strong

and transparent leadership has aided success in Paquera-Tambor. Trainings and education to build leadership and organizational capacity may be useful for the other areas, but this takes time and must be sufficiently supported. Second, rule enforcement and maintenance of boundary buoys are a problem throughout the gulf. Of course, fishers should follow the boundary and gear rules, but this is difficult when they ‘know no other way’ or past experiences suggest that individual efforts to follow the rules may disadvantage them because so many others don’t. This scenario is a classic social dilemma (Ostrom et al. 1994, Schlager 2004) leading to a ‘race to the bottom’ of overfishing (Sampson et al. 2015).

Similarly, although the gulf is large, it is small to a fisher with a fast boat seeking to improve a catch. The concept of local roving banditry (Cox et al. 2017) explains this problem of unclear boundaries with low enforcement. Fishers move around the gulf as they want, and fish where they think is best. Spatially static property rights arrangements (i.e. the AMPR boundaries) for governing mostly mobile resources doesn’t help, and may even be misfit to the inherent nature of marine ecosystem dynamics reciprocal fishing behavior because these are fluid across space and time. Serious efforts to reduce ambiguity of boundaries and advance the AMPR governance model should consider making the entire gulf a single large AMPR. This was done with Golfo Dulce in southwestern Costa Rica. Small AMPRs do not seem to motivate behavioral change without substantial incentives. Skepticism that benefits will manifest increases when boundaries are unclear, enforcement is low and costly, and when gear groups fight for influence in decision-making processes. Similarly, the continued use of gillnets normalizes illegality, reducing social pressures for rule compliance within communities, or at least creates tolerance for non-compliance. Expanding the AMPR would bring other issues, and enforcing broader compliance would need to ensure that many fishers are not marginalized due to gear restrictions that result in smaller catches and lower income. Alternative livelihoods would need to support many to ensure improvements in wellbeing. Aquaculture has considerable potential for expansion throughout the gulf but requires more wide spread technical knowledge and up-front investments, both of which would have to come from external sources. Terrestrial and coastal tourism in Costa Rica is already well established, and willing entrepreneurs in rural fishing communities are likely to find opportunities to extract money from foreign tourists instead of extracting fish from the sea. However, there is still a need to find alternative livelihood solutions, which are made difficult by a general lack of terrestrial property rights for local communities, strict government regulations, and skepticism of the government that foreign and wealthy investors are given priority to property rights concessions and development permits over local communities.

Reflections on applying the social-ecological systems framework (SESF)

The SESF has certainly been useful to unpack the complexity of AMPR governance, and as a theoretical framework to examine collective action. The framework has shown to be particularly useful for the study of small-scale fisheries (Basurto et al. 2013, Lozano and Heinen 2015, Guevara et al. 2016, London et al. 2017). In general, we encourage its use for future research and its continued development as a diagnostic tool, particularly in diverse cases other than fisheries to test its generalizability. This study used the SESF for many aspects of the research process, but

primarily as a tool for comparative analysis, applying the common set of variables to each case to enable systematic comparison. The SESF was very useful for this, but comparing cases becomes more difficult as they become more diverse. Even with a common set of variables, there are still many methodological steps and gaps that make comparison difficult such as how each variable is defined, indicators used for measurement, measurement or observation methods for data collection and how data is analyzed and transformed. All these steps create degrees of abstraction, hindering the ability for direct comparison. On the other hand, this is what makes the SESF useful, its ability to be an adaptable tool. There is a methodological tradeoff between its adaptability and its ability to provide a common set of variables for systematic comparison. To ensure comparability, this study used a common data collection method across cases (i.e. qualitative data) and developed common indicators, interview questions and analysis methods in all cases. However, even with three relatively homogenous (i.e. all SSF in the same external settings) this was methodologically challenging. To help build a tool box of methods to apply the framework, we briefly reflect on some of these challenges below.

The SESF is useful for designing interview questions, as it provides a checklist of topics for diagnostic inquiry. It would be useful to aggregate the lists of questions related to each variable from all studies who do this to guide future research. Similarly, the SESF is useful as a qualitative data coding tool, helping to sort the complexity of qualitative data as it relates to each variable. However, during project design and data collection, determining the appropriate measurement or observation methods for each variable can be difficult, particularly if the variable requires specific indicators to measure it, which need to be selected and defined. This study used only qualitative methods, and many variables are difficult to analyze qualitatively. The same could be stated for an entirely quantitative analysis. Mixed methodological approaches for data collection would improve the ability to sufficiently collect data on all relevant variables, but heterogeneous data types are more difficult to analyze cohesively and require multidisciplinary knowledge to ensure robust measures and analysis. Heterogeneous data may also present more challenges for comparability of that data to other cases applying the SESF. This is a trade-off. Analyzing the interactions between variables remains another challenge. The qualitative analysis in this study provided rich descriptions of variable influences and interactions in each case, but can make comparisons between cases more difficult. Methods to develop more direct quantitative measures to analyze variable interactions would be a welcomed and complimentary task for future research. Overall, we encourage future applications of the SESF to explore new methods and to convey those methods as transparently as possible. This will help learning and help to build a tool box of methods for its continued application.

Conclusion

Our research shows that AMPRs, and the Gulf of Nicoya as a whole, can be characterized as SESs. Each AMPR is a unique system with its own challenges. Although they use a generic co-management model, this model should be adapted to each AMPR to make it work effectively. However, there are also common features and challenges facing each AMPR, which makes the

comparison of similarities and differences a useful methodological approach for understanding how co-management can be adapted, and for learning between cases. The most common and foundational feature of AMPR co-management is the necessity for collective action. Fishers and communities need to self-organize and work together with other actors. The AMPR concept proposes a simple idea, empower local people to govern themselves. However, this is not so easy in practice. The responsible government agencies need to provide as much support as possible and a wide variety of social and ecological conditions influence whether collective action is more or less likely to be successful. We argue that AMPRs are a step in the right direction; they represent a shift towards more inclusive, participatory and collaborative environmental governance for small-scale fisheries in Costa Rica. Nonetheless, persistent efforts are still needed to make collective action a social process that is truly inclusive of all actors and motivated by a belief that it will bring desired outcomes. Applying the SESF has been a useful tool for comparing results between cases by using the common set of variables. It is particularly useful for small-scale fishers, and for guiding the collection and analysis of qualitative data. Numerous methodological challenges exist for future research applying the SESF, but we encourage its future use and development.

Acknowledgements

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Research 7: Transforming the social-ecological systems framework into a participatory management and deliberation tool

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Abstract

The social-ecological system framework (SESF) can be useful for applied research and management practice beyond its traditional academic applications. In this article we transform the SESF into a practical tool to facilitate participatory management and deliberation processes within collaborative environmental governance settings. We develop a transdisciplinary methodology to transform the SESF into simple and context relevant images that are understandable by non-specialists, yet the image-based framework still conveys its core tenets of systems thinking, a checklist for system complexity and conceptualizing social-ecological interactions. We then demonstrate a mixed-method approach for testing the usefulness of the image-based framework for enhancing deliberation and participatory management processes. We show how the academic uses of the SESF, its core tenets, can serve the same purpose for non-academic actors. When transformed, the SESF has potential to be a tool that can enhance communication and knowledge exchange between actors. We demonstrate our methodology, i.e., how to transform and test the usefulness of the image-based framework, with small-scale fishers involved with co-management in the Gulf of Nicoya, Costa Rica. In the example, we show how scientists must learn from fishers, to understand how they view their system, in order to co-design an effective tool. We then test its usefulness by exploring the hypothesis that the image-based framework can help fishers discuss with more depth and complexity because it provides a simple conceptual base for systems thinking and a core set of variables to consider as interacting. Using such a tool may be able to convey known academic knowledge about the complexity of environmental governance in a way that potentially mediates conflicts resulting from perceived or actual hierarchies existing among authorities, scientists, and other actors. Furthermore we explore how using the framework during deliberation may be able to alter the social-psychological outcomes of participants using field experimental methods. We discuss our methodology and potential future applications, intending to provide a new concept and way of thinking about how the SESF can be useful for applied research and practice.

Keywords

Collaborative environmental governance | experiment | participation | social learning | transdisciplinary

Introduction

Finding more effective ways to communicate and exchange knowledge between science, policy and practice is of significant interest for global environmental governance (Cornell et al. 2013, Dietz 2013, McAllister and Taylor 2015). Rapid social-ecological change requires urgent and well informed solutions (Steffen et al. 2015a, Bodin 2017). However, difficulties with communication and exchanging different types of knowledge between diverse actors can hinder constructive decision-making (Dietz 2013, Medin and Bang 2014). Solutions are not simple, and barriers are manifold. It is not always clear at which level, phase or through which mechanisms different types of knowledge can best inform governance in meaningful and mutually accepted ways (Newig and Fritsch 2009, Raymond et al. 2010, Tengö et al. 2014). Similarly, it is not always clear when or how different actors can or should participate and bring their knowledge into governance processes (Reed 2008, Schneider and Buser 2017). The political nature of decision-making, power asymmetries or hierarchical actor relationships can create substantial barriers (Brecht et al. 2002, Underdal 2010).

As trends in environmental governance now shift towards more collaborative approaches (Roberts 2004, US NRC 2008, Kenter et al. 2014, Bodin 2017), the development of inclusive and participatory management processes for communication and knowledge exchange are increasingly common (Berkes 2009). There are many definitions of collaborative governance but all involve two core principles, the participation of different actors and deliberation. Participation broadly refers to the processes by which the values and opinions of various stakeholder groups are incorporated into decisions of interest to the public at large (Fung and Wright 2001, US NRC 2008). Participation and deliberative processes are social spaces for communicating ideas, collective action, creating or resolving conflicts and for engaging in social learning (Stern 2005, Reed et al. 2010, Tengö et al. 2014). Deliberation involves reasoned dialogue to negotiate issues of mutual interest and to seek information. This includes learning from one another and consideration of evidence, other viewpoints and values in dialogue, to provide decision support (Carpini et al. 2004, Carlsson and Berkes 2005, Kenter et al. 2014, Dryzek and Pickering 2017). Deliberation is a pillar for group decision-making, and involves in-depth discussion towards a normative goal. However, while deliberation is essential for effective collaborative governance, it is not an inherently easy or simple process to facilitate.

Communication and knowledge exchange during deliberation and participatory management processes can face substantial barriers when diverse actors attempt to work together who have different knowledge, past experiences, preferences and understandings of a system (Dietz 2013, Dryzek and Pickering 2017). Simply bringing people together is often not enough to generate constructive outcomes, a complex array of social and political processes can manifest (Crona and Hubacek 2010, Curşeu and Schrujier 2017). Actors may face difficulties conveying their preferences, experiences and knowledge about a system in a way that is understandable and useful to other actors. For example, from a scientific perspective it is understood that environmental governance involves dealing with a complex system that has many social and ecological variables that interact to shape outcomes. However, scientists may face difficulties

communicating with non-specialists due to the esoteric nature of scientific terminology and concepts (Wong-Parodi and Strauss 2014). Similarly, diverse groups of actors may have knowledge or preferences on many aspects related to a system or governance, but hitting all the points and guiding deliberation in a way that accounts for all important aspects can be difficult (Castella et al. 2007). Facilitation is often needed to guide fruitful deliberation. Structured agendas or tools such as checklists, visual aids and frameworks may be useful to help overcome barriers (Lynam et al. 2007, Rodríguez Estrada and Davis 2015).

Scientific frameworks serve numerous purposes for communication and knowledge exchange in academia, but they can also be useful for the same reasons in collaborative governance settings. Frameworks often distill complex concepts or theories into core components or variables, typically in simple ways using key terminology and visual aids (Binder et al. 2013). In this article we specifically refer to and use Ostrom's social-ecological systems framework (SESF) (Ostrom 2009, McGinnis and Ostrom 2014). The SESF conveys the complex concept of social-ecological systems (SES) in a simple way by illustrating how the core components of the system interact visually (Figure 1). The first-tier variables, or core components, include the 'Resource systems (RS)', 'Resource units (RU)', 'Governance systems (GS)' and 'Actors (A)'. The SESF acts as a common language between academics. It also acts as a checklist to guide the analysis of complex systems, to help ensure that no important aspects are overlooked.

A scientific framework, like Ostrom's SESF, can serve similar functions in participatory and deliberative governance settings. It can help convey systems thinking in a simple way and act as a checklist to ensure that all the core components of a complex system have the potential to be discussed and considered during deliberation and decision-making processes. From a scientific perspective, it is known that environmental governance deals with complex social-ecological system interactions (Liu et al. 2007a, Ostrom 2007, Bodin 2017). Having a tool that can communicate the basic tenets of systems thinking and prompt actors to bring in their own knowledge, beliefs or preferences about the core components of a system may be useful for facilitating more in-depth and constructive dialogue.

However, there are still challenges for making a scientific framework, in this case the SESF, useful in practice. The SESF is not linked to a particular context and it uses non-context specific and specialist terminology. Both aspects may hinder the ability of actors to associate the core concepts and components to a practical governance context. Complexity and the level of detail in a deliberative tool can also be a barrier to communication, as scientists may tend to err on the side of precision and complexity (Knight et al. 2006, Sandker et al. 2010). To make the SESF a useful tool in practice, all aspects of the framework need to be understood by actors (i.e., non-specialists) in a meaningful way. Developing methods to transform the framework for use by non-specialists, while retaining its core concepts and components, can potentially make the framework a more useful practical tool.

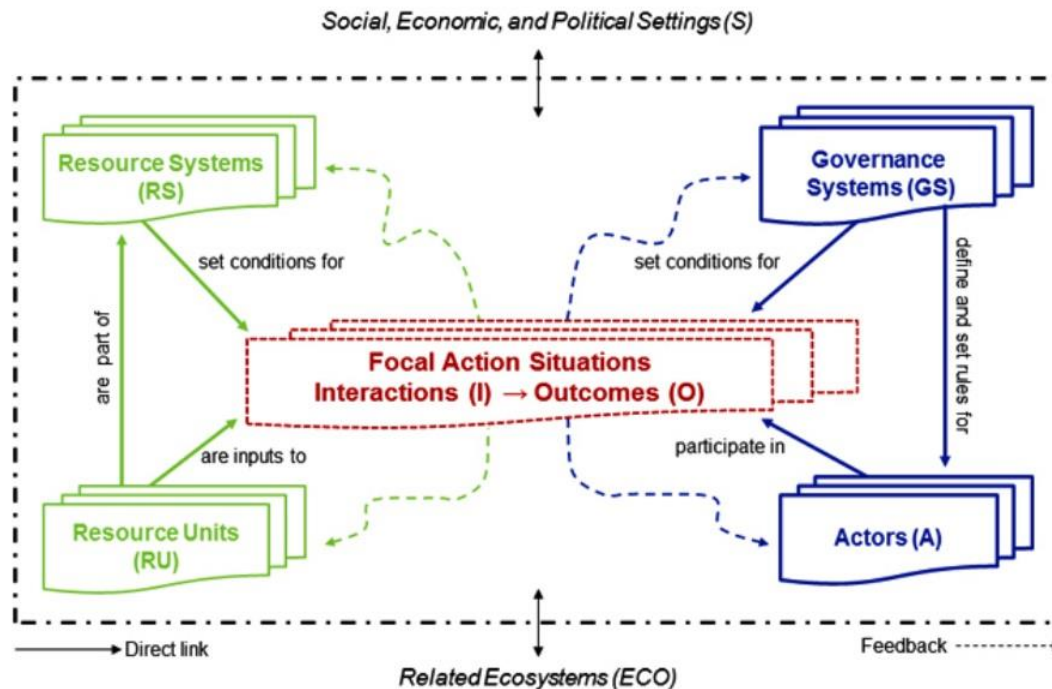


Figure 1. The first-tier variables of the social-ecological systems (SES) framework (McGinnis and Ostrom, 2014).

The purpose of this article is to rethink how the SESF can be useful as a practical tool for enhancing communication and knowledge exchange during participation and deliberation processes in collaborative environmental governance. To do this, we have developed a methodology for transforming Ostrom’s SESF (Ostrom 2009, McGinnis and Ostrom 2014) into images related to a specific governance context. We demonstrate this methodology by transforming the framework for use by small-scale fishers participating in fisheries co-management in the Gulf of Nicoya, Costa Rica. We then demonstrate how to measure the usefulness of the transformed framework. We test its ability to facilitate dialogue with more depth and complexity as well as its impact on social-psychological metrics of actors using Before-After Control-Impact (BACI) field experimental methods. Ultimately this article proposes a new way of using the SESF for applied research and practice, and demonstrates a methodology for testing if it may work. We explore numerous hypotheses, which are shown in Table 1.

Table 1. Hypothesis and methods used in this study.

Hypothesis	Methodology
H1: The SESF can be transformed into simple and context relevant images, making it easier for non-academics to understand and engage with.	See Table 2.
H2: The image-based SESF can structure deliberative dialogue, helping to ensure that all important aspects of a system have the opportunity to be discussed if necessary.	Participatory observation of deliberative dialogue Field experiment

H3: The image-based SESF facilitates deliberation with more depth and complexity because it provides a simple conceptual base for systems thinking as well as the core social and ecological variables in an accessible and non-academic language.	Participatory observation of deliberative dialogue Field experiment
H4: The image-based SESF can enhance knowledge sharing between actors by creating space for actors to share opinions by stimulating discussion.	Field experiment
H5: The image-based SESF as a tool to structure discussions can alter the mental models and social-psychological metrics of actors.	Field experiment

Measuring experimental outcomes

The effectiveness of a policy or the outcome of a treatment intervention can be measured in many ways; the specific metric depends on the context, and expected and/ or desired outcome.

However, equally important to all of them is the experimental (or quasi-experimental) control (Hurlbert 1984, Meyer 1995). Studies that compare subjects before and after a treatment risk the spurious influence of some unrecorded factor that may happen to occur at the same time as the treatment. One such factor may be the researcher themselves, as the presence of an observer (e.g. a scientist) can change people's behavior (Franke and Kaul 1978). For example, social desirability bias may cause people to tell researchers what they want to hear (Nunnally 1967). A control theoretically helps to filter these effects, as observer and social desirability effects are held constant between groups. Studies that only compare control and treatment may be affected by other unobserved systematic differences between subjects, though this may be mitigated by random sampling and large sample sizes (Stewart-Oaten et al. 1986).

This group of analyses are called Before-After Control-Impact (BACI) analysis (Green 1979, Stewart-Oaten et al. 1986) in the ecological literature, and is also known as the difference in differences (DD) model (Orley and Card 1985). An illustration of this analysis can be seen in Figure 2, where a variable is measured before a treatment, and after. Individuals are also randomly assigned to either a treatment or control group. Individual measurements may change over time, and differ systematically between the control and treatment in ways unrelated to the treatment itself, but the difference between these differences (i.e. the interaction between change over time and treatment; BACI) is the treatment effect. In this illustration, if we only compared before-measurements to after-measurements, we may incorrectly assume the treatment was associated with an increase in the variable. The control group shows a similar but slightly smaller increase over time; this is differenced out in the analysis.

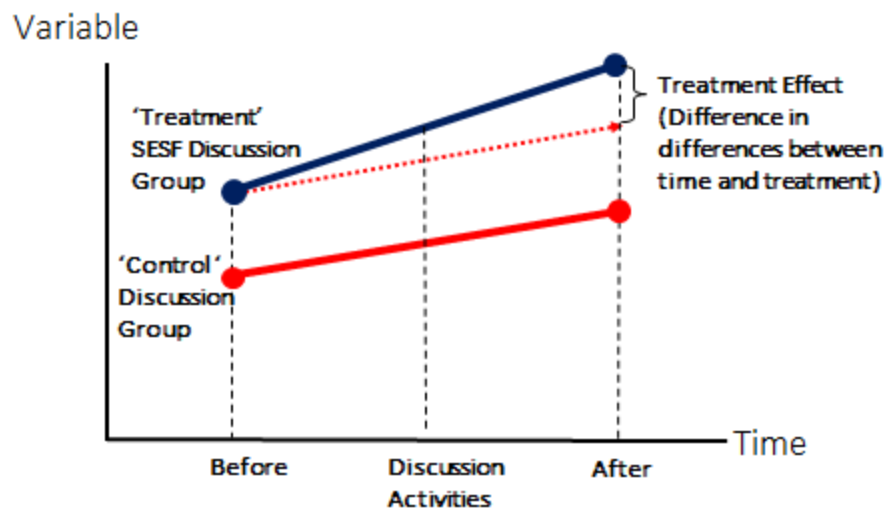


Figure 2. Graphical representation of analyzing controlled experiments via before-after-control-impact or difference in differences

Measuring deliberative outcomes and hypothesis testing

Any management process or decision involves implicit normative criteria and goals, and efforts must be taken to treat these as explicitly and carefully as biophysical management and socioeconomic targets (Cooke et al. 2009, Fenichel et al. 2013). Participatory management and deliberation create venues to consider both normative and positive goals, but they also operate with broader implicit normative goals of, for example, increasing pro-environmental or pro-social outcomes (US NRC 2008). As stated above, there are many context-specific methods to measure the outcomes of deliberative processes, but a very useful one involves environmental psychology, as it addresses implicit normative goals of deliberation, provides information useful to the deliberative and management process, and allows for hypothesis testing.

Environmental psychology is an important field that works to understand the motivations behind particular environmental behaviors, and evaluate how to change behaviors to be more pro-environmental (Stern 2000, Saunders et al. 2006). Environmental theories of behavior such as the theory of planned behavior (TPB; (Ajzen 2005)) or the cognitive hierarchy (Vaske and Donnelly 1999) help understand the psychological processes underlying decisions and assume a hierarchy of psychological constructs that exert influence on one another and ultimately inform behavior. For example, according to the TPB, an intention to perform a specific pro-environmental

behavior is related to performance of that behavior. That increases as the personal norm, (i.e., feeling of obligation, of how one ‘should’ behave), subjective norm (i.e., the perception of what others think one should do), attitude toward the behavior (i.e., a positive or negative evaluation of the behavior), and perceived behavioral control (i.e., the belief that the behavior is under one’s volitional control) increases. The attitude toward a behavior is in turn influenced by one’s mental models and beliefs about the consequences of behavior. These constructs have been shown to have great relevance in a variety of conservation contexts (Cooke et al. 2009, Decker et al. 2012, Milner-Gulland 2012), and are relevant to both managers and policy makers. Constructs both act as a baseline to understand what is acceptable and feasible, and as a relevant and useful way to measure the impact of participatory interventions (Fujitani et al. 2017).

Psychometrics provide a way to measure psychological phenomena such as knowledge and mental models (e.g., fundamental beliefs), transcendental values, and contextual precursors of behavior (Klößner 2013). Numerous psychometric constructs exist including knowledge sharing, mental models, and others connected with perceptions and performance of pro-environmental behaviors. These constructs can be statistically analyzed for hypothesis testing (Nunnally 1967). Further, many of the hypotheses associated with assumed effects of participation and deliberation are very appropriate for measurement using psychometric methods (Kenter et al. 2014, Fujitani et al. 2017). For example, a stated aim of deliberation is to discuss and develop contextual values, to shape and elicit social values, and iteratively update individual values (Kenter et al. 2014). Other important assumed outcomes of deliberation are knowledge sharing and an increase in feelings of empowerment (US NRC 2008). Important aspects of all of these outcomes are covered by environmental theories of behavior, such as values in Value Belief Norm theory (Stern 2000), fundamental beliefs in the cognitive hierarchy (Vaske and Donnelly 1999), and subjective norms, attitudes, and perceived behavioral control in the Theory of Planned Behavior (Ajzen 2005).

Small-scale fisheries and Responsible Fishing Areas (AMPRs) in Costa Rica

The Gulf of Nicoya is the largest tropical estuary in Central America, located on the Pacific Ocean coast of Costa Rica. The gulf supports more than 11,000 small-scale fishers. The Costa Rican Institute for Fisheries and Aquaculture (INCOPECA) is supporting a small-scale fisheries management program to create Responsible Fishing Areas (AMPRs). AMPRs have explicit goals to enhance ecological conservation by supporting community-based co-management with INCOPECA to develop mutually accepted rules for fishing such as reducing harmful gear usage and overall effort. AMPRs also have the explicit goal to enhance conservation and social welfare by pursuing alternative livelihood opportunities not based on resource extraction such as aquaculture and tourism. Fishing communities who are willing and able to self-organize their own fishing association and develop a management plan can formally apply to get legal support from INCOPECA. AMPRs have the exclusive rights to fish and enforce regulations within a spatially defined marine area (Lozano and Heinen 2015, 2016). Both the process of creating the local fishing associations and interactions with INCOPECA involve deliberation about rules and management strategies for the AMPR, which necessarily involves the inclusion of multiple

groups of fishers using different gear types. Constructive deliberation and collective action for co-management are necessary foundations for AMPR success. There are currently seven AMPRs in the Gulf of Nicoya. All fishers in this study live in communities with AMPRs, and have vested interest in its management.

Methods

The methods outlined below are divided into two sections: (1) methods for how the SESF could be transformed into context relevant images, and (2) methods to measure the usefulness and impact of an image-based framework on deliberation processes and the social-psychological outcomes of the individual actors who participate.

Transforming the framework

A methodology for transforming the SESF into context relevant images is shown in Table 1, testing hypothesis 1. Step 1 was conducted in the community of Costa de Pajaros, an AMPR co-management area in the Gulf of Nicoya. Exploratory semi-structured and open ended interviews were conducted with small-scale fishers, local community leaders, non-fisher community members and researchers from Costa Rican universities who focus on marine related issues. This step was guided by a general diagnostic approach using the SESF to build an understanding of which variables are most relevant for understanding the management of small-fisheries in the Gulf of Nicoya (Cox 2011, Hinkel et al. 2015, Partelow 2016) .

For Step 2, the relevant variables from SESF were selected for transformation. We limited our scope to the first-tier variables. This was done for two reasons. Methodologically, this allowed us to use the second-tier variables as indicators for a content analysis of deliberation transcripts. This was to done compare the depth (how many variables) and complexity (the evenness of content discussed between the first-tiers of the SESF) of deliberation transcripts between control and treatment groups (explained below). The second reason to limit images to the first-tier variables is for simplicity. Having images for each second-tier was thought to be too overwhelming and complex for our context. This would undermine the goal of having an approachable tool, while still emphasizing some of the tradeoffs between accuracy and complexity when working with stakeholders during participatory modeling (Knight et al. 2006, Castella et al. 2007).

Step 3 involved generating or finding images for each first-tier variable. Drawings and online searches generated usable open-access images. In Step 4, all images were discussed again with fishers in Costa de Pajaros. We primarily asked two questions. First, what they thought the images represented, and second, what images may better represent the first-tier variables based on their understanding of the system (i.e., for RS, RU, Gov, A). In Step 5, the feedback in Step 4 was used to refine and modify the images further. Step 4 and 5 were done twice to get feedback and refine the images in two rounds. The final images were organized into the conceptual structure of the framework.

In Step 6, the final image-based version of the SESF was used in a trial deliberation process with a group of fishers. We asked this group to discuss challenges facing small-scale fisheries in the Gulf of Nicoya and the management of their AMPR.. The fishers discussed using the framework under passive observation by our research team. In the end, they were asked to provide feedback on whether the image-based framework was useful. Feedback was combined with our observations of the process. Minor adjustments were made to images and the presentation of the image-based framework for use in Step 7.

Table 2. Methodological steps developing an image-based deliberation tool from a SES framework.

Steps	Outcome	Guiding literature
(1) Exploratory research, guided by the framework (e.g. the SESF), to understand the social and ecological context.	<ul style="list-style-type: none"> ● Knowledge of social and ecological characteristics. ● Identify the relevant actors and groups. 	(McGinnis and Ostrom 2014, Cox 2015, Hinkel et al. 2015, Partelow 2016)
(2) Decide which variables from the SESF should be transformed considering the context?	<ul style="list-style-type: none"> ● Contextualize the depth and content of what is conveyed in the framework. 	(See Step 1)
(3) Find or generate images representing the variables in the appropriate context.	<ul style="list-style-type: none"> ● Compilation of initial images related to variables of the SESF. 	(Trumbo 1999, Medin and Bang 2014, Rodríguez Estrada and Davis 2015)
(4) Gather feedback on images from actors to refine them. This could be done with interviews, workshops or discussion groups.	<ul style="list-style-type: none"> ● Feedback on images to better fit the context. ● Initial impressions of how actors perceive the images. 	(Leventon et al. 2016, Talley et al. 2016, Schneider and Buser 2017)
(5) Refine images and organize into the structure of the framework. Repeat Step 3 if necessary.	<ul style="list-style-type: none"> ● Refined images that better fit the context and understanding of local actors 	(See Step 3)
(6) Trial run deliberation process with actors to get feedback and insight into how the images inform what is being discussed. Refine the framework.	<ul style="list-style-type: none"> ● Understanding of how actors use the framework in a deliberative setting. ● Refined framework. 	(Talwar et al. 2011, Kenter et al. 2014, 2016)
(7) Use framework for practical deliberation and/ or in an experimental setting to measure its impact.	<ul style="list-style-type: none"> ● Applying framework in a deliberative setting. ● Increase knowledge on how deliberation tools enhance outcomes. 	(Cooke et al. 2009, Rodela 2013, Birnbaum et al. 2015, Dryzek and Pickering 2017, Fujitani et al. 2017)

Field experiments to measure impact

Small-scale before-after control-impact field experiments were conducted to pilot test our hypotheses as a proof of concept. Groups of 3-4 fishers were gathered and asked to deliberate general challenges facing the management of fisheries for up to 30 minutes. Two control groups were asked to deliberate with no visual or information aids, just to discuss amongst themselves. Five treatment groups were given the transformed SESF, and were told they could use it as an aid for discussion. Each group discussion was recorded with informed consent from the participants. Before and after each group discussion, each fisher completed a standardized questionnaire.

Measuring depth and complexity

To test hypotheses 2 and 3, transcripts from the deliberation groups were translated into English and transcribed into the qualitative data analysis program MaxQDA. A content analysis (Stemler 2001) of each transcript was conducted using the second-tier variables of the SESF as a coding framework, as indicators to categorize discussion content. Coding was consensus based, using a coding protocol developed by two authors. Transcripts were then first coded by one author, then again by a second author to confirm that the coding was done based on the established consensus and to ensure the content appropriately related to the second-tier variables. After coding, the analysis involved the number of coded segments for each second-tier variable in each transcript. The sum total of second-tier variables within each first-tier, for each transcript, was used as a measure of discussion depth (i.e. the amount of content in each transcript related to each first-tier). The number of second-tier variables was averaged across the control and treatment groups separately for each first-tier variable (Table 3). The complexity of each discussion can be examined and compared in Table 3 (i.e. the relative proportion or evenness of focus between first-tier variable content in the control and treatment groups).

Measuring individual changes

Elements from the theory of planned behavior (TPB; (Ajzen 2005)) and the cognitive hierarchy were used to understand the behavioral intention to support the AMPR (Appendix A) to assess hypothesis 5. This included the constructs of ‘perceived behavioral control towards the AMPR’ (i.e., whether achieving the AMPR objectives are within their control), ‘attitude towards collective action for the AMPR’ (positive or negative assignment about collective action for the AMPR), ‘attitude towards regulatory authority with regards to the AMPR’ (i.e., whether they support and respect the regulations), and ‘personal and subjective norms towards the AMPR’ (i.e., whether they and the people they respect support the AMPR). We also evaluated the belief that the AMPR supports fishers. Items to measure beliefs, attitudes, and norms were constructed ad hoc based on qualitative preliminary work, as well as adapted from the literature. The reliability of measures was checked by assessing internal consistency with Cronbach’s alpha and by confirmatory factor analysis.

To evaluate hypotheses 3 and 4 from a different angle, we asked self-assessment questions to participants post-activity on the depth and complexity of the discussion (H3) as well as how the activity facilitated knowledge sharing (H4) through discussion as well as aiding personal reflection (Appendix B).

Constructs were obtained from mean Likert scales and analyzed with parametric methods. In the case where multi-item scales were not available, we applied the interval assumption to individual items with 5-point Likert response formats, as is a common practice because the interval assumption is conservative as it increases the likelihood of type II error. Treatment effects were assessed via linear mixed models (LMM) fit by restricted maximum likelihood in the statistical package R (<http://cran.r-project.org>), with the Likert scale construct as the dependent variable with dummy coefficients for fixed effects for the pre-test vs. the post-test, control vs. SESF treatments, and the interaction between the two (the treatment effect), with individual nested within region random effects parsed from global variance. Where only SESF treatment versus control measurements were available (i.e., post-activity assessments), the two groups were compared with Welch's *t*, given the unbalanced sample size and variance.

Results

Our image-based SESF is shown in Figure 3, transformed to the context of small-scale fishers in the Gulf of Nicoya, Costa Rica. The original conceptual structure of the SESF is retained and images are used to represent each first-tier variable, without reference to specific second-tier variables. In 'Resource systems' and 'Resource units', images represent multiple co-occurring first-tiers. The 'Resource systems' tier was labelled 'Ecosystems' and shows four co-occurring first-tier systems: a mangrove forest, a reef, a riverine estuary and a shoreline going out into the open sea. The 'Resource units' tier was labelled 'Resources' and shows a diversity of different species caught in the fishery. The 'Actors' tier retained its label and shows different co-occurring first-tiers (i.e., groups of actors) including fishers, coast guard, the community, patrons (i.e., middlemen) and interest groups (e.g. NGOs). The 'Governance systems' tier retained its name and shows the different governance systems including images related to rules, co-management, knowledge exchange, formal and informal governance settings. The original version of the text in Figure 3 was generated in Spanish for use by local fishers, and was translated to English for this article. The development of the image-based SESF supports our hypothesis (H1) that it is possible to transform the framework into a contextualized image-based tool for use by non-academics. The process of transformation was accomplished by engaging local fishers through iterative learning, where we the researchers learned from fishers about how they view and understand their own system to generate the appropriate images.

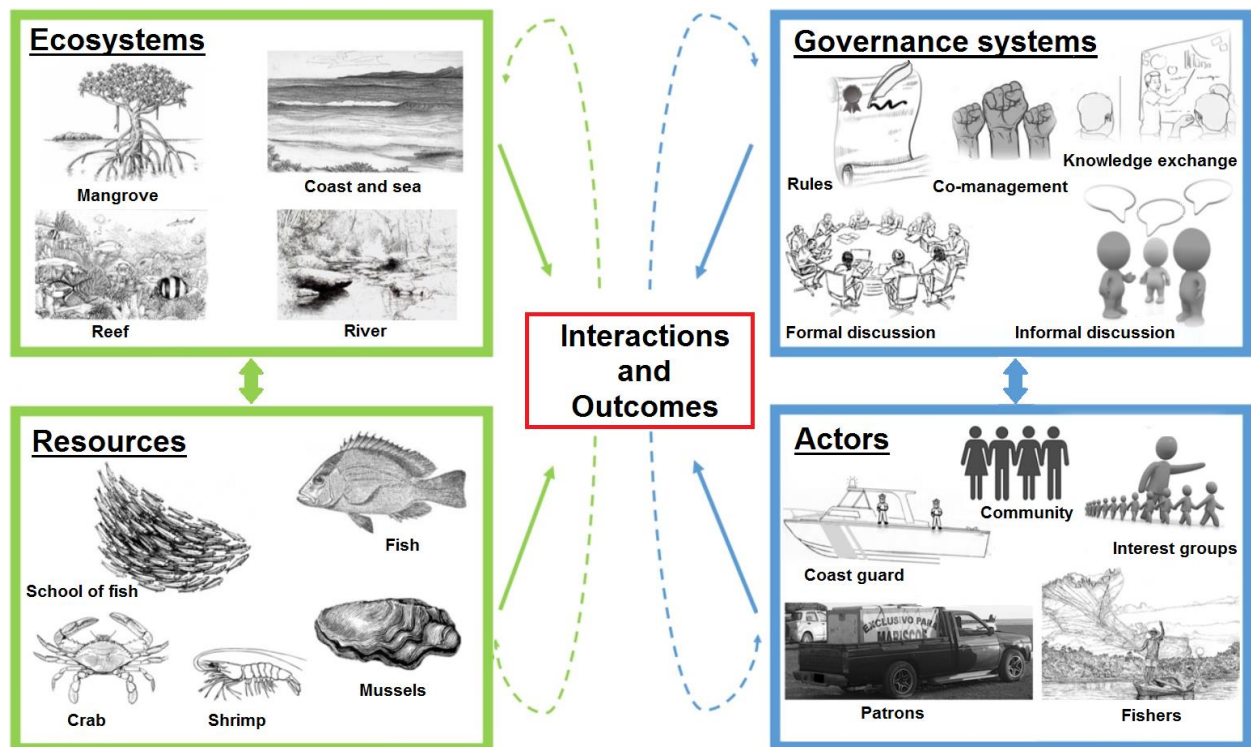


Figure 3. An image-based SESF transformed for use by fishers in the Gulf of Nicoya, Costa Rica. The image-based framework translates the general concept of systems thinking and social-ecological interactions through simple images and text.

Depth and complexity of deliberation

The structure and content of discussions differed between treatment and control groups. Treatment groups used the image-based SESF to loosely structure the content of discussion, often going through each of the four first-tier categories systematically. This supports our hypothesis (H2) that the SESF can provide structure to deliberation compared to the control. Treatment groups discussed with more depth, except on ‘Governance systems’ because control tended to discuss more exclusively content related to ‘Governance systems’. Treatment groups also discussed with more evenness than control groups. The control groups tended to start immediately discussing governance, monitoring and compliance issues, thus discussing in more depth on content related to the ‘Governance systems’ tier than the treatment group. However, overall they discussed with less depth on the other variables. The control groups (without the SESF) discussed with less complexity or evenness across variables (Table 3). These initial findings generally support our hypothesis (H3) (Table 3). The ‘Social, economic and political settings’ and ‘External ecosystems’ first-tier variables were not included in our image-based framework, and no discussion content related to those variables. ‘Actors’ variables were the most frequently discussed in both groups, with a large portion of the content relating to the second-tier variable ‘Knowledge of SES/ mental models’, where fishers expressed their perceptions and opinions about issues of concern to the group.

Table 3. Each deliberation transcript from the treatment and control groups was coded for content in relation to the SESF second-tier variables. This table shows the mean number of coded segments from each group aggregated to each first-tier variable. The table allows comparison of the depth (i.e. amount of content within each first-tier) and complexity (i.e. the proportionality/ evenness of content between first-tiers) of dialogue between the treatment and control groups.

SESF first-tier variables	Average number of coded segments for each variable in the treatment groups (N= 5)	Average number of coded segments for each variable in the control groups (N= 2)
Social, economic, and political settings (S)	0	0
Resource systems (RS)	20.6	6
Resource units (RU)	22.4	13.5
Actors (A)	58	40.5
Governance systems (GS)	33.8	38
Interactions (I)	27.2	22
Outcomes (O)	11.2	11.5
Related ecosystems (ECO)	0.2	0

Impact of deliberation on individuals

Fishers across all sites indicated very positive personal norms and attitudes towards the AMPR, as well as beliefs that the AMPR was intended to benefit fishers. Perceived behavioral control towards achieving AMPR objectives was slightly lower. There was also more diversity among the regions with regards to the social norm of supporting the AMPR through observance of the regulations, and to a lesser extent positive attitudes towards regulatory authority (Figure 4). Participants in the discussion activities indicated overall agreement that the activity aided discussion complexity and depth, personal reflection about the topic, and facilitated knowledge exchange beyond what would occur without the activity (Figure 5.) Respondents deliberating with the aid of the visual SESF had a higher mean agreement than the control deliberators; however this difference is not statistically significant (Table 4).

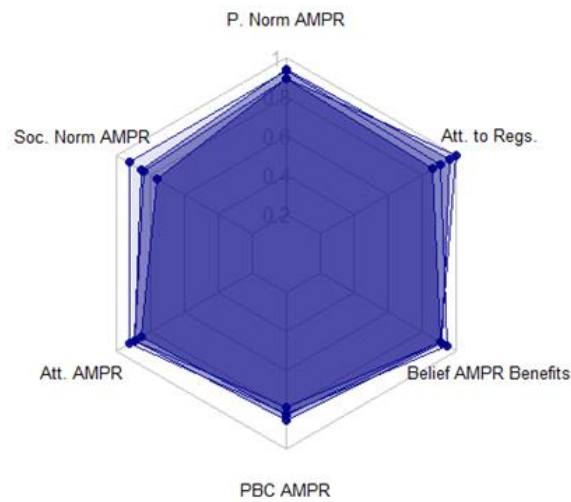


Figure 4. Radar plot of baseline mean psychometric constructs for each of the four survey regions; scaled between 1 (more positive towards the AMPR and regulatory authority) and 0.

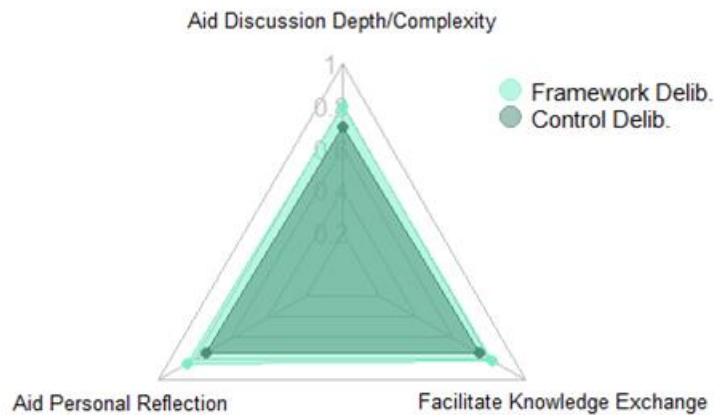


Figure 5. Radar plot of post-discussion assessments by the participants of the activity; scaled between 1 (strong agreement) and 0 (strong disagreement).

Given the limited and unbalanced sample size, it is unsurprising that measured constructs did not differ significantly between treatment and control groups (Tables 4 and 5). Post-hoc analyses show very small to moderate effect sizes and very low statistical power (Tables 4 and 5). However, this work fulfills the goals of demonstrating proof of concept to guide future studies. We have evidence of good reliability in many of our constructs ($\alpha > 0.7$; (Nunnally 1967)), and they can be used in similar contexts, as no context-specific scales yet exist in the literature. In contrast, we would need to re-visit our items measuring perceived behavioral control and attitude towards regulatory authority in this context.

Though we did not find statistically significant differences between the treatment and control groups, it may be taken as an indication to further research, that, for example the differenced treatment group means were lower than the control group means (Table 5). As a thought experiment, this difference, if ‘real’ from a frequentist perspective, would indicate stronger agreement that the SESF discussion had more depth and complexity, aided personal reflection, and was useful to facilitate discussion, relative to the control. This information guides both future hypothesis development and future experimental planning, as this provides empirical grounds to set a sample size. From a frequentist perspective, if the lack of significant treatment effects were due to a lack of statistical power to resolve these differences, we can use power analysis to calculate a necessary sample size given observed effect sizes and desired statistical power (Cohen 1988). Figure 6 shows the necessary sample size given desired statistical power (the inverse of the type II error level, the probability of incorrectly failing to reject the null hypothesis), with type I error level (probability of incorrectly rejecting the null hypothesis) set at the conventional 0.05, and a range of observed effect sizes in the field experiment. Given the moderate effect sizes a prudent sample size with sufficient power would range from 30-100 participants per treatment, in line with other workshop-based participation and deliberation studies e.g., (Lienhoop and MacMillan 2007, Carnoye and Lopes 2015).

Table 4. Measured constructs.

Construct	No. items	Reliability (α) before	Reliability (α) after	Treatment coefficient*	SE*	p-value*	Effect size (Cohen's d)**	Power **
Perceived behavioral control towards the AMPR	3	0.34	0.46	0.14	0.41	0.41	0.28	0.10
Attitude towards collective action for the AMPR	3	0.66	0.83	0.16	0.40	0.69	0.15	0.06
Personal norm towards the AMPR	3	0.83	0.77	0.00	0.18	0.99	0.04	0.05
Subjective norm regarding the AMPR	1	NA	NA	0.01	0.39	0.98	0.06	0.05
Belief the AMPR benefits fishers	5	0.83	0.8	-0.18	0.25	0.47	-0.29	0.11

Part 3: Empirical research

Attitude towards regulatory authority	4	0.5	0.54	0.19	0.29	0.52	0.37	0.14
* From linear mixed model of difference in differences								
** for t-test with unbalanced sample sizes								

Table 5. Results between control and treatment.

Variable	No. items	Reliability (α)	Mean Control	Mean Treatment	Welch's t	p-value	SE (total)	Effect size	Power
Aid to discussion depth and complexity	2	0.77	1.95	1.64	0.91	0.38	0.75	-0.41	0.17
Aid to personal reflection	3	0.80	1.80	1.50	1.08	0.30	0.59	-0.51	0.24
Utility and facilitation of exercise	2	0.82	1.80	1.58	0.75	0.47	0.61	-0.36	0.24

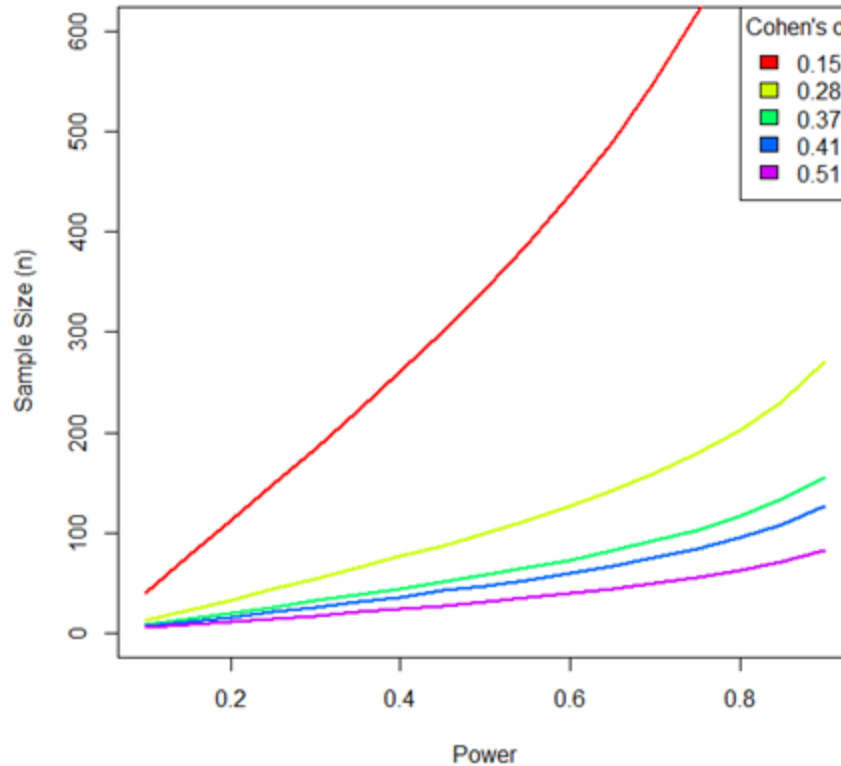


Figure 6. Plot of necessary sample sizes given desired statistical power, over a range of observed effect sizes from the field experiment (Cohen's d), at significance level 0.05.

Discussion

Despite recognized shifts towards collaborative environmental governance (Roberts 2004, US NRC 2008, Kenter et al. 2014, Bodin 2017), making participation and deliberation work in practice remains a substantial challenge (Newig and Fritsch 2009, Curşeu and Schruijer 2017). Communication and knowledge exchange is critical for progress (Cornell et al. 2013) as difficulties for working together are exacerbated when actors have different experiences, knowledge, beliefs, and understandings of a system (Bohensky and Maru 2011, Cornell et al. 2013). This study has approached these challenges as an opportunity to think outside-the-box and develop new applied research methods. In particular we focus on the role of developing facilitation tools and testing their usefulness as interventions in participatory and deliberative environmental governance settings. We have tried to rethink how an existing academic tool, the SESF (McGinnis and Ostrom 2014), can be used in new ways. We show that the framework can be useful as a practical tool when transformed into a 'common language' of images for non-specialists, arguing that images can ground the framework into a relevant governance context for

non-specialists. The SESF can be a useful tool to convey systems thinking, social-ecological interactions and a checklist of core system components through those images. In this sense, our study provides proof of concept to the idea that the usefulness of the SESF for scientists may be paralleled by its usefulness for practitioners.

Ultimately, the transformed SESF explores one potential facilitation tool to make collaborative environmental governance more effective. Facilitation tools may be able to remove existing barriers for communication and knowledge exchange during deliberation. For science, developing facilitation tools can be viewed as a methodological challenge (Lynam et al. 2007). It has been suggested that deliberation may improve through better linking scientific analysis and the participation of other actors (Dietz 2013). However, new practical mechanisms and methodologies are needed to explore this idea further, and we have proposed numerous hypotheses to test how and why tools like the transformed SESF may be useful. We encourage further testing and critique of these hypotheses in more robust ways and in different contexts. There are a large variety of different types of collaborative environmental governance arrangements to explore (Berkes 2009), and different cooperative arrangements with diverse types of actors likely warrant contextualized approaches. We argue that the approach outlined in this study may be generalizable in different contexts (e.g., beyond small-scale fisheries) because it allows images to be tailored to context through active engagement and co-designing with actors. However, we recognize that this needs further exploration and testing, which we encourage. Our study did not co-design the image-based framework with the actors who then used it for deliberation, for reasons related to testing its usefulness as an intervention with experiments. However, in a practical setting, co-designing the framework with the actors who will use it may be beneficial and allow more participation and deliberation surrounding the process of development as well.

Furthermore, this study has demonstrated the idea of using an existing scientific tool (i.e., the SESF). However, many other social-ecological systems frameworks exist (Binder et al. 2013) with similar core concepts such as ecosystem services (Partelow and Winkler 2016). There is potential to explore the role of using scientific frameworks in general, not just the SESF, to help communicate and exchange known scientific concepts related to environmental governance. For example, some core concepts are critical to consider when developing management policies such as social-ecological complexity and interactions as well as how those may occur at different levels and scales (Cash et al. 2006, Liu et al. 2007a). There are numerous frameworks built on these core concepts (Binder et al. 2013). Subsequently, actors should be able to decide what to do with this knowledge once they have it, and the image-based SESF may be able to transfer some of this knowledge in a passive way, without the active intercession of a scientist. There is a need to flatten perceived power or epistemic hierarchies that might be associated with having specialists actively involved in deliberative settings (Fung and Wright 2001, Klenk et al. 2015). For example, the presence of a perceived expert or the frontal presentation of knowledge has been shown to hinder the engagement or contributions of non-specialists (Lord 1999, Voinov and Gaddis 2008). However, many formal collaborative governance arrangements have formal settings, for example on a deliberation or management council, where scientists are necessarily one of the actors involved. In other cases, scientists may be involved in a consulting capacity, or

not formally involved at all, such as in the Gulf of Nicoya. Similarly, there will inevitably be power asymmetries between other actors, and facilitation tools that are transparent and collaborative in design may help flatten those to ensure more equitable participation (US NRC 2008).

It is necessary that knowledge exchange and communication is multi-directional, and not just a one-way transfer of scientific knowledge to other actors. Numerous studies have shown that this can increase the perceived legitimacy and acceptability of governance processes, ultimately leading to the development of more effective management, rules and compliance (Berkes 2009, Tengö et al. 2014, Bennett 2016). We argue that the usefulness of the SESF is not limited to conveying scientific knowledge to other actors. It is equally important to improve communication and the exchange of knowledge between actors (e.g., between fishers) through social learning. Social learning is a critical process for human development and cooperation (Reed et al. 2010, Cundill and Rodela 2012, Dietz 2013). It can help build trust and mitigate conflict between actors if it can be well facilitated in deliberative settings (Berkes 2009). However, there are many layers and complexities associated with social learning processes (Reed et al. 2010), and one important aspect is the role of actor perceptions in governance processes (Bennett 2016, Beyerl et al. 2016). If the perceptions of other actors, and of the governance process, are that they are legitimate and acceptable, it is likely that they will participate, communicate and exchange knowledge in more constructive ways, leading to better outcomes for both people and nature (Bennett 2016).

While this study conducts an applied research project, it is evident that there is considerable potential to use a transformed SESF in a practical setting and we encourage exploring practical uses in future work. Critical questions remain about what influences constructive actor participation and deliberation, what influences communication and knowledge exchange and how to design research that can help test potential tools for supporting these processes. There are many methodological approaches to explore these questions, some of which are demonstrated above. Measuring and testing changes in environmental psychology, mental models and prosocial behavior are promising inquiries. These are integral dimensions for understanding how individual changes lead to collective behavioral phenomena or manifest into decision-making for resource use and governance (Saunders et al. 2006, Swim et al. 2009). Field experimental methods and the BACI method are useful for parsing out differences in treatment effects, and we have demonstrated how to do this in our study. However, there is also room to explore these methods with larger sample sizes, but also with additional methods such as participatory workshops and qualitative research to more in-depthly examine social-psychological changes in individuals and groups.

Conclusion

Shifts towards collaborative environmental governance are promising, but in order to ensure that such arrangements lead to beneficial outcomes for both people and nature, they require the participation of different actors and constructive deliberation between them. Communication and

knowledge exchange are critical to this process, and facilitation tools may be able to support deliberative processes that lead to more effective outcomes, both collectively and at the individual level. This study has demonstrated how the social-ecological systems framework (SESF) can be transformed into an image-based facilitation tool that can help actors discuss with more depth and complexity. The transformed framework can convey basic scientific knowledge that is generally important for governance such as systems thinking and social-ecological complexity in a passive and simple way. The SESF may also help knowledge exchange and communication among actors. We believe this study has shown a proof of concept for the ideas and hypotheses outlined above, and we encourage future studies to explore them further.

Part 4: Synthesis and conclusions

Research 8: A review of the social-ecological systems framework: Methods, modifications and challenges

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Abstract

The social-ecological systems framework (SESF) is arguably the most comprehensive conceptual framework for diagnosing interactions and outcomes in social-ecological systems (SES). This article systematically reviews the literature applying and developing the SESF and discusses methodological challenges for its continued use and development. Six types of research approaches using the SESF are identified as well as the context of application, types of data used and commonly associated concepts. I analyze the frequency of how each second-tier variable is used across articles. A summary list of indicators used to measure each second-tier variables is provided. Articles suggesting modifications to the framework are summarized and linked to the specific variables. The discussion reflects on the results and focuses on methodological challenges for applying the framework. First, how the SESF is situated epistemologically in relation to commons and collective action research. This affects its continued development in relation to inclusion criteria for variable modification. The framework may evolve into separate modified versions for specific resource use sectors (e.g. forestry, fisheries, food production, etc.), and a general framework would aggregate the commonalities between them. I further discuss methodological challenges for applying the SESF related to research design, transparency and cross-case comparison. I refer to these as methodological ‘gaps’ which allow the framework to be malleable to context but create transparency and data abstraction issues. These include the variable-definition gap, variable-indicator gap, the indicator-measurement gap and the data transformation gap. An obvious benefit of the framework has been its ability to be malleable and multi-purpose, bringing a welcomed pluralism of methods, data and associated concepts. However, pluralism creates challenges for synthesis, data comparison and mutually agreed upon methods for modifications. Databases are a promising direction forward to help solve this problem. In conclusion I discuss continuing directions by reflecting on the different ways the SESF may continue to be a useful tool through (1) being a general but adaptable framework, (2) enabling comparison and (3) as a neutral tool for theory building.

Introduction

The social-ecological systems framework (SESF) (Ostrom 2007, 2009, Poteete et al. 2010) is a conceptual framework providing list of variables which may be interacting and affecting outcomes in social-ecological systems (SES). The evolution of the framework is supported by a long history of empirical research on the commons and collective action e.g., (Ostrom 1990, Agrawal 2001, Meinzen-Dick et al. 2002, Wollenberg et al. 2007, Poteete et al. 2010). However, the SESF is now viewed less as a theoretical framework to advance collective action theory and more as a general tool to diagnose the sustainability of social-ecological systems (Ostrom 2009). This transition has brought wider engagement over the last ten years, and its core literature (above) has now been cited in combination more than 6,500 times (Google Scholar, as of Feb. 2018). However, critical methodological questions remain regarding how the framework can be applied empirically and operationalized in new contexts (Leslie et al. 2015, Partelow et al. 2018b).

This article reviews the SESF literature to help examine these methodological challenges and to guide those interested in continued engagement with the framework. First, by (1) reviewing the trends in the peer-reviewed literature and (2) by providing an extensive discussion of different methods and methodological considerations for applying the framework. This article builds on previous reviews by McGinnis and Ostrom (2014) who provide substantial contributions to the framework's conceptual development, and by Thiel et al., (2015) who review 20 articles using the framework for empirical research. This article continues and considerably expands on these two efforts by examining more than 90 articles which engage with the SESF either conceptually, empirically and/ or for meta-analysis. In the discussion I critically reflect on how the SESF is situated epistemologically in relation to commons and collective action research, and how this relates to potential inclusion criteria for variable modification, and ultimately the framework's continued development. Numerous methodological challenges are discussed for applying the framework for future research. This review and discussion are guided by the following research questions:

- What are the trends in the SESF literature (i.e. sectors, data types, methods used)?
- What are the different ways the SESF is being applied (i.e. types of research)?
- What variable modifications have been suggested to the framework?
- What are the directions forward and potential challenges for the frameworks continued development?

A brief history of the framework

Although countless articles and books have written far more comprehensively about the evolution of Elinor Ostrom's research on the commons and collective action, leading to the SESF, the nature of this article warrants a brief overview. Initiated by her book *Governing the Commons* (1990), Ostrom and her many colleagues began accumulating empirical evidence on the variables and types of institutional arrangements which were most likely to enable actors to work together and solve social dilemmas in systems with common-pool resources (CPR) and public goods (Olson 1965, Ostrom et al. 1994, Schlager 2004). Her work directly challenged Garrett Hardin's conclusions in the *Tragedy of the Commons* (Hardin 1968), showing that resource users are not helpless in their ability to solve social dilemmas, which are exacerbated by the rivalry and excludability characteristics of CPRs, but they can actually develop self-organized institutions to govern the commons without the need for privatizing common property or imposing state regulation.

Based on the early work of many commons scholars, an empirically supported list of variables began to emerge showing the multitude of influences that affect the development of governance institutions (Agrawal 2003, Ostrom 2005). These variables became a comprehensive list of social and ecological variables influencing cooperation and self-organized governance under a theory of collective action (Olson 1965, Ostrom 1990, Poteete et al. 2010). Collective action theory in the commons literature explores a central hypothesis that actors can cooperate and self-organize the development of institutions for natural resource governance. However, the success of this cooperation is likely to vary under different social and ecological conditions. It became evident that the development of successful institutional arrangements for governance was in part dependent on understanding complex and interdependent linkages between these social and ecological variables. It soon became difficult to develop a strong set of theoretical claims that any group of variables will influence sustainability outcomes in predictable and generalizable ways across diverse cases. Instead, a non-theoretical list of variables was conceptualized as a diagnostic checklist, a list of potentially influential variables that can be used to guide the diagnosis of key variables and interactions influencing outcomes. The approach is similar to medical practitioners who diagnose patients with a checklist of key components and interactions in the human body to find the appropriate treatments (McGinnis and Ostrom 2014). The concept of diagnosis can be applied to environmental problems if a list of key variables and interactive processes can be identified, i.e. variables that are common across all systems for examination. The SESF proposes a list of generalizable variables that can be used as a diagnostic tool (Ostrom 2007). Thus, the SESF intendeds to be in part generalizable (Ostrom 2009), in part removed from commons research and collective action theory which guided the selection of variables (Ostrom 1990, Ostrom et al. 1994).

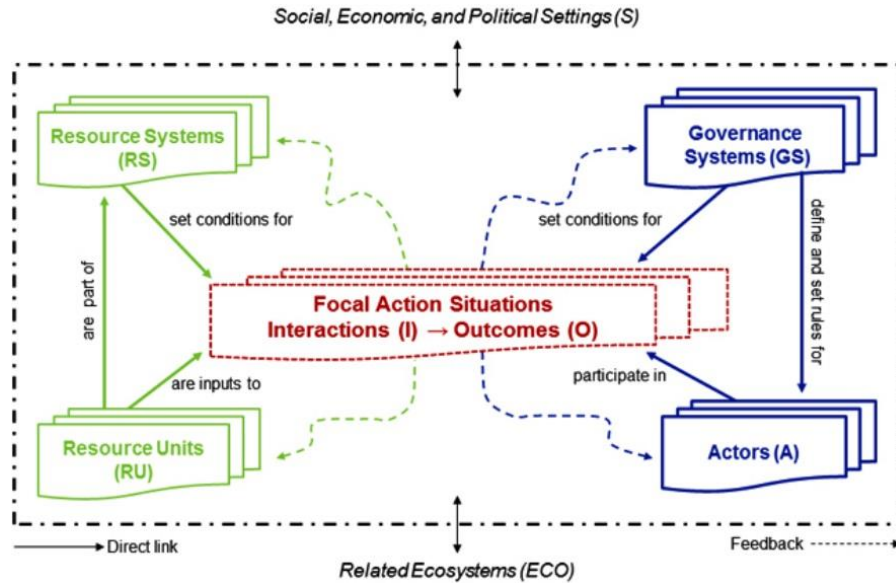


Figure 1. Conceptualization of the social-ecological systems framework from McGinnis and Ostrom (2014). First tier variables are shown with their interactions and outcomes.

The SESF is structured into tiers of nested and related concepts and variables (Figure 1). The first-tiers include the Resource System (RS), Resource Units (RU), Governance System (Gov), Actors (A), Social, Economic and Political Settings (S), Interactions (I), External Ecosystems (Eco) and Outcomes (O). Second-tier variables are nested within each first-tier (Table 1). Beyond its visible structure, the framework emerges from the convergence of political theory and institutional economics (North 1990, Ostrom 1990, Coase 1998, Klein 2009). The epistemology of the framework places an institutional and anthropocentric lens on the analysis of sustainability through suggesting the need to understand how and why cooperation influences governance arrangements and their outcomes. However, it is evident that the framework is useful beyond the scope of commons and collective action research, as it has been proposed as a general tool to diagnose the sustainability of social-ecological systems (Ostrom 2009) and to develop new theories in SES (Cox et al. 2016).

Part 4: Synthesis and conclusions

Table 1. The first and second-tier variables of the SESF from McGinnis & Ostrom (2014).

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) 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	Governance Systems (GS) GS1- Government organizations GS2- Non-governmental organizations GS3- Network structure GS4- Property-rights systems GS5- Operational rules GS6- Collective choice rules GS7- Constitutional rules GS8- Monitoring and sanctioning
Resource Units (RU) 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	Actors (A) 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
Interactions (I) 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	Outcomes (O) O1- Social performance measures O2- Ecological performance measures O3- Externalities to other SESs
Related Ecosystems (ECO) ECO1- Climate patterns ECO2- Pollution patterns ECO3- Flows into and out of SES	

Social-ecological systems and sustainability

The social-ecological systems (SES) concept has evolved into a mainstreamed field of research focused on the interdependent linkages between social and environmental change and what this means sustainability (Berkes et al. 2000, Liu et al. 2007a, Fischer et al. 2015). SES research is focused on understanding many dimensions of system functioning, making it an interdisciplinary field, but also on the development and implementation of normative goals related to sustainability (Abson et al. 2014, Partelow et al. 2018a). What we would ultimately like to know about SES is how they can be sustainable for different people and places around the world. However, with these broad and often ambiguous goals, SES scholarship has become diverse and pluralistic (Miller et al. 2008, Partelow and Winkler 2016). It associates with many different concepts, theories and methods under two broad conceptual pillars: (1) understanding social-ecological system functioning and (2) understanding all aspects related to the development, implementation and transformation towards normative sustainability goals. A large majority of SES research attempts, in some way, to link these two core pillars, including the SESF. The SESF provides one of many conceptual frameworks attempting to do this, but many others exist (Binder et al. 2013, Partelow and Winkler 2016).

Methods

A systematic review of peer-reviewed literature was conducted from the scholarly databases Scopus and Web of Science. Searches were conducted on both databases to find literature directly engaged with the SESF in any context or type of research. Search strings were guided by an extensive list of search terms related to ‘social-ecological system’, ‘framework’ and/ or ‘Ostrom’ resulting in more than 120 articles from both databases. This list was refined manually by reading abstracts, and the full text if necessary, to check for applicability to the scope. 93 articles were included for final review. Each article was read and evaluated with standardized criteria on the following categories: source, year of publication, type of research, contextual focus, major discussion points, type of data, type of analysis, variables used, indicators used and suggested modifications.

Results

Trends and gaps

The SESF is extensively cited and associated with other concepts in the broader SES discourse, including other theories, concepts and frameworks (Binder et al. 2013). The most common associations are with ecosystem services (Daily 1997, Partelow and Winkler 2016), resilience

(Berkes et al. 2000) and variety of other environmental governance theories (Folke et al. 2005, Cox et al. 2016) including multi-level governance, polycentric governance and adaptive co-management (). The cross pollination of literature in SES research has created a plurality of nested conceptual approaches regarding the contexts in which the framework is applied and the methodologies for its application (Table 2).

The SESF has been applied to a wide variety of empirical contexts (Table 2). Much of the literature remains focused on commons scholarship with a large focus on community-based systems such as irrigation systems (Meinzen-Dick 2007, Cox 2014b, Hoogesteger 2015, Mccord et al. 2016), small-scale fisheries (Basurto et al. 2013, Leslie et al. 2015, Lozano and Heinen 2015, Partelow and Boda 2015, Guevara et al. 2016, Oviedo and Bursztyn 2016, Blythe et al. 2017, London et al. 2017, Nakandakari et al. 2017) and forestry (Fleischman et al. 2010, Oberlack et al. 2015, Davenport et al. 2016). However, use of the framework has expanded beyond those resource use sectors to general food production systems (Marshall 2015), aquaculture systems (Partelow et al. 2018b), terrestrial conservation and rangeland management (Falk et al. 2012, Risvoll et al. 2014, Addison and Greiner 2015, Baur and Binder 2015, Taggart-Hodge and Schoon 2016, Yandle et al. 2016, Guariguata et al. 2017), watershed management (Mansee et al. n.d., Madrigal et al. 2011, Nagendra and Ostrom 2014, Villamayor-Tomas et al. 2014, Bennett and Gosnell 2015, Naiga et al. 2015, Silva et al. 2015, Falk et al. 2016, Hileman et al. 2016), marine conservation and marine ecosystem management (Cinner et al. 2012, Stevenson and Tissot 2014, Ban et al. 2015, 2017, Williams and Tai 2016), coastal development (Kanwar et al. 2016, Schlüter et al. 2018), energy systems (Ye 2014, Bauwens et al. 2016), and pollution management (Amblard 2012, Epstein et al. 2014b).

Table 2. The diversity of methods, contexts and thematic areas under which the SESF is applied are shown with the relevant literature. Different types of research approaches include meta-analysis and empirical analysis with the types of data analysis used. The specific sectors in which the framework has been applied are shown. Associated concepts and databases related to the framework are indicted.

Type of engagement with the SESF	Focus	Literature
Meta or large comparative analysis	Quantitative	(Gutiérrez et al. 2011, Cinner et al. 2012, Rahimi et al. 2016)
	Qualitative	(Thiel et al. 2015)
	Mixed	(Kelly et al. 2015)
Empirical analysis with single or multiple cases	Quantitative	(Macneil and Cinner 2013, Leslie et al. 2015)
	Qualitative	(Amblard 2012, Ban et al. 2015, Hoogesteger 2015, Lozano and Heinen 2015, Naiga et al. 2015, Oberlack et al. 2015, London et al. 2017)
	Mixed	(Ernst et al. 2013, Cox 2014b, Guevara et al. 2016)

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	Temporal analysis	(Epstein et al. 2014a, Ban et al. 2015)
Empirical analysis on specific or select variables	Experimental	(Aswani et al. 2013, Falk et al. 2016)
General development of the framework	Multi-dimensionality of first tier variables	(McGinnis and Ostrom 2014)
	Application through mixed methods and disciplinary approaches	(Poteete et al. 2010)
	Specifically adding and/ or modifying variables. Ontological consistency.	(Epstein et al. 2013, McGinnis and Ostrom 2014, Frey and Cox 2015, Thiel et al. 2015, Vogt et al. 2015)
Sector specific	Small-scale fisheries (general)	(Gutiérrez et al. 2011, Cinner et al. 2012, Schlüter and Madrigal 2012, Delgado-Serrano and Andres Ramos 2015, Lozano and Heinen 2015, Partelow 2015, Guevara et al. 2016, Rahimi et al. 2016)
Sector specific Use in combination with other approaches or concepts	Coral reef fisheries	(Cinner et al. 2012, Stevenson and Tissot 2014)
	Benthic fisheries	(Basurto et al. 2013)
	Lobster fisheries	(Hearn 2008, Ernst et al. 2013, Partelow and Boda 2015)
	Large-scale fisheries	(Epstein et al. 2014a)
	Recreational fisheries	(Hunt et al. 2013, Arlinghaus et al. 2017, Lanz 2017)
	Aquaculture	(Partelow et al. 2018b)
	Marine and coastal systems (general)	(Schlüter et al. 2013, 2018)
	Food production systems	(Marshall 2015)
	Irrigation	(Meinzen-Dick 2007, Cox 2014b, Mccord et al. 2016)
	Forestry	(Fleischman et al. 2010, Oberlack et al. 2015, Davenport et al. 2016)
	Pasture/ rangelands	(Cole et al. 2014, Risvoll et al. 2014)
	Watershed/ stormwater management	(Villamayor-Tomas et al. 2014, Bennett and Gosnell 2015, Silva et al. 2015, Flynn and Davidson 2016)
	Drinking water management	(Madrigal et al. 2011)

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	Institutional Analysis and development (IAD) framework	(Ostrom and Cox 2010, Partelow and Boda 2015, Mccord et al. 2016)
Use in combination with other approaches or concepts Other	Ecosystem services (general)	(Ban et al. 2015, Partelow and Winkler 2016, Rova and Pranovi 2017)
	Payment for ecosystem services	(Yin et al. 2013, Addison and Greiner 2015, Bennett and Gosnell 2015, Rodríguez-Robayo and Merino-Perez 2017)
	Sustainability science	(Partelow 2016)
	Resilience	(Risvoll et al. 2014, Arlinghaus et al. 2017)
	Framework as a boundary object	(Hertz and Schlüter 2015, Partelow and Winkler 2016)
Associated databases	Social-Ecological Systems Meta-Analysis Database (SESMAD)	(Cox 2014a) https://sesmad.dartmouth.edu/
Associated databases	SESGO	http://141.48.2.108:8080/ses_db_test/index
	SES Library	https://seslibrary.asu.edu/
	CPR Database	https://seslibrary.asu.edu/cpr
	NIIS Online Database	https://ulrichfrey.eu/en/niis/
	IFRI Database	http://www.ifriresearch.net/resources/data/

Substantial portions of the SESF literature is focused on small-scale CPR systems, dominated by fisheries, marine and coastal systems (Table 3). Still, many articles focus on forestry and irrigation systems, following the history of commons scholarship (Meinzen-Dick et al. 2002, Wollenberg et al. 2007). Single case study research is the most common type of analysis, followed by a considerable number of papers focused on the framework's continued development, either conceptually, methodologically or for building theory. However, a large majority of research with the SESF relies on secondary data or a mix of primary and secondary data.

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Table 3. (A) The most frequent journals publishing research directly related to SES framework. (B) The main sectors being focused on. (C) The types of articles being published. (D) The data sources used for research.

(A) Sectors of focus	# of articles	(B) Types of articles	# of articles	(C) Data sources	# of articles
Fisheries/ marine/ coastal	39	Empirical - single case	46	Secondary data	52
Forestry	16	Conceptual/ method/ theoretical	22	Primary & secondary	25
Irrigation/ agriculture	10	Empirical - multiple cases	12	Primary	15
Watershed management	2	Meta-analysis/ comparative analysis	12		

The most recent version of the SESF from McGinnis and Ostrom (2014) contains 56 second-tier variables (Table 1), however, not all variables are equally focused on or analyzed. Figure 2 compares the frequency at which each second-tier variable is explicitly included as part of an analysis or application of the framework across the literature. Social system variables (i.e. Gov. and Actor tiers) are more frequently focused on compared to ecological system variables (i.e. RS and RU tiers). The remaining variables (i.e. S, I, O and ECO tiers) receive considerably less focus comparatively. When this is further divided into focus on different resource use sectors, the trend remains the same, there is a general disproportionate focus on social system variables (Table 4).

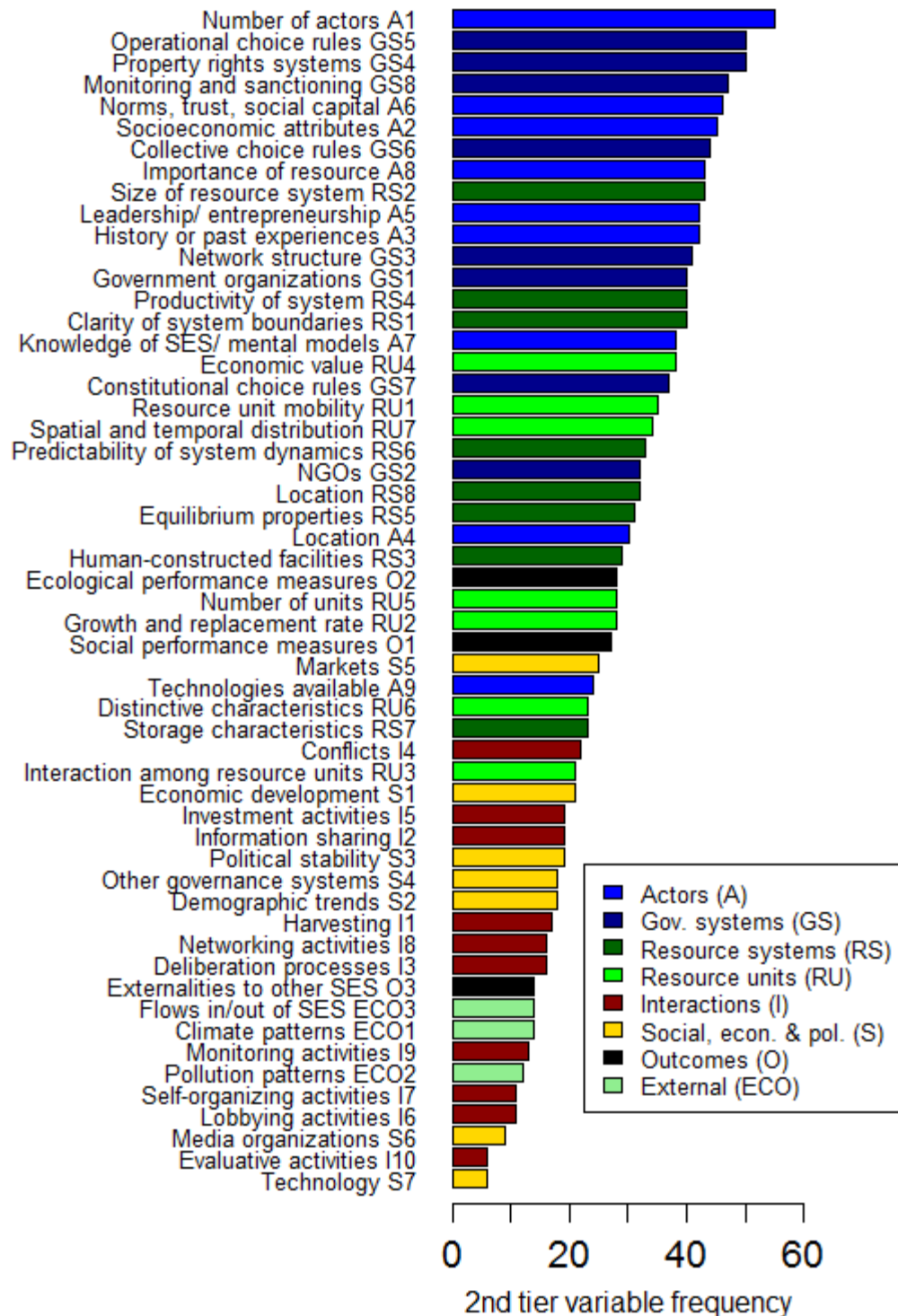


Figure 2. The frequency of 2nd tier variables which have been analyzed across all relevant articles.

Table 4. First-tier variable frequency of all articles. ‘All’ shows the sum of second-tier variables at the first-tier from Figure 2. ‘All’ includes all types of articles. The sum total of ‘All’ is then subdivided by those articles which have an empirical focus in major sectors.

First-tier variables from SESF	Sum frequency of all nested 2nd tier variables					
	All	Fisheries	Forestry	Irrigation	Water management	Other
(A) Actors	365	126	35	15	27	44
(GS) Governance	341	101	34	14	24	43
(RS) Resource system	271	101	33	15	22	35
(RU) Resource units	207	77	26	12	23	27
(S) Social, economic, political	116	44	13	0	14	23
(I) Interactions	150	52	27	12	18	21
(O) Outcomes	69	26	9	6	8	6
(ECO) External ecosystems	40	17	6	0	6	8

Modification of variables

Ostrom (2007, 2009) iterates that the framework will need to be adapted to context and further developed as new empirical analysis supports the identification of new and/ or more refined variables at the second, third and subsequent tiers. Many articles have since suggested modifications, i.e. the addition, subtraction or modification of variables. Table 5 presents a synthesis of the literature that has suggested modifications. The degree of generalizability is different between articles, as many may only be relevant to specific contexts (e.g. fisheries or forestry). Furthermore, many articles do not make a distinction between what constitutes a new variable versus an indicator for measuring a variable. There is a difference between developing indicators to measure second-tier variables versus developing nested subconcepts of a variable at the third-tier. Similarly, not all second-tier variables are defined in the same way across contexts, and often definitions are not explicitly stated. Some second-tier variables represent very broad concepts such as ‘Socioeconomic attributes (A2)’, ‘Social performance measures (O1)’,

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‘Ecological performance measures (O2’), and ‘Equilibrium properties (RS6).’ These variables have more suggested modifications to refine them at the third-tier. Similarly, some variables combine multiple concepts such as ‘Norms (trust-reciprocity)/ social capital (A6)’, ‘Knowledge of SES/ Mental models (A7)’, ‘Leadership/entrepreneurship (A5)’, ‘History or past experiences (A3)’, ‘Monitoring and sanctioning (GS8)’ and ‘Spatial and temporal distribution (RU7)’. These variables have also received multiple suggested modifications.

Table 5. Articles suggesting modifications to variables of the SESF. The table is organized by the variables, articles and context. Many articles suggest modifications, however, this is not an exhaustive list. Most articles focus on many variables, but only suggest modifications to a few. ‘All’ refers to all second-tier variables within the first-tier variable.

First-tier	Variables	Article	Context
<i>Social, economic and political settings (S)</i>	All	Delgado-Serano and Ramos (2015)	Water; Forestry; Fisheries
	Economic development Political stability	Guevarra et al. (2016)	Fisheries
<i>Resource systems (RS)</i>	All	Vogt et al., (2015)	Forestry
	Ecological rules	Epstein et al., (2013) Vogt et al., (2015)	Lake systems; Forestry
	Clarity of system boundaries Equilibrium properties	Delgado-Serano and Ramos (2015)	Water; Forestry; Fisheries
	Storage characteristics	Basurto et al., (2013)	Benthic fisheries
	Productivity of system	Basurto et al., (2013)	Benthic fisheries
<i>Resource units (RU)</i>	All	Vogt et al., (2015)	Forestry
	Resource unit mobility	Partelow and Boda (2015)	Fisheries
	Economic value	Bennett and Gosnell (2015); Vogt et al., (2015) ; Delgado-Serano and Ramos (2015) Partelow and Boda (2015)	PES*; Forestry Water; Fisheries
	Number of units	Partelow and Boda (2015)	Fisheries
	Interactions among resource units Spatial and temporal distribution	Basurto et al., (2013)	Benthic fisheries

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	Distinctive characteristics	Partelow and Boda (2015) Basurto et al., (2013)	Fisheries Benthic fisheries
<i>Governance systems (GS)</i>	All	McGinnis and Ostrom (2014) Basurto et al., (2013) Partelow and Boda (2015)	General Benthic fisheries Fisheries
	Rules-in-use	Blanco (2011)	Tourism
	Governmental organizations	Delgado-Serano and Ramos (2015) Williams and Tai (2016)	Water; Forestry; Fisheries MPAs**
	Non-governmental organizations	Williams and Tai (2016)	MPAs**
	Network structure	Delgado-Serano and Ramos (2015)	Water; Forestry; Fisheries
	Property-rights systems	Delgado-Serano and Ramos (2015)	Water; Forestry; Fisheries
	Monitoring and sanctioning	Delgado-Serano and Ramos (2015)	Water; Forestry; Fisheries
<i>Actors (A)</i>	All	Partelow and Boda (2015)	Fisheries
	Number of relevant actors	Duff (2017) Delgado-Serano and Ramos (2015)	Agriculture Water; Forestry; Fisheries
	Socioeconomic attributes	Bennett and Gosnell (2015) Delgado-Serano and Ramos (2015)	PES* Water; Forestry; Fisheries
	Technologies	Duff (2017) Basurto et al., (2013)	Agriculture Benthic fisheries
	History and past experiences	Basurto et al., (2013)	Benthic fisheries
	Norms /social capital	Delgado-Serano and Ramos (2015)	Water; Forestry; Fisheries
	Knowledge of SES/mental models	Delgado-Serano and Ramos (2015)	Water; Forestry; Fisheries

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	Dependence	Basurto et al., (2013)	Benthic fisheries
<i>Interactions (I)</i>	Harvesting levels	Delgado-Serano and Ramos (2015)	Water; Forestry; Fisheries
	Information sharing	Duff (2017) Delgado-Serano and Ramos (2015)	Agriculture Water; Forestry; Fisheries
	Power differentials	Blythe et al., (2017)	Fisheries
	Deliberation processes	Duff (2017) Delgado-Serano and Ramos (2015)	Agriculture Water; Forestry; Fisheries
	Conflicts	Duff (2017) Delgado-Serano and Ramos (2015)	Agriculture Water; Forestry; Fisheries
	Monitoring activities	Bennett and Gosnell (2015)	PES*
	Investment activities	Bennett and Gosnell (2015)	PES*
	Networking activities	Delgado-Serano and Ramos (2015)	Water; Forestry; Fisheries
	(Cross level application)	Oberlack et al., (2015)	Forestry
<i>Outcomes (O)</i>	Social outcomes	Duff (2017) Blythe et al., (2017) Delgado-Serano and Ramos (2015)	Agriculture; Water; Forestry; Fisheries
	Ecological outcomes	Duff (2017) Delgado-Serano and Ramos (2015)	Agriculture Water; Forestry; Fisheries
<i>External ecosystems (ECO)</i>	Pollution patterns	Duff (2017)	Agriculture
*Payments for ecosystem services **Marine Protected Areas			

Types of research applying the SESF

The SESF can be used as a tool for different types of research. Table 6 provides an overview of six types of research in which the framework has been applied. These include (1) Conducting a mixed method diagnosis of a single case study, (2) Conducting a qualitative diagnosis of a single case study, (3) Conducting a quantitative diagnosis of a single case study, (4) Conducting a meta-analysis of the literature, (5) comparative analysis diagnosing multiple case studies (using either of the first three types) and (6) using the framework as deliberation tool. The general purpose of each type of research, its benefits, potential challenges and related literature are provided.

Table 6. Approaches for applying the SES framework for different types of research.

Type of research	Purpose, benefits (+) and challenges (-)	Example literature
(1) Mixed method diagnosis or characterization of a case study	<i>Purpose:</i> Comprehensive analysis of a case study (+) Comprehensive and more holistic analysis (+) Most robust type of case study analysis (+/-) Multi-disciplinary knowledge and/or team needed (+/-) Multiple types of data generated (-) Data integration, transformation and analysis can be difficult (-) Extensive field work/ data collection period	(Ernst et al. 2013, Cox 2014b, Barnett and Eakin 2015, Guevara et al. 2016, Partelow et al. 2018b)
(2) Qualitative diagnosis or characterization of a case study	<i>Purpose:</i> Focused analysis of a case study (+) Potential for in-depth analysis of social system (+) Discursive understanding (+/-) Qualitative data analysis techniques (-) Potential lack of data on ecological system if no secondary data (-) Smaller N sampling potential	(Ban et al. 2015, Hoogesteger 2015, Naiga et al. 2015, Oberlack et al. 2015, London et al. 2017)
(3) Quantitative diagnosis or characterization of a case study	<i>Purpose:</i> Focused analysis of a case study (+) All variable measurements quantified and comparable (+) Larger N sampling potential (+/-) Statistical data analysis techniques (-) Difficult to develop quantifiable indicators to measure all variables (-) Lack of discursive elements (-) Potential difficulties in access to needed data or sampling (-) Potential loss of depth by quantification of complex variables	(Hearn 2008, Madrigal et al. 2011, Leslie et al. 2015, Sharma et al. 2016)
(4) Meta-analysis of the literature	<i>Purpose:</i> Empirical or discursive synthesis of second-hand literature, case studies or data to advance theory, concepts or the	(Blanco 2011, Stevenson and

	<p>characterization of a field of study.</p> <p>(+) Synthesis across contexts with common framework (+) Increased comparability of findings (-) Lack of access to primary data/ data abstraction (-) Difficulties integrating data</p>	<p>Tissot 2014, Kelly et al. 2015, Thiel et al. 2015, Mahon et al. 2017)</p>
(5) Comparative analysis of case studies	<p><i>Purpose:</i> Empirical comparison or synthesis of typically first-hand data to advance theory, concepts or characterization of a field of study.</p> <p>(+) Provides a structure and variables for comparison (-) Finding common definitions which apply across cases (-) Data often abstracted out of context</p>	<p>(Gutiérrez et al. 2011, Cinner et al. 2012, Oberlack et al. 2016, Rahimi et al. 2016, Ban et al. 2017)</p>
(6) As a deliberation tool	<p><i>Purpose:</i> Transform SESF into a tool to facilitate deliberation or deliberative processes.</p> <p>(+) Applied use of framework (+) Knowledge exchange within and between actor groups (-) Transformation of SESF to a contextually understandable form</p>	

Discussion

This discussion focuses on the current methodological challenges for applying the SESF and challenges for its continued modification by reflecting on the results above. I argue that current trends in the literature help to spotlight many of the existing challenges, and discuss how current trends relate to the history of the framework and why it is important to consider how the framework is situated epistemologically. Thus, this discussion attempts to guide future applications of the SESF by summarizing some of these methodological challenges, and to signpost where to look in the literature for additional reflection. To start, I briefly discuss the results above and potential reasons why certain trends may exist. This is followed by discussion of the challenges for modifying the framework. For the remainder of the paper I focus on specific methodological gaps for applying the SESF and discuss whether the framework has made progress in helping achieve some of the goals it was claimed to be useful for (Ostrom 2007, 2009).

Trends in SESF research highlight methodological challenges

SESF research remains largely focused on small-scale CPR systems and public goods, similar to the majority of research in common scholarship (Meinzen-Dick et al. 2002, Wollenberg et al.

2007). Similarly, case studies remain focused on the ‘classic’ CPR systems of fisheries, forestry and irrigation systems. There is certainly room to expand the scope of where the SESF is applied beyond the scope of these classic commons and beyond small-scale systems. This review is not an overview of all commons scholarship, just those applying the SESF, but it nonetheless shows the tight link between the two and some current trends. It has long been assumed that knowledge generated on small-scale CPR system is to a large extent generalizable. This claim can be further tested with more applications of the SESF to diverse cases. Few papers have recently begun to shift the focus to large scale commons (Ban et al. 2015, 2017) and hybrid or overlapping commons like coastal systems (Schlüter et al. 2018) and pond aquaculture (Partelow et al. 2018b).

Perhaps the most interesting trend is the extensive use of secondary data. This may be occurring for numerous reasons. Many authors are simply re-analyzing existing data, using the SESF as conceptual tool to re-frame, re-structure or integrate data for new analysis. This also suggests that many scholars are revisiting existing case studies to provide a new conceptual lens for analysis. The combination of primary and secondary data is common and is likely a result of the difficulties with collecting sufficient primary data on all the relevant second-tier variables in a case study. If scholars are returning to previous case studies, it is likely that previous data exists. In addition, meta-analysis studies are using secondary data as well as many comparative analysis studies. Nonetheless I would argue that many scholars find it difficult to design empirical research approaches using the SESF from scratch. There are substantial methodological challenges with applying the SESF to a new case study, which likely explains why relatively few articles use primary data. Primary empirical data collection guided by the SESF involves considerable methodological attention to detail, familiarity with framework’s history and multi-disciplinary knowledge on the potential relevance of second-tier variables in a case study. Studies that re-analyze existing data do not have this difficulty to the same extent. Secondary data typically involves some sort of data coding procedure (Ratajczyk et al. 2016). This might explain why the framework is a useful conceptual tool but is less applied empirically due to a lack of methodological knowledge or guidance on how to do so.

Modifying the SESF

Many have argued for the need to modify variables in the SESF. For example, numerous articles have suggested modifications to include more biophysical variables e.g., (Epstein et al. 2013, Vogt et al. 2015), suggesting a bias towards social system variables. This review identifies that this bias exists. This is most likely due to the development and almost exclusive use of the framework by social scientists. However, when suggesting modifications, a key question needs to be asked in relation to epistemological congruence (i.e. what theory is supporting the modification of variables and does it align with how variables were included historically?). Below I discuss whether this is important or not. The framework does have a history which justified the inclusion of variables into a theoretical framework because they were shown to influence collective action. However, if variables are being modified for a reason other than their influence on collective action, there is a conflict with congruence in the framework’s development. This is

not inherently problematic, it seems likely that the SESF may take numerous developmental trajectories as it becomes useful for different purposes. However, difficulties and confusion in the literature may arise when explicit distinctions are not made between differing goals. For example, are variable modifications being suggested because they have been shown to influence collective action (i.e. building a theoretical framework of collective action), or because they help better characterize a case study as a SES (i.e. building a theoretical/ conceptual framework of general SES)?

This issue arises due to a problem in the logic of how a theory neutral framework should continue developing without theoretical inclusion criteria for new variables. It is clear that a large majority of research using the framework engages with collective action theories. However, it is also clear that many studies do not focus on collective action, and that knowledge on collective action theory is not necessary for the SESF to be a useful research tool. The literature suggests that the SESF is useful for characterizing a system as a SES, and for diagnosing general challenges for sustainability. These applications do not have to be related to the collective action theoretical framework aspect of the SESF. Nonetheless, there are also clear benefits of having a theory neutral framework, as envisioned by Ostrom. This makes it appealing to a broader research audience and can allow for the development of new theory.

From the argument above, it becomes clear that the SESF does not provide a list of all relevant intrinsic variables and interactions in a social or ecological system. Certainly there would be more variables if there was no theoretical inclusion criteria. Many more variables could be identified as simply being part of a social or ecological system. Perhaps broader theoretical inclusion criteria could be related to a more general social-ecological systems theory. Variables would then be included if causal interactive effects can be shown between new and existing variables. This would broaden the theoretical scope of inclusion criteria, away from collective action theory, but this would then shift the epistemological trajectory of the frameworks development. This debate should find roots in future research.

This raises a second point. It is important to recognize how the framework's theoretical history and epistemology has shaped its development (i.e. collective action, CPR theory). This has implications for how we view a SES and how we interpret the concept of sustainability. What is worth knowing about a SES, from an Ostromian perspective, is how different parts of the system influence cooperation and resource use behavior through the development of institutions for governance. Sustainability, from this perspective, is arguably the development and maintenance of contextually appropriate institutions that can enable actors to cooperate and use resources in a way that allows for the long-term and equitable availability of those resources. Certainly the concept of sustainability is not limited to this Ostromian view, but it must be recognized that this is its underlying epistemology, and this creates a refined and in some ways path dependent discourse on sustainability.

It is worth reflecting on the how manifestation of this epistemology has evolved into the SESF, and how that has shaped broader SES discourse. This leads to a critical reflection on the discourse that the SESF has created with its terminology. 'Resource systems' and 'Resource units' are the terminology used for biophysical variables in the framework. This terminology has creates an

anthropocentric discourse on how the SESF portrays the biophysical environment. Arguably the SESF portrays the biophysical environment through a lens of economic and institutional utility. This is the most obvious example, but many other variables in the framework portray a similar discursive lens, and it is worth acknowledging how this discourse shapes a certain social-ecological worldview.

In a separate but related terminological discussion. Reference to and application of the SESF requires the use of certain practical terminology. The variables of the framework are referred to with a large variety of terms including: variables, tiers, components, processes, indicators, dimensions, concepts, interactions, elements, attributes and system dynamics, among others. While inconsistent terminology when referring to the first and second-tier variables is not inherently problematic, it may create confusion or a lack of clarity in the literature and in the interpretation of findings, particularly confusion between variables and indicators. This may stem from the lack of clarity and clear definitions for many of the second-tier variables. Some are well-defined and nuanced while others represent broader concepts which often need further refinement or defining in the context. Not all of the second-tier variables are created equal in this way, and may require modification as the framework evolves.

Many articles have suggested variable modifications (see Table 5). This is an inevitable progression as more empirical analysis emerges. However, reflection is warranted on whether suggested variable modifications are actually new variables, or, are indicators for measuring a variable. Also, what the level of generalizability of suggested modifications is in relation to other cases and sectors. It is evident that separate frameworks are likely to evolve for use in specific sectors because many relevant variables in specific sectors may not be generalizable (Figure 3) e.g., (Basurto et al. 2013, Marshall 2015, Partelow and Boda 2015). The role of some variables is likely to be unique to certain sectors.

As discussed above, one of the methodological difficulties is that there are no rules or guidelines for variable modifications. Frey and Cox (2015) suggest the use of a consistent ontological logic for adding new variables, such as having at least a pair of nested sub-concepts that are nested under the parent variable. Having an ontological logic would certainly create consistency, but it does not address the theoretical inclusion criteria problem. Second, it is important to recognize that indicators used to measure second-tier variables are not necessarily nested sub-concepts that warrant inclusion into the framework. Many articles do not make this distinction. For example, Partelow and Boda (2015) suggest a substantially modified framework that is specific to lobster fisheries but they do not make a clear distinction between what modifications are nested subconcepts of potentially new variables, and which are indicators for simply measuring the parent variable. They also do not follow a clear ontological logic. The review in this article supports conclusions from Thiel et al., (2015), that most applications and modifications to the framework remain unstructured in this way and largely scattered in their attempt to jointly improve the framework with cohesive rules or inclusion criteria. Future research could focus on this problem.

In reflection on methodological challenges outlined above, four aspects are useful to consider when suggesting modifications. (1) Is there a structural or ontological consistency when making

modifications? (see Frey and Cox, 2014, p. 14). (2) What is the empirical evidence for any modifications (e.g. case studies or meta-analysis)? (3) What are the theoretical inclusion criteria? (4) To what degree of generalizability do the modifications apply, to all systems, or only to a specific resource use sector (e.g. fisheries, forestry)?

A final point on modifications is warranted on the ‘Interactions (I)’ variables of the SESF and how they relate to the Institutional Analysis and Development (IAD) framework (Ostrom 2005, McGinnis 2011b). It is unclear that applications of framework in the literature retain the original idea of the ‘action situation’ when relating to the ‘Interactions (I)’ variables. These variables arguably have the strongest theoretical link to institutional change and collective action theories. They are also some of the least focused on second-tier variables. I would argue this is related to a lack of theoretical knowledge about their origin as the framework has gained a wider audience. Perhaps ‘interactions’ could evolve into archetypes, typologies or bundles of interacting second-tier variables from the other tiers. This could be viewed as a process of building a general theory of social-ecological systems interactions. This would alter the conceptual and epistemological trajectory of the framework but may clarify the ‘Interactions (I)’ variables and make this aspect of the framework more generally applicable to cases and scholars that do not relate directly to the study of institutions.

Applying the SESF: Methodological challenges

A primary benefit of the SESF framework is its malleability as a general tool. The variables can be defined, modified and measured, as needed, in different contexts (Ostrom 2007, 2009). However, this has led to substantial heterogeneity in how it is applied, relating to definitions, indicators for measurement and modifications. Furthermore, multiple data collection and analysis methods are often used. It is important to note that these methodological challenges are not unique to the framework; they are general challenges to science. In relation to the framework, the extent to which methodological heterogeneity compromises comparison is not clear, but it certainly presents more difficulties. On the other hand, it is clear that malleability has brought substantial benefits and wider engagement. This is a trade-off. Would it be better to make the framework more malleable by further disassociating it from collective action theory through broader inclusion criteria for variables? Or, should scholars try to follow more rigid rules for applying the framework in systematic ways that better facilitates comparison to build specific theory? It seems that both trajectories occur simultaneously. This is not inherently problematic, but would be benefited by increased transparency in methods and purpose for applying and developing the framework in written articles.

There are no general methods, guidelines or procedures for applying the SESF, although numerous articles have provided conceptual guidance e.g., (Hinkel et al. 2015, Partelow 2016) and case examples. However, there is lack of reflection between them regarding the benefits and challenges of different methods. There is no right or wrong way to apply the framework. The discussion below highlights the lessons and reflections learned across the literature and from my

applications of the framework. I refer to numerous methodological gaps and steps along the way which may be useful to consider.

Variable definition gap

Many variables are not well defined and/ or can have multiple meanings or interpretations when viewed in different contexts. If common definitions of variables and concepts are not used across cases, additional layers of abstraction will hinder the ability for synthesis and comparison. However, there is a trade-off here between specificity and generalizability, as it is often necessary to define variables differently across contexts. For example, the concept of social capital (A6) is not well defined and can vary in meaning across contexts. Social capital may refer to the structure, connectedness and types of exchanges in a social network (Pretty 2003, Borgatti et al. 2009), or it may refer to degrees of trust, reciprocity and prosocial or antisocial behavior in a group (Gutiérrez et al. 2011, Basurto et al. 2016). Definitions can dictate what will be measured and the theoretical conclusions drawn from that data. Many other variables in the framework create similar challenges. Using common variables has been argued as a strong point of the framework to facilitate comparison, but many variables are defined and measured differently, compromising the ability for comparison if these varied definitions are not transparent to readers or those conducting synthesis research.

The variable-to-indicator gap

The variable-indicator gap refers to which indicators are selected to empirically measure or code variables. Many variables represent broad concepts that are not directly measurable or easily defined such as socioeconomic attributes (A2), norms, trust and social capital (A6), resource unit value (RU4), equilibrium properties (RS6), predictability of system dynamics (RS7), and outcomes (O). Context specific indicators to measure these variables are often needed to ground empirical measurement and analysis, or at least to be able to understand a variable in the case context. Two studies may examine the same variable with the same definition, but they may select different indicators to measure them. This creates a level of abstraction for comparative research, where common variables are examined but with different indicators. For example, indicators to measure actor location (A4) could be the distance between the home of an actor to the place where they access the resource system (RS) or resource units (RU), or, it could be the distance from the home to other actors or community meeting places where collective decisions are taken. The two indicators will provide different data with different implications for how the variable is interpreted as relevant in the system. This is often related to definition, adding to the need for transparency.

The measurement gap

The measurement gap refers to how variables or indicators are actually measured or coded. It is evident that two studies can examine the same variable, use a common definition and even use a

common indicator, but still measure it in a different way. For examples, economic value (RU4) may be defined as the market value of the resource unit, and both studies use the indicator of price per kilogram. However, one study may employ qualitative methods, asking individual users (e.g. fishers) to recall the prices they receive on the market over the last month by asking the user to explain variability and how prices are negotiated in patron-client relationships (i.e. middlemen between fishers and the market). In contrast, a second study may go to a patron and collect the quantitative data on patron-client relationships to establish price averages over the last six months. The studies may draw different conclusions on the real economic value of the resource and the role that market variability has on system dynamics. Multiple methods of measurement would be useful to cross-check findings, but many studies only use a single method, and this makes comparison between studies difficult.

Data transformation gap

The data transformation gap refers to how raw data is transformed into usable or presentable data in an analysis, graphic or written text form. Or, how published data is recorded or transformed from literature review or meta-analysis for additional analysis. Transforming data into different structures (e.g. continuous, ordinal, categorical, text) is often necessary to conduct an integrated analysis. Many different data types have been used to analyze the variables and their interactions in the SESF. The transformation of raw data into a different form is another level of abstraction which can hinder the ability to accurately interpret findings or conduct meaningful synthesis and comparative research. For example, raw qualitative interview data may be coded, synthesized and transformed into ordinal or categorical data for further analysis or presentation. Resource users may be interviewed in different villages and asked to describe the importance of the resource (A8), the raw qualitative data may be coded into themes and transformed into ordinal data (e.g. low, medium or high) to compare responses between villages. When raw data is transformed its original meaning is abstracted. Methodological transparency becomes of high importance for interpreting findings. This problem occurs in both qualitative and quantitative research. For example, in quantitative research the measurement of equilibrium properties (RS6) in an aquaculture pond involves collecting continuous numerical data on pH, salinity and temperature. However, this data may need to be normalized between 0 and 1, or categorized (e.g. good, bad) to compare the biophysical suitability of each pond for aquaculture. Different studies will inevitably used different methods, stressing the need for methodological transparency, clarity in the description of methods and sharing of raw data when possible.

Is the SESF achieving its goals?

Ostrom (2007, 2009) argued that the SESF could provide numerous benefits for scholars, including (1) a general framework that could be adapted and applied to diverse cases, (2) a core set variables and a common language to better enable comparison and (3) a theory neutral framework, enabling new theories to be developed through analysis of interlinkages between variables and outcomes. Each is briefly discussed below.

(1) A general but adaptable framework

The framework is useful for sorting out the complexity in SES and providing an overall conceptual framework to better understand SES dynamics. The framework can be tailored to a study by modifying the definitions, indicators, data collection and analysis methods. As a result the framework has been applied to a wide variety of cases. It is clear that applying the framework has led to many suggested modified variables and versions. Some articles suggest more generalizable modifications (McGinnis and Ostrom 2014) and some for use in specific sectors (Basurto et al. 2013, Delgado-Serrano and Andres Ramos 2015, Partelow and Boda 2015, Vogt et al. 2015). It appears that both the general framework will evolve but also specific frameworks for use in specific sectors (e.g. small-scale fisheries, forestry, and irrigation). Figure 3 conceptualizes this potential evolutionary process. Applying the framework to specific cases within a resource use sector will provide observations and testing for sector specific modifications and contextually appropriate indicators that may not be generalizable outside the sector. This would contribute to evolving sector specific frameworks. All sector specific frameworks would contribute to evolving a general framework when their modifications can be empirically assessed for their degree of generalizability. The evolving general framework would provide a common base for theorization within social-ecological systems. Specific theories are likely to evolve as well. All theories would be supported by the trickle-up of transparent empirical case study data.

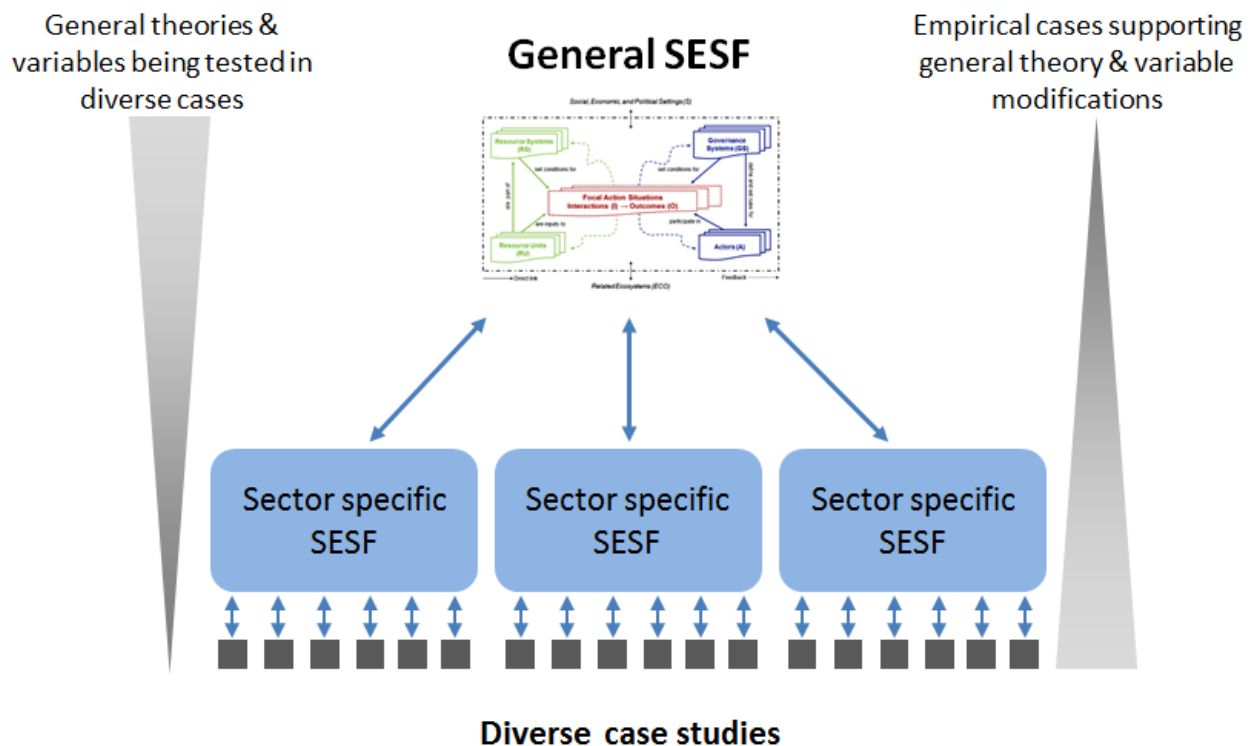


Figure 3. Conceptualizing the potential evolution of the SESF. Application of the framework to case studies contributes new variables and data to specific resource use sectors (e.g. small-scale fisheries,

forestry, irrigation). Different sectors may evolve separate versions of the SESF. Commonalities between all sectors contribute to the development of the general framework. Theory building may follow a similar path. General theory building across sectors would be informed by cross-sectoral commonalities.

(2) Enabling comparison

The literature applying the SESF is heterogeneous, and it is unclear the extent to which the empirical data can be compared in a meaningful way across cases without substantial re-coding, transforming or simplifying heterogeneous data. Meta-analysis of empirical case studies would currently be a monumental effort to derive a cohesive data set. A few studies have been successful with large comparative studies, but they have largely relied on highly systematized primary data collection on common variables controlled by the authors e.g., (Cinner et al. 2012, Leslie et al. 2015) Cinner et al., 2012; Leslie et al., 2015) or substantial secondary data mining and coding efforts e.g., (Gutiérrez et al. 2011, Oberlack et al. 2016, Rahimi et al. 2016). Either way successful comparative studies are made easier when the data available was collected with the intention to be compared. However, many individual case studies are not designed with this intention.

Databases are a promising way forward for enabling comparison, where the authors of individual studies format their data themselves into common structures. This eliminates data abstraction barriers by non-authors but also requires incentives for authors to contribute to common databases, a collective action dilemma itself. Many of the databases presented in Table 2 are attempting to facilitate this but their success requires the largely voluntary contributions. Individual incentives to contribute are difficult to align with the group interest for case comparisons through systematic data integration and analysis.

(3) A neutral theory building tool

The SESF is not a theory neutral tool. Historically, the inclusion criteria for most variables were based on their influence on collective action in small-scale CPR systems. However, the generalizability of these variables seems to be broad spanning with numerous studies using the variables to generally characterize SES or to develop other closely related theory on natural resource governance (Cox et al. 2016). It is evident that the framework's variables provide a template for expanding commons research and asking new theoretical questions about social-ecological interactions and outcomes. This has not yet been fully explored in the literature. Perhaps the framework has the most potential to contribute to building general theories of social-ecological interactions, identifying typologies or archetypes of social-ecological interactions (Oberlack et al. 2016). Integrating the framework with other conceptual and theoretical frameworks may expand its usefulness for contributing to other theories in associated fields of research (Partelow and Winkler 2016). This would somewhat remove the theoretical history with

collective action theory. However, there is also recognition that collective action theory is nested within broader concepts of SES and sustainability, both of which will continue to evolve.

Conclusion

The SESF is one of many frameworks focused on better understanding the links between social and environmental change has emerged as a useful tool for advancing SES research, an anchor point for advancing the general concept of SES to a broader audience and mainstreaming the use of diagnostic approaches in the environmental social sciences. The framework has been applied in heterogeneous ways, demonstrating its applicability for many different types of research in different contexts. However, this presents challenges for comparability between cases for theory building. Methodological pluralism is advancing the complexity of SES research but also creates challenges for transparency. Clear methodological steps can help guide research with the framework. It seems inevitable that the framework will continue to be modified. The extent to which empirical analysis in specific sectors can inform the modification of the general framework will be dependent on the ability to compare research across cases through transparency. This process faces a myriad of challenges, a collective action problem in itself as individual research projects will contextualize the framework to suit their needs and motivation to find compromises in study designs for the collective benefit lacks clear incentives. Databases for storage and comparison greatly benefit this process, but motivations to contribute are not clear or accessible to many. Overall, this article has aimed to provide a guidepost for finding and interpreting the literature engaged with the SESF and to provide some reflection on progress and challenges going forward.

Overall thesis limitations

In this section I reflect on limitations. I elaborate on three areas. First, limitations of the empirical analysis. Second, limitations of the generalizability of results, and third, the limitations of framing the thesis around methods.

Empirical analysis

Most of the research in this thesis is social science, and a large majority of the data used is qualitative. I do not view the extensive use of social science or qualitative data as a limitation itself since both are essential for current SES research and comparatively under-emphasized as useful and underfunded to the natural sciences. However, as the thesis argues for the development and testing of new methods, and particularly for the integration of different methods across disciplines, the use of primarily qualitative data could be considered a limitation to my central thesis and empirical analysis. I do argue that using multiple methods can help cross check data and analysis on research questions, and that multiple or integrated methods can provide a more holistic understanding of a social-ecological system. For this I would argue that the scope of the thesis is limited in what it can achieve. In addition, the focus on qualitative social sciences methods was largely done due to the need for foundational knowledge within each case as a starting point. Analyzing complexity has been a primary research question within each case study, and this requires rich descriptive qualitative analysis where data is lacking. Quantitative data collection and analysis were used in parts of the thesis, but they were not equally balanced, and thus the conclusions we draw from our data must be considered in relation to the methods used and any particular biases that may arise. However, all qualitative and quantitative data collection and analysis methods have benefits and limitations depending on the research questions asked. The need to provide thick qualitative descriptions of case studies was a necessary starting point in the three case studies. I would argue that this initial thick qualitative knowledge is needed before designing structured quantitative surveys and designing well suited studies to measure biophysical variables in the system. Further research in the case study areas would build on the qualitative knowledge developed in this thesis, and provided a template for a wider variety of methods to collect further data.

Much of the research in this thesis is focused on theory building and conceptual exploration. Although not explicit to the core research questions outlined in the introduction, the empirical articles all explore the question of social-ecological complexity. We want to explore the social-ecological complexity of coastal systems, and qualitative data is well suited for this. We are not testing hypotheses exclusively, although we align much of the research with existing findings related to collective action. A more explicit deductive approach to hypothesis testing may then favor quantitative methods. In contrast, much of my research could be considered exploratory in the sense of describing social-ecological complexity and using this knowledge as a support structure to build on existing findings of what conditions influence collective action. This may

not be so much of a limitation as it is a reflection on the use of the SESF, and how different methods can use the SESF for different purposes.

Generalizability and comparing results

The thesis is framed around methods, and the primary reason for this is that I argue the lessons learned are to some extent generalizable. However, I would not argue that the methods to apply the framework are generalizable in a static way. I do not suggest that the outcomes should now be taken and applied without further reflection. I would argue that the process of critical reflection, transparency and exploration of new ideas while recognizing some of the foundational building blocks of the framework are what is generalizable. As I mentioned in the introduction, I do not believe that there is a right or wrong way to use or apply the SESF, only different ways that are useful for different research questions and projects. To say there is a right way would be a limitation. In this sense this reflection relates to Feyerabend's quote in the introduction. Uses for the SESF are certainly moving beyond what Ostrom envisioned in her literature for the framework. I would not want to limit this process, because it has resulted from not being stuck on a particular method or theory related to the framework's past. I would rather encourage the exploration of new ideas and methods, as Feyerabend deemed necessary for progress.

Nonetheless, the generalizability of the empirical findings could be considered a limitation due to the limited focus on tropical coastal systems, specifically on small-scale fisheries and pond aquaculture case studies. Similarly, only a few case studies are used, and the more empirical cases the better the ability to test generalizability of methods, theory and new ideas. I would of course agree that the contextual and theoretical conclusions are heavily dependent on context, but, to what extent are the methods for applying the framework context dependent? I would argue that the process of applying the framework is itself generalizable, irrespective of the specific details of the data collection and analysis methods in each case or context. For example, all applications of the framework will need to identify the relevant variables and define them, as a general methodological process. However, the actual relevant variables and definitions will of course vary across contexts. I argue that this thesis has mostly attempted to identify a generalizable process for applying the SESF, and to reflect on the challenges for this process. When the case studies are viewed from this perspective, it becomes less about the specific details and more about the usefulness of the SESF for facilitating a research process. However, I recognize that there could be process variation when the framework is applied to diverse contexts, which I did not discover because my case studies are limited to a specific context. Overall, a critique of this thesis could be that I did not focus a whole article or chapter on explicitly outlining a generalizable process for applying the SESF. To some extent I am reluctant to do this as it may limit the explorative nature of future studies to design their own processes. Nonetheless, it would probably be beneficial for those who seek guidance.

Two additional methodological concerns can be raised about methods for applying the SESF, which this thesis and the RECODE project intended to do. This includes cross case empirical comparison of the case studies using the SESF, and the comparison of data overtime within each

case. The data collection and analysis was not standardized across the case study sites, because the relevant variables and definitions varied between them, as described above. Therefore the thesis was purposefully designed to not directly compare empirical results as its main contribution, but to compare methodological processes for applying the framework across cases instead. There was still an ambition to conduct an empirical cross case analysis with the SESF; and this was done in Research 7. We conducted a comparison of three sub-case studies within our research in the Gulf of Nicoya. Similarly an initial aim of RECODE and this thesis was to analyze each case over time, because all cases were previous ZMT areas with existing data. The only case study where this was feasible, however, was in Brazil, where extensive data was available and the study location remained the same over time. For largely practical and bureaucratic reasons, the locations in Indonesia and Costa Rica had to be moved from their initially intended area of focus outlined in the project proposal. Ultimately this benefited the thesis, as we found more suitable sites and then tailored the research to comparing different methods for applying the framework. This came at the cost of not doing a temporal comparative analysis in Indonesia and Costa Rica. Nonetheless, we have done this in Brazil to demonstrate the ability of the SESF to organize and analyze qualitative data over time.

Theoretical and context contributions

The following paragraph reflects on the overall framing of the thesis, which necessarily limits the ability to focus extensively on other aspects of the research. Beyond the contributions to advance methods for applying the SESF, other contributions have been made which have received less focus in the overall framing here. These include advancing collection action hypotheses and testing existing theory in coastal systems. For example, our pond aquaculture findings provide a new context to test the generalizability of CPR and collective action theory in a new and hybrid commons context. Our findings show how diverse social-ecological conditions at the land-sea interface create asymmetric social dilemmas for providing effective water quality and distribution infrastructure for all, impeding development progress despite substantial state support. We argue that using CPR theory helps to identify the challenges facing subsidy aid because it does not incentivize collective efforts to solve the underlying collective action problem. Similarly, in both Braganca and the Gulf of Nicoya, we critically examine the difficulties with making area-based co-management work for small-scale fisheries. We largely conclude that while both cases have promising targets on paper, making co-management work in practice involves understanding a complex interplay of social and ecological variables which influence collective action processes across space and time. It is evident that it has not been easy in either case, and we suggest that adaptive and inclusive co-management is needed to make the area-based approaches better fit local needs and conditions.

There is undoubtedly room to explore the commonalities between the case studies from a theoretical and policy perspective. As to why I did not elaborate on these contributions here, I would argue that more cases studies are needed to make more generalizable conclusions about theory in the small-scale fisheries context. The case studies are complex. Methods are first needed to better enable how we analyze social-ecological system complexity and interdependencies as a

Part 4: Synthesis and conclusions

foundation for future research. Nonetheless, the theoretical conclusions I can draw are important, and I acknowledge that there is a trade-off here in framing the overall contributions of the thesis. It would have also been possible to frame the thesis around collaborative environmental governance theory and policy recommendations in the marine realm using the SESF for analysis. However, I argue methods for SES research and for applying the SESF are the largest gap in the current literature, and that this gap needs to be filled because it is the general foundation for theory building across all contexts.

Overall thesis conclusions

In this section, I summarize the main contributions and conclusions as they relate to the core research questions about advancing methods to apply the SESF. Below I distinguish the contributions by individual research question, but I first reflect on how the broader theme of methods to apply the SESF relates to sustainability.

Finding sustainability

This thesis, commons scholarship, and many other related fields are ultimately trying to find which social-ecological system conditions, societal goals and transformative process will better enable sustainability, but none have found the right combinations yet. In one sense this is a metaphor, an idealistic goal and a catchy phrase. On the other hand, it is a sobering practical reality. Finding the conditions that enable governance to be effective in achieving societal goals in a way that does not create undesirable trade-offs between humanity and the earth system has remained elusive. The broader narrative of this thesis, the reason why I argue that advancing methods to apply the SESF is a relevant pursuit, is that methods are a core foundation that will allow science to advance the state-of-the-art in ‘finding’ the conditions and settings that enable better cooperative solutions, governance and sustainability. This thesis has tried to find such conditions in coastal systems, but I believe the methodological insights are to some extent generalizable across contexts.

Research question 1: How is the SESF situated within, and able to advance, concepts of social-ecological systems research and sustainability science?

The SESF has a history in commons scholarship and collective action theory, but I conclude that its usefulness and potential for future development is much broader than its history. Multiple methods and uses for the SESF are emerging, including application in its traditional role, but also in new trajectories with different research goals (Research 8). The SESF is undoubtedly useful in its traditional role for studying collective action (Research 4, 5, 6), but also as a tool for characterizing SES or as a deliberation tool for applied and transdisciplinary research (Research 7). Future applications of the framework may benefit by drawing on the literature from closely associated concepts such as sustainability science (Research 2) and ecosystem services (Research 3). Sustainability science is a problem-driven and solution-oriented field. A diagnostic tool could thus advance this goal and help better integrate the social-ecological systems concept into empirical sustainability science research. The ecosystem services concept intends to increase the recognition for functions, services and values that natural systems provide to humanity. These undoubtedly have implications for governance and collective action which the development of the SESF can build on. Exploring opportunities for learning between the two concepts, and research

fields, may provide useful inspiration for future development of the SESF. However, epistemological congruence in their development trajectories should be considered (Research 8).

Research question 2: What are the different types of research that can be done using the SESF?

I have identified six different types of research drawn from my experience applying the SESF to the case studies in this thesis (Research 4, 5, 6) and a review of the literature (Research 8). These encompass: (1) Conducting a mixed method diagnosis of a single case study, as done to analyze pond aquaculture on Lombok, Indonesia (Research 3); (2) Conducting a qualitative diagnosis of a single case study, as done to analyze RESEX co-management in Braganca, Brazil (Research 5); (3) Conducting a quantitative diagnosis of a single case study; (4) Conducting a meta-analysis of the literature part of Research 1); (5) A comparative analysis diagnosing multiple case studies (using either of the first three methods), as done to analyze AMPR co-management in the Gulf of Nicoya (Research 6); (6) Using the framework as deliberation tool, as demonstrated in the Gulf of Nicoya (Research 7). However, it is likely that other types of research exist and are likely to develop in the future.

Research question 3: What data collection and data analysis methods can be used to apply the SESF?

A key conclusion is that the challenges for data collection and analysis depend heavily on the type of research project, the research questions and the context in which the framework is applied. This thesis and the literature have demonstrated entirely qualitative, as well as mixed methods, data collection and analysis approaches to apply the SESF. Nonetheless a few key points can be reiterated about general applications of the framework, drawing primarily on the content in Research 8. These key points do not relate to specific field methods and analysis procedures, but general methodological processes. For example, defining the unit of analysis is essential in nearly all applications of the SESF and in SES research in general; Complex systems are typical case studies operating across multiple levels and scales. A clear unit of analysis and research questions is key for starting the methodological process of applying the framework to a case study. Similarly, most applications of the SESF engage with the second-tier variables, but often not all variables are relevant for each study. A process for variable selection and definition is likely needed. Variables will need to be measured and analyzed, and this may require indicators and specially tailored methods for each variable. These are all general methodological processes to consider when applying the SESF. I argue that each step in this process creates potential ‘methodological gaps’, and these gaps (outlined in Research 8) require consideration to ensure methodological transparency and data comparability.

Research question 4: What methodological challenges exist for applying the SESF?

While there are many more nuanced challenges for applying the SESF, here I highlight what I consider the most important and general challenges for individual studies applying the SESF. As mentioned in the introduction, the SESF has been well cited as a useful conceptual tool but there are far fewer empirical applications of the framework. I argue this is due to a lack of knowledge on how to apply it. There are several reasons why. Applying the SESF requires a series of sequential methodological steps in nearly all cases. The SESF is not a method itself, and numerous data collection and analysis methods need to be built around it to make the conceptual framework useful empirically. However, there is no single method way to do this. Multiple approaches have been demonstrated, and the main lesson learned is that multiple methods have to be linked and combined from different fields or disciplines into a cohesive and useful research approach or process. Missing or unclear pieces in this process can create confusion or difficulties for the whole. Each study will likely have different pieces and a different process that uses the framework in a way that is specifically tailored to its research design and context. Nonetheless, there are general lessons and steps that can be considered in all cases. These may include specifying the problem orientation to be diagnosed or examined, defining clear units of analysis, identifying relevant variables, deciding on data collection methods, data analysis methods as well as data presentation. Designing a cohesive research approach often requires a wide variety of multi-disciplinary knowledge, and often interdisciplinary knowledge on how data can be jointly measured and analyzed. The evolution of different methodological processes is, I argue, a central barrier for its continued use.

Research question 5: What considerations and reflections are needed to continue developing the SESF as a useful tool for future research?

For the conclusion in relation to this research question I argue that there are generalizable methodological procedures to consider when applying the SESF framework, but that the usefulness of these procedures will vary across different types of research and contexts. In addition, by no means should any application of the SESF framework be limited by any of the methods, procedures or lessons learned in this thesis. I only state that those who aim to apply the SESF may find it useful to draw on previous studies, as I have. In part, a simultaneous challenge and benefit of the SESF is that it has both individual and collective uses. In some way the development of the framework is a collective action problem itself, because its development is dependent on bring together the knowledge gained from applying it in diverse cases. I argue that there is no right or wrong way to use the framework or for how it evolves, it should be used in whichever way is most useful to the specific research questions. The framework, after all, is a generalizable and malleable tool. The collective action problem exists in that each researcher should use the framework in their own useful way, but collectively this knowledge should be brought together to inform its cohesive development. We can see in the quote from Feyerabend

(1975) in the introduction, attempting to restrain undesired methodological evolution can ultimately be a limiting endeavor for making methodological progress in specific cases. Methodological evolution in specific cases should be encouraged. On the other hand, there are collective goals to continue developing the framework cohesively from the aggregation of knowledge from diverse cases. Conceptual development trajectories may aggregate knowledge within specific sectors or theoretical frameworks. One major trajectory is the continued identification of variables contributing to collective action theory, and using the theoretical foundation of collective action as the primary decision criteria and justification for the inclusion of new variables and the conceptualization of variable interactions. A different trajectory would be to continue developing the SESF as a characterization tool, where the justification and foundation for adding new variables and conceptual development is not based on collective action theory, but possibly SES theory more broadly. Other uses such as its development as a deliberation tool may also evolve. It may also be likely that the SESF evolves differently in different resource use sectors (e.g. fisheries, tourism, and forestry).

References

- Abson, D. J., H. von Wehrden, S. Baumgärtner, J. Fischer, J. Hanspach, W. Härdtle, H. Heinrichs, A. M. Klein, D. J. Lang, P. Martens, and D. Walmsley. 2014. Ecosystem services as a boundary object for sustainability. *Ecological Economics* 103:29–37.
- Acheson, J. M. 2003. *Capturing the commons: devising institutions to manage the Maine lobster industry*. UPNE.
- Acheson, J. M. 2006. Institutional Failure in Resource Management. *Annual Review of Anthropology* 35(1):117–134.
- Addison, J., and R. Greiner. 2015. Applying the social–ecological systems framework to the evaluation and design of payment for ecosystem service schemes in the Eurasian steppe. *Biodiversity and Conservation*.
- Agrawal, A. 2001. Common Property Institutions and Sustainable Governance of Resources. *World Development* 29(10):1649–1672.
- Agrawal, A. 2003. SUSTAINABLE GOVERNANCE OF COMMON-POOL RESOURCES : Context, Methods, and Politics. *Annual Review of Anthropology* 32(1):243–262.
- Agrawal, A. 2014. Studying the commons, governing common-pool resource outcomes: Some concluding thoughts. *Environmental Science and Policy* 36:86–91.
- Agrawal, A., and A. Chhatre. 2011. Against mono-consequentialism: Multiple outcomes and their drivers in social–ecological systems. *Global Environmental Change* 21(1):1–3.
- Ajzen, I. 2005. *From intentions to actions. Attitudes, personality and behavior*. (I. Ajzen, editor). 2nd edition. Open University Press, Maidenhead, United Kingdom.
- Alexander, S. M., M. Andrachuk, and D. Armitage. 2016. Navigating governance networks for community-based conservation. *Frontiers in Ecology and the Environment* 14(April):155–164.
- Allegretti, M. 1987. *Reservas Extrativistas: uma proposta de desenvolvimento da Floresta Amazônica*. Curitiba.
- Allegretti, M. 1994. Extrativistas: Parâmetro para uma política de desenvolvimento Sustentável na Amazônia. in A. et al. Anderson, editor. *O Destino da Floresta: reservas extrativistas e desenvolvimento sustentável na Amazônia*. Instituto de Estudos Amazônicos, Rio de Janeiro.
- Almeyda, A. M., E. N. Broadbent, M. S. Wyman, and W. H. Durham. 2010. Ecotourism impacts in the Nicoya Peninsula, Costa Rica. *International Journal of Tourism Research* 12(July):803–819.
- Álvarez-Romero, J. G., R. L. Pressey, N. C. Ban, K. Vance-Borland, C. Willer, C. J. Klein, and S. D. Gaines. 2011. Integrated Land-Sea Conservation Planning: The Missing Links. *Annual Review of Ecology, Evolution, and Systematics* 42(1):381–409.
- Amaral, L., O. Almeida, and D. G. McGrath. 2008. Co-Gestão e o Sistema de Monitoramento

Voluntário: a Desistência dos Agentes Ambientais Voluntários no Baixo Amazonas. IV Encontro Nacional da Anppas.

Amblard, L. 2012. The potential of collective action for the control of nonpoint source pollution in European rural areas. Pages 1–19 *Design and Dynamics of Institutions for Collective Action*.

Anderies, J. M., A. a Rodriguez, M. a Janssen, and O. Cifdaloz. 2007. Panaceas, uncertainty, and the robust control framework in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America* 104(39):15194–9.

Araya, S. S. 2013. Situación actual de la pesca artesanal en costa rica:311–342.

Arkema, K. K., G. M. Verutes, S. a. Wood, C. Clarke-Samuels, S. Rosado, M. Canto, A. Rosenthal, M. Ruckelshaus, G. Guannel, J. Toft, J. Faries, J. M. Silver, R. Griffin, and A. D. Guerry. 2015. Embedding ecosystem services in coastal planning leads to better outcomes for people and nature. *Proceedings of the National Academy of Sciences* 112:201406483.

Arlinghaus, R., J. Alós, B. Beardmore, K. Daedlow, M. Dorow, M. Fujitani, D. Hühn, W. Haider, L. M. Hunt, B. M. Johnson, F. Johnston, T. Klefoth, S. Matsumura, C. Monk, T. Pagel, J. R. Post, T. Rapp, C. Riepe, H. Ward, and C. Wolter. 2017. Understanding and Managing Freshwater Recreational Fisheries as Complex Adaptive Social-Ecological Systems. *Reviews in Fisheries Science and Aquaculture* 25(1).

Armitage, D., M. Marschke, and R. Plummer. 2008. Adaptive co-management and the paradox of learning. *Global Environmental Change* 18(1):86–98.

Armitage, D. R., R. Plummer, F. Berkes, R. I. Arthur, A. T. Charles, I. J. Davidson-Hunt, A. P. Diduck, N. C. Doubleday, D. S. Johnson, M. Marschke, P. McConney, E. W. Pinkerton, and E. K. Wollenberg. 2009. Adaptive co-management for social-ecological complexity. *Frontiers in Ecology and the Environment* 7(2):95–102.

ASU CSID. 2014. Social-Ecological Systems library.
<https://seslibrary.asu.edu/seslibrary/welcome>.

Aswani, S., G. G. Gurney, S. Mulville, J. Matera, and M. Gurven. 2013. Insights from experimental economics on local cooperation in a small-scale fishery management system. *Global Environmental Change* 23(6).

Ayales Cruz, I., V. Solís Rivera, M. Borrás Fonseca, P. Madrigal Cordero, D. Chacón Rojas, and L. Morales Rojas. 2013. *Fortaleciendo la gobernaza marina desde las comunidades de pesca artesanal : Áreas marinas de pesca responsable y la visión desde sus protagonistas en el mar*.

Azim, M. E., M. C. J. Verdegem, H. Khatoon, M. A. Wahab, A. A. Van Dam, and M. C. M. Beveridge. 2002. A comparison of fertilization, feeding and three periphyton substrates for increasing fish production in freshwater pond aquaculture in Bangladesh. *Aquaculture* 212(1-4):227–243.

Babeu, A., K. Cabral, J. Hartmann, and K. Poti. 2012. *Establishing Socioeconomic Baselines of Sustainable Fishing Communities A Study of the Fishermen of Palito and Montero*. San Jose, Costa Rica.

- Baland, J.-M., and J.-P. Platteau. 1996. *Halting degradation of natural resources: is there a role for rural communities?*
- Ban, N. C., T. E. Davies, S. E. Aguilera, C. Brooks, M. Cox, G. Epstein, L. S. Evans, S. M. Maxwell, and M. Nenadovic. 2017. Social and ecological effectiveness of large marine protected areas. *Global Environmental Change* 43:82–91.
- Ban, N. C., L. S. Evans, M. Nenadovic, and M. Schoon. 2015. Interplay of multiple goods, ecosystem services, and property rights in large social-ecological marine protected areas. *Ecology and Society* 20(4):2.
- Ban, N. C., M. Mills, J. Tam, C. C. Hicks, S. Klain, N. Stoeckl, M. C. Bottrill, J. Levine, R. L. Pressey, T. Satterfield, and K. M. a Chan. 2013. A social-ecological approach to conservation planning: Embedding social considerations. *Frontiers in Ecology and the Environment* 11:194–202.
- Barnett, A. J., and H. C. Eakin. 2015. “We and us, not I and me”: Justice, social capital, and household vulnerability in a Nova Scotia fishery. *Applied Geography* 59.
- Basurto, X., E. Blanco, M. Nenadovic, and B. Vollan. 2016. Integrating Simultaneous Pro-social and Anti-social Behaviour into Theories of Collective Action. *Science Advances*(March):1–22.
- Basurto, X., S. Gelcich, and E. Ostrom. 2013. The social–ecological system framework as a knowledge classificatory system for benthic small-scale fisheries. *Global Environmental Change* 23(6):1366–1380.
- Basurto, X., and M. Nenadovic. 2012. A Systematic Approach to Studying Fisheries Governance. *Global Policy* 3(2):222–230.
- Basurto, X., and E. Ostrom. 2009. The Core Challenges of Moving Beyond Garrett Hardin. *Journal of Natural Resources Policy Research* 1(3):255–259.
- Battaglione, S. C., J. Evizel Seymour, and C. Ramofafia. 1999. Survival and growth of cultured juvenile sea cucumbers, *Holothuria scabra*. *Aquaculture* 178(3-4):293–322.
- Baur, I., and C. R. Binder. 2015. Modeling and assessing scenarios of common property pastures management in Switzerland. *Ecological Economics* 119.
- Bauwens, T., B. Gotchev, and L. Holstenkamp. 2016. What drives the development of community energy in Europe? the case of wind power cooperatives. *Energy Research and Social Science* 13.
- Bayazid, Y. 2016. The daudkandi model of community floodplain aquaculture in Bangladesh: A case for Ostrom’s design principles. *International Journal of the Commons* 10(2):854–877.
- Bene, C. 2004. Empowerment reform, yes . . . but empowerment of whom? Fisheries decentralization reforms in developing countries: a critical assessment with specific reference to poverty reduction. *Aquatic Resources, Culture and Development* 1(1):35.
- Béné, C., E. Belal, M. O. Baba, S. Ovie, A. Raji, I. Malasha, F. Njaya, M. Na Andi, A. Russell, and A. Neiland. 2009. Power Struggle, Dispute and Alliance Over Local Resources: Analyzing “Democratic” Decentralization of Natural Resources through the Lenses of

- Africa Inland Fisheries. *World Development* 37(12):1935–1950.
- Bennett, A., and X. Basurto. 2018. Local Institutional Responses to Global Market Pressures: The Sea Cucumber Trade in Yucatán, Mexico. *World Development* 102:57–70.
- Bennett, D. E., and H. Gosnell. 2015. Integrating multiple perspectives on payments for ecosystem services through a social-ecological systems framework. *Ecological Economics* 116:172–181.
- Bennett, E. M., W. Cramer, A. Begossi, G. Cundill, S. Díaz, B. N. Egoh, I. R. Geijzenborgh, C. B. Krug, S. Lavorel, E. Lazos, L. Lebel, B. Martín-López, P. Meyfroidt, H. A. Mooney, J. L. Nel, U. Pascual, K. Payet, N. P. Harguindeguy, G. D. Peterson, A.-H. Prieur-Richard, B. Reyers, P. Roebeling, R. Seppelt, M. Solan, P. Tschakert, T. Tschardt, B. L. Turner, P. H. Verburg, E. F. Viglizzo, P. C. L. White, and G. Woodward. 2015. Linking biodiversity, ecosystem services, and human well-being: three challenges for designing research for sustainability. *Current Opinion in Environmental Sustainability* 14:76–85.
- Bennett, N. J. 2016. Using perceptions as evidence to improve conservation and environmental management. *Conservation Biology* 30(3):582–592.
- Bennett, N. J., and P. Dearden. 2014. From measuring outcomes to providing inputs: Governance, management, and local development for more effective marine protected areas. *Marine Policy* 50:96–110.
- Bennett, N. J., R. Roth, S. C. Klain, K. Chan, P. Christie, D. A. Clark, G. Cullman, D. Curran, T. J. Durbin, G. Epstein, A. Greenberg, M. P. Nelson, J. Sandlos, R. Stedman, T. L. Teel, R. Thomas, D. Veríssimo, and C. Wyborn. 2017. Conservation social science: Understanding and integrating human dimensions to improve conservation. *Biological Conservation* 205:93–108.
- Bentes, B., V. J. Isaac, T. Espírito-Santo, R. V. D. Frédou, M. C. D. Almeida, K. R. M. Mourão, and F. L. Frédou. 2012. Multidisciplinary approach to identification of fishery production systems on the northern coast of Brazil. *Biota Neotropica* 12(1):81–92.
- Berkes, F. 2008. Commons in a Multi-level World. *International Journal of the Commons* 2(1):1–6.
- Berkes, F. 2009. Evolution of co-management: Role of knowledge generation, bridging organizations and social learning. *Journal of Environmental Management* 90(5):1692–1702.
- Berkes, F., C. Folke, and J. Colding. 2000. *Linking social and ecological systems: Management practices and social mechanisms for building resilience. Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience.*
- Berkes, F., C. Folke, and M. Gadgil. 1995. Traditional ecological knowledge, biodiversity, resilience and sustainability. *Biodiversity Conservation*. Kluwer Academic Publishers.
- Berkes, F., T. P. Hughes, R. S. Steneck, J. a Wilson, D. R. Bellwood, B. Crona, C. Folke, L. H. Gunderson, H. M. Leslie, J. Norberg, M. Nyström, P. Olsson, H. Osterblom, M. Scheffer, and B. Worm. 2006. Globalization, roving bandits, and marine resources. *Science (New York, N.Y.)* 311(5767):1557–8.

Part 4: Synthesis and conclusions

- Bettencourt, L. M. a, and J. Kaur. 2011. Evolution and structure of sustainability science. *Proceedings of the National Academy of Sciences of the United States of America* 108(49):19540–5.
- Beyerl, K., O. Putz, and A. Breckwoldt. 2016. The Role of Perceptions for Community-Based Marine Resource Management. *Frontiers in Marine Science* 3(238).
- Binder, C., J. Hinkel, P. W. G. Bots, and C. Pahl-Wostl. 2013. Comparison of frameworks for analyzing social-ecological systems. *Ecology and Society* 18(4):26.
- Binet, T., P. Failler, and A. Thorpe. 2012. Migration of Senegalese fishers: A case for regional approach to management. *Maritime Studies* 11(1):1–14.
- Birnbaum, S., Ö. Bodin, and A. Sandström. 2015. Tracing the sources of legitimacy: the impact of deliberation in participatory natural resource management. *Policy Sciences* 48(4):443–461.
- Biswal, R., D. Johnson, and F. Berkes. 2017. Social wellbeing and commons management failure in a small-scale bag net fishery in Gujarat, India. *International Journal of the Commons* 11(2):684–707.
- Blanco, E. 2011. A social-ecological approach to voluntary environmental initiatives: The case of nature-based tourism. *Policy Sciences* 44(1).
- Blanco, E., M. C. Lopez, and S. Villamayor-Tomas. 2015. Exogenous degradation in the commons: Field experimental evidence. *Ecological Economics* 120:430–439.
- Blythe, J., P. Cohen, H. Eriksson, J. Cinner, D. Boso, A.-M. Schwarz, and N. Andrew. 2017. Strengthening post-hoc analysis of community-based fisheries management through the social-ecological systems framework. *Marine Policy* 82(February):50–58.
- Bodin, Ö. 2017. Collaborative environmental governance: Achieving collective action in social-ecological systems. *Science* 357(6352):eaan1114.
- Bodin, Ö., and B. I. Crona. 2009. The role of social networks in natural resource governance: What relational patterns make a difference? *Global Environmental Change* 19(3):366–374.
- Bohensky, E. L., and Y. Maru. 2011. Indigenous Knowledge, Science, and Resilience: What Have We Learned from a Decade of International Literature on “Integration”? *Ecology and Society* 16(4):art6.
- Boonstra, W. J., E. Björkvik, L. J. Haider, and V. Masterson. 2016. Human responses to social-ecological traps. *Sustainability Science* 11:877–889.
- Borgatti, S. P., a Mehra, D. J. Brass, and G. Labianca. 2009. Network analysis in the social sciences. *Science* 323:892–895.
- Borges, R., A. C. Ferreira, and L. D. Lacerda. 2017. Systematic Planning and Ecosystem-Based Management as Strategies to Reconcile Mangrove Conservation with Resource Use. *Frontiers in Marine Science* 4(November):1–13.
- Bowen, B. W., L. a. Rocha, R. J. Toonen, and S. a. Karl. 2013. The origins of tropical marine biodiversity. *Trends in Ecology and Evolution* 28(6):359–366.

- Bragança. 2009. Carta de Bragança. Forum paraense sobre o Caranguejo-Uca: Debate sobre benefício sociais, econômicos e responsabilidade ambiental do pescador de caranguejo-uça do litoral paraense.
- Brandt, P., A. Ernst, F. Gralla, C. Luederitz, D. J. Lang, J. Newig, F. Reinert, D. J. Abson, and H. Von Wehrden. 2013. A review of transdisciplinary research in sustainability science. *Ecological Economics* 92:1–15.
- Brazil. 2005. Instrução Normativa IBAMA.
- Brazil. 2013a. Instrução Normativa IBAMA.
- Brazil. 2013b. Instrução Normativa MPA.
- Brazil. 2017. Instrução Normativa Interministerial MPA/MMA.
- Brechin, S. R., P. R. Wilshusen, C. L. Fortwang, and P. C. West. 2002. Beyond the square wheel: toward a more comprehensive understanding of biodiversity conservation as a social and political process. *Society and Natural Resources* 15:41–64.
- Brewer, J. F. 2012. Don't Fence Me In: Boundaries, Policy, and Deliberation in Maine's Lobster Commons. *Annals of the Association of American Geographers* 102(2):383–402.
- Bryman, A. 2012. *Social research methods*. 4th edition. Oxford University Press, Oxford.
- Bull, J. W., N. Jobstvogt, A. Böhnke-Henrichs, A. Mascarenhas, N. Sitas, C. Baulcomb, C. K. Lambini, M. Rawlins, H. Baral, J. Zähringer, E. Carter-Silk, M. V. Balzan, J. O. Kenter, T. Häyhä, K. Petz, and R. Koss. 2016. Strengths, Weaknesses, Opportunities and Threats: A SWOT analysis of the ecosystem services framework. *Ecosystem Services* 17:99–111.
- Cardinale, B. J., J. E. Duffy, A. Gonzalez, D. U. Hooper, C. Perrings, P. Venail, A. Narwani, G. M. Mace, D. Tilman, D. A. Wardle, A. P. Kinzig, G. C. Daily, M. Loreau, J. B. Grace, A. Larigauderie, D. S. Srivastava, and S. Naeem. 2012. Biodiversity loss and its impact on humanity. *Nature* 489:326–326.
- Carlsson, L., and F. Berkes. 2005. Co-management: Concepts and methodological implications. *Journal of Environmental Management* 75(1):65–76.
- Carnoye, L., and R. Lopes. 2015. Participatory Environmental Valuation: A Comparative Analysis of Four Case Studies. *Sustainability* 7:9823–9845.
- Carothers, C., and C. Chambers. 2012. Fisheries Privatization and the Remaking of Fishery Systems. *Environment and Society: Advances in Research* 3:39–59.
- Carpini, M. X. D., F. L. Cook, and L. R. Jacobs. 2004. Public deliberation, discursive participation, and citizen engagement: A review of the empirical literature. *Annual Review of Political Science* 7:315–344.
- Cash, D. W., W. N. Adger, F. Berkes, P. Garden, L. Lebel, and P. Olsson. 2006. Scale and Cross-Scale Dynamics : Governance and Information in a Multilevel World. *Ecology and Society* 11(2).
- Castella, J.-C., S. P. Kam, D. D. Quang, P. H. Verburg, and C. T. Hoanh. 2007. Combining top-

- down and bottom-up modelling approaches of land use/cover change to support public policies: Application to sustainable management of natural resources in northern Vietnam. *Land Use Policy* 24:531–545.
- Castello, L., J. P. Viana, G. Watkins, M. Pinedo-Vasquez, and V. A. Luzadis. 2009. Lessons from integrating fishers of arapaima in small-scale fisheries management at the mamirauá reserve, amazon. *Environmental Management* 43(2):197–209.
- Castree, N., W. M. Adams, J. Barry, D. Brockington, B. Büscher, E. Corbera, D. Demeritt, R. Duffy, U. Felt, K. Neves, P. Newell, L. Pellizzoni, K. Rigby, P. Robbins, L. Robin, D. B. Rose, A. Ross, D. Schlosberg, S. Sörlin, P. West, M. Whitehead, and B. Wynne. 2014. Changing the intellectual climate. *Nature Climate Change* 4(September):763–768.
- Cavender-bares, J., S. Polasky, E. King, and P. Balvanera. 2015. A sustainability framework for assessing trade-offs in ecosystem services. *Ecology and Society* 20(1).
- Chan, K. A. I. M. A., R. M. Pringle, J. A. I. Ranganathan, C. L. Boggs, Y. L. Chan, P. R. Ehrlich, P. K. Haff, N. E. Heller, K. Al-khafaji, and D. P. Macmynowski. 2007. When Agendas Collide: Human Welfare and Biological Conservation. *Conservation Biology* 21(1):59–68.
- Chan, K. M. A., P. Balvanera, K. Benessaiah, M. Chapman, S. Díaz, E. Gómez-Baggethun, R. Gould, N. Hannahs, K. Jax, S. Klain, G. W. Luck, B. Martín-López, B. Muraca, B. Norton, K. Ott, U. Pascual, T. Satterfield, M. Tadaki, J. Taggart, and N. Turner. 2016. Opinion: Why protect nature? Rethinking values and the environment. *Proceedings of the National Academy of Sciences* 113(6):1462–1465.
- Chan, K. M. A., T. Satterfield, and J. Goldstein. 2012a. Rethinking ecosystem services to better address and navigate cultural values. *Ecological Economics* 74:8–18.
- Chan, K. M., A. D. Guerry, P. Balvanera, S. Klain, T. Satterfield, and X. Basurto. 2012b. Where are Cultural and Social in Ecosystem Services ? A Rameworic for Constructive Engagement. *BioScience* 62(8):744–756.
- Chaudhary, S., A. McGregor, D. Houston, and N. Chettri. 2015. The evolution of ecosystem services: A time series and discourse-centered analysis. *Environmental Science & Policy* 54:25–34.
- Christy, F. T. 1982. *Territorial use rights in marine fisheries: definitions and conditions*. No. 227. FAO.
- Chuenpagdee, R., and A. M. Song. 2012. Institutional thinking in fisheries governance: broadening perspectives. *Current Opinion in Environmental Sustainability* 4(3):309–315.
- Cinner, J. 2014. Coral reef livelihoods. *Current Opinion in Environmental Sustainability* 7(April 2014):65–71.
- Cinner, J. E., T. R. McClanahan, M. a. MacNeil, N. a. J. Graham, T. M. Daw, a. Mukminin, D. a. Feary, a. L. Rabearisoa, a. Wamukota, N. Jiddawi, S. J. Campbell, a. H. Baird, F. a. Januchowski-Hartley, S. Hamed, R. Lahari, T. Morove, and J. Kuange. 2012. Comanagement of coral reef social-ecological systems. *Proceedings of the National Academy of Sciences* 109(14):5219–5222.

Part 4: Synthesis and conclusions

- Di Ciommo, R. C. 2007. Gender, tourism, and participatory appraisals at the Corumbau Marine Extractive Reserve, Brazil. *Human Ecology Review* 14(1):56–67.
- Clark, W. C. 2007. Sustainability science: a room of its own. *Proceedings of the National Academy of Sciences of the United States of America* 104(6):1737–1738.
- Clark, W. C., and N. M. Dickson. 2003. Sustainability science: the emerging research program. *Proceedings of the National Academy of Sciences of the United States of America* 100(14):8059–61.
- Coase, R. 1998. The New Institutional Economics. *The American Economic Review* 88(2):72 – 74.
- Cole, D. H., G. Epstein, and M. D. McGinnis. 2014. Digging deeper into Hardin’s pasture: The complex institutional structure of “the tragedy of the commons.” *Journal of Institutional Economics* 10(3).
- Comberti, C., T. F. Thornton, V. Wyllie de Echeverria, and T. Patterson. 2015. Ecosystem services or services to ecosystems? Valuing cultivation and reciprocal relationships between humans and ecosystems. *Global Environmental Change* 34:247–262.
- Cooke, I. R., S. A. Queenborough, E. H. Mattison, A. P. Bailey, D. L. Sandars, A. Graves, J. Morris, P. W. Atkinson, P. Trawick, and R. P. Freckleton. 2009. Integrating socio-economics and ecology: a taxonomy of quantitative methods and a review of their use in agro-ecology. *Journal of Applied Ecology* 46:269–277.
- Cornell, S., F. Berkhout, W. Tuinstra, J. D. Tàbara, J. Jäger, I. Chabay, B. de Wit, R. Langlais, D. Mills, P. Moll, I. M. Otto, A. Petersen, C. Pohl, and L. van Kerkhoff. 2013. Opening up knowledge systems for better responses to global environmental change. *Environmental Science and Policy* 28:60–70.
- Costello, A., and A. Zumla. 2000. Moving to research partnerships in developing countries. *The BMJ* 321.
- Cox, J. C., E. Ostrom, V. Sadiraj, and J. M. Walker. 2012. Provision versus Appropriation in Symmetric and Asymmetric Social Dilemmas. *Southern Economic Journal*:30.
- Cox, M. 2011. Advancing the diagnostic analysis of environmental problems. *International Journal of the Commons* 5(2):346–363.
- Cox, M. 2014a. Understanding large social-ecological systems : introducing the SESMAD project. *International Journal of the Commons* 8(2):265–276.
- Cox, M. 2014b. Applying a Social-Ecological System Framework to the Study of the Taos Valley Irrigation System. *Human Ecology* 42(2):311–324.
- Cox, M. 2015. A basic guide for empirical environmental social science. *Ecology and Society* 20(1).
- Cox, M., G. Arnold, and S. V. Tomas. 2010. A Review of Design Principles for Community-based Natural Resource Management. *Ecology and Society* 15(4).
- Cox, M., F. Payton, T. Pavlowich, C. Resor, M. Wilson, and N. Dewees. 2017. The Dominican

- fishery of Manzanillo: A coastal system in transition. *Ocean and Coastal Management*:1–11.
- Cox, M., S. Villamayor-tomas, G. Epstein, L. Evans, N. C. Ban, F. Fleischman, M. Nenadovic, and G. Garcia-lopez. 2016. Synthesizing theories of natural resource management and governance. *Global Environmental Change* 39(January):45–56.
- Creswell, J., and V. Clark. 2011. *Designing and conducting mixed methods research*. 2nd edition. Sage Publications.
- Cripps, G., and C. J. Gardner. 2016. Human migration and marine protected areas: Insights from Vezo fishers in Madagascar. *Geoforum* 74:49–62.
- Crona, B., and K. Hubacek. 2010. The Right Connections : How do Social Networks Lubricate the Machinery of Natural Resource Governance ? *Ecology and Society* 15(4).
- Cundill, G., and R. Rodela. 2012. A review of assertions about the processes and outcomes of social learning in natural resource management. *Journal of Environmental Management* 113:7–14.
- Curşeu, P. L., and S. G. Schruijer. 2017. Stakeholder diversity and the comprehensiveness of sustainability decisions: the role of collaboration and conflict. *Current Opinion in Environmental Sustainability* 28:114–120.
- Daily, G. C. 1997. *Nature's services : societal dependence on natural ecosystems*. (G. C. Daily, editor). Island Press, Washington D.C.
- Daniel, T. C., A. Muhar, A. Arnberger, O. Aznar, J. W. Boyd, K. M. A. Chan, R. Costanza, T. Elmqvist, C. G. Flint, P. H. Gobster, A. Grêt-Regamey, R. Lave, S. Muhar, M. Penker, R. G. Ribe, T. Schauppenlehner, T. Sikor, I. Soloviy, M. Spierenburg, K. Taczanowska, J. Tam, and A. von der Dunk. 2012. Contributions of cultural services to the ecosystem services agenda. *Proceedings of the National Academy of Sciences of the United States of America* 109(23):8812–9.
- Dasgupta, A., and V. Beard. 2007. Community Driven Development, Collective Action and Elite Capture in Indonesia. *Development and Change* 38(2):229–249.
- Davenport, R. B., P. H. May, P. Nogueira, and P. C. Nunes. 2016. A policy mix to prevent a non-commons tragedy for collective forest reserves in agrarian settlements in northwest Mato Grosso | Um mix de políticas para evitar a privatização dos recursos naturais nas reservas florestais coletivas dos assentamentos rurais. *Revista de Economia Contemporanea* 20(3).
- Davies, K. K., K. T. Fisher, M. E. Dickson, S. F. Thrush, and R. Le Heron. 2015. Improving ecosystem service frameworks to address wicked problems. *Ecology and Society* 20(2):art37.
- DeCaro, D., C. Arnold, E. Frimpong Boamah, and A. Garmestani. 2017. Understanding and applying principles of social cognition and decision making in adaptive environmental governance. *Ecology and Society* 22(1).
- Decker, D. J., S. J. Riley, and W. F. Siemer. 2012. *Human dimensions of wildlife management*. JHU Press.

- Delgado-Serrano, M. del M., and P. Andres Ramos. 2015. Making Ostrom's framework applicable to characterise social ecological systems at the local level. *International Journal of the Commons* 9(2):808–830.
- Díaz, S., S. Demissew, J. Carabias, C. Joly, M. Lonsdale, N. Ash, A. Larigauderie, J. R. Adhikari, S. Arico, A. Báldi, A. Bartuska, I. A. Baste, A. Bilgin, E. Brondizio, K. M. Chan, V. E. Figueroa, A. Duraipappah, M. Fischer, R. Hill, T. Koetz, P. Leadley, P. Lyver, G. M. Mace, B. Martin-Lopez, M. Okumura, D. Pacheco, U. Pascual, E. S. Pérez, B. Reyers, E. Roth, O. Saito, R. J. Scholes, N. Sharma, H. Tallis, R. Thaman, R. Watson, T. Yahara, Z. A. Hamid, C. Akosim, Y. Al-Hafedh, R. Allahverdiyev, E. Amankwah, S. T. Asah, Z. Asfaw, G. Bartus, L. A. Brooks, J. Caillaux, G. Dalle, D. Darnaedi, A. Driver, G. Erpul, P. Escobar-Eyzaguirre, P. Failler, A. M. M. Fouda, B. Fu, H. Gundimeda, S. Hashimoto, F. Homer, S. Lavorel, G. Lichtenstein, W. A. Mala, W. Mandivenyi, P. Matczak, C. Mbizvo, M. Mehrdadi, J. P. Metzger, J. B. Mikissa, H. Moller, H. A. Mooney, P. Mumby, H. Nagendra, C. Nesshover, A. A. Oteng-Yeboah, G. Pataki, M. Roué, J. Rubis, M. Schultz, P. Smith, R. Sumaila, K. Takeuchi, S. Thomas, M. Verma, Y. Yeo-Chang, and D. Zlatanova. 2015. The IPBES Conceptual Framework — connecting nature and people. *Current Opinion in Environmental Sustainability* 14:1–16.
- Diegues, A. 2008. Marine protected areas and artisanal fisheries in Brazil. International Collective in Support of Fishworkers.
- Diele, K., A. Araujo, M. Glaser, and U. Salzmann. 2010. Artisanal fishery of the Mangrove Crab *Ucides cordatus* (Ocypodidae) and First Steps towards a Successful Co-Management in Bragança, North Brazil. Pages 287–298 in U. Saint-Paul and H. Schneider, editors. *Mangrove dynamics and management in North Brazil*. Springer Berlin Heidelberg.
- Diele, K., and V. Koch. 2010. Comparative Population Dynamics and Life Histories of North Brazilian Mangrove Crabs, Genera *Uca* and *Ucides* (Ocypodoidea). Pages 275–285 in U. Saint-Paul and H. Schneider, editors. *Mangrove dynamics and management in North Brazil*.
- Dietz, T. 2013. Bringing values and deliberation to science communication. *Proceedings of the National Academy of Sciences* 110(Supplement_3):14081–14087.
- Dietz, T., E. Ostrom, and P. C. Stern. 2003. The struggle to govern the commons. *Science (New York, N.Y.)* 302(5652):1907–12.
- DiPaolo, D. F. 2017. Cajueiro: Agroextrativismo e relações sociais de gênero em contexto socioambiental na Amazonia paraense. Universidade Federal do Pará.
- Domptail, S., and M. H. Easdale. 2013. Managing Socio-Ecological Systems to Achieve Sustainability: A Study of Resilience and Robustness. *Environmental Policy and Governance* 23(1):30–45.
- Drew, J. A. 2005. Use of Traditional Ecological Knowledge in Marine Conservation. *Conservation Biology*:1286–1294.
- Dryzek, J. S., and J. Pickering. 2017. Deliberation as a catalyst for reflexive environmental governance. *Ecological Economics* 131:353–360.
- Dufrene, M., and P. Legendre. 1997. Species Assemblages and Indicator Species: The Need for a Flexible Asymmetrical Approach. *Ecological Monographs* 67(3):345–366.

Part 4: Synthesis and conclusions

- Edgar, G. J., R. D. Stuart-Smith, T. J. Willis, S. Kininmonth, S. C. Baker, S. Banks, N. S. Barrett, M. a Becerro, A. T. F. Bernard, J. Berkhout, C. D. Buxton, S. J. Campbell, A. T. Cooper, M. Davey, S. C. Edgar, G. Försterra, D. E. Galván, A. J. Irigoyen, D. J. Kushner, R. Moura, P. E. Parnell, N. T. Shears, G. Soler, E. M. a Strain, and R. J. Thomson. 2014. Global conservation outcomes depend on marine protected areas with five key features. *Nature* 506(7487):216–20.
- Edwards, P. 2015. Aquaculture environment interactions: Past, present and likely future trends. *Aquaculture* 447:2–14.
- Epstein, G., M. Nenadovic, and A. Boustany. 2014a. Into the deep blue sea: Commons theory and international governance of Atlantic Bluefin Tuna. *International Journal of the Commons* 8(2):277–303.
- Epstein, G., I. Pérez, M. Schoon, and C. L. Meek. 2014b. Governing the invisible commons: Ozone regulation and the Montreal Protocol. *International Journal of the Commons* 8(2):337–360.
- Epstein, G., J. Pittman, S. M. Alexander, S. Berdej, T. Dyck, U. Kreitmair, K. J. Raithwell, S. Villamayor-Tomas, J. Vogt, and D. Armitage. 2015. Institutional fit and the sustainability of social–ecological systems. *Current Opinion in Environmental Sustainability* 14:34–40.
- Epstein, G., J. M. Vogt, S. K. Mincey, M. Cox, and B. Fischer. 2013. Missing ecology: Integrating ecological perspectives with the social–ecological system framework. *International Journal of the Commons* 7(2):432–453.
- Eriksson, H., H. Österblom, B. Crona, M. Troell, N. Andrew, J. Wilen, and C. Folke. 2015. Contagious exploitation of marine resources. *Frontiers in Ecology and the Environment* 13(October):435–440.
- Eriksson, H., G. Robinson, M. J. Slater, and M. Troell. 2012. Sea cucumber aquaculture in the Western Indian Ocean: Challenges for sustainable livelihood and stock improvement. *Ambio* 41:109–121.
- Erler, D. M., D. P. Lima, and A. Schiavetti. 2015. Ecological fishing networks in a marine protected area: One possibility for evaluating objectives. *Ocean and Coastal Management* 104:106–114.
- Ernst, B., J. Chamorro, P. Manríquez, J. M. L. Orensanz, A. M. Parma, J. Porobic, and C. Román. 2013. Sustainability of the Juan Fernández lobster fishery (Chile) and the perils of generic science-based prescriptions. *Global Environmental Change* 23(6).
- Von Essen, L. M., S. C. a Ferse, M. Glaser, and A. Kunzmann. 2013. Attitudes and perceptions of villagers toward community-based mariculture in Minahasa, North Sulawesi, Indonesia. *Ocean and Coastal Management* 73:101–112.
- Esterci, N. 2002. Conflitos ambientais e processos classificatórios na Amazonia brasileira. *Boletim Rede Amazonia: Diversidade sociocultural e politicas ambientais* 1(1).
- Everard, M. 2015. Communicating ecosystem services. *Ecosystem News*.
- Fagerholm, N., M. Torralba, P. J. Burgess, and T. Plieninger. 2016. A systematic map of

Part 4: Synthesis and conclusions

- ecosystem services assessments around European agroforestry. *Ecological Indicators* 62:47–65.
- Falk, T., M. Kirk, D. Lohmann, B. Kruger, and C. Hüttich. 2012. The Profits of Excludability and Transferability in the Social-ecological Systems of Land Reform in Central.
- Falk, T., D. Lohmann, and N. Azebaze. 2016. Congruence of appropriation and provision in collective water provision in Central Namibia. *International Journal of the Commons* 10(1).
- FAO. 1995. Code of Conduct for Responsible Fisheries.
- FAO. 2014a. *SMALL-SCALE FISHERIES: Overall Goal*.
- FAO. 2014b. *Improving governance of aquaculture employment. A global assessment. FAO Fisheries and Aquaculture*. FAO.
- FAO. 2014c. *Contribución De La Pesca Y La Acuicultura a La Seguridad Alimentaria Y El Ingreso Familiar En Centroamérica*. FAO, Panama.
- FAO. 2015. *Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the context of Food Security and Poverty Eradication*. FAO.
- FAO. 2016. *The State of World Fisheries and Aquaculture*. Rome.
- Fargier, L., H. J. Hartmann, and H. Molina-Ureña. 2014. Marine Areas of Responsible Fishing: A Path Toward Small-Scale Fisheries Co-Management in Costa Rica? Perspectives from Golfo Dulce. Pages 155–179 *Fisheries Management of Mexican and Central American Estuaries*.
- Faysse, N., and A. Ben Mustapha. 2017. Finding common ground between theories of collective action : the potential of analyses at a meso-scale. *International Journal of the Commons* 11(2):928–949.
- Feder, G., and T. Onchan. 1987. Land Ownership Security and Farm Investment in Thailand. *American Journal of Agricultural Economics* 69(2):311–320.
- Feeny, D., F. Berkes, B. J. McCay, and J. M. Acheson. 1990. The Tragedy of the Commons : Twenty-Two Years Later. *Human Ecology* 18(1):1–19.
- Fenichel, E. P., B. Gentner, and R. Arlinghaus. 2013. Normative considerations for recreational fishery management: a bioeconomic framework for linking positive science and normative fisheries policy decisions. *Fisheries Management and Ecology* 20(2-3):223–233.
- Fernandez Carvajal, D. 2013. Artisanal Fishing and Poverty in the Communities Near the Nicoya ´ S Gulf. *Ciencias Sociales* 2013(Ii):137–152.
- Ferrol-Schulte, D. ., S. C. A. . Ferse, and M. . b Glaser. 2014. Patron-client relationships, livelihoods and natural resource management in tropical coastal communities. *Ocean and Coastal Management* 100:63–73.
- Feyerabend, P. 1975. *Against Method*. Verso.
- Fischer, J., T. A. Gardner, E. M. Bennett, P. Balvanera, R. Biggs, S. Carpenter, T. Daw, C. Folke,

Part 4: Synthesis and conclusions

- R. Hill, T. P. Hughes, T. Luthe, M. Maass, M. Meacham, A. V Norstrom, G. Peterson, C. Queiroz, R. Seppelt, M. Spierenburg, and J. Tenhunen. 2015. Advancing sustainability through mainstreaming a social–ecological systems perspective. *Current Opinion in Environmental Sustainability* 14:144–149.
- Fisher, R., B. T. Radford, N. Knowlton, R. E. Brainard, F. B. Michaelis, and M. J. Caley. 2010. Global mismatch between research effort and conservation needs of tropical coral reefs. *Conservation Letters* 4(1):64–72.
- Fleischman, F., K. Boenning, G. A. Garcia-Lopez, S. Mincey, M. Schmitt-Harsh, K. Daedlow, M. C. López, X. Basurto, B. C. Fischer, and E. Ostrom. 2010. Disturbance, Response, and Persistence in Self-Organized Forested Communities: Analysis of Robustness and Resilience in Five Communities in Southern Indiana. *Ecology and Society* 15(4).
- Fleischman, F. D., N. C. Ban, L. S. Evans, G. Epstein, G. Garcia-lopez, and S. Villamayor-tomas. 2014. Governing large-scale social-ecological systems : Lessons from five cases. *International Journal of the Commons* 8(2):428–456.
- Flick, U. 2014. *An Introduction To Qualitative Research*. Fourth Edi. Sage.
- Flynn, C. D., and C. I. Davidson. 2016. Adapting the social-ecological system framework for urban stormwater management: The case of green infrastructure adoption. *Ecology and Society* 21(4).
- Folke, C. 2006. The Economic Perspective: Conservation against Development versus Conservation for Development. *Conservation Biology* 20(3):686–688.
- Folke, C., S. R. Carpenter, B. Walker, M. Scheffer, and T. Chapin. 2010. Resilience Thinking : Integrating Resilience , Adaptability and. *Ecology & Society* 15(4).
- Folke, C., T. Hahn, P. Olsson, and J. Norberg. 2005. Adaptive Governance of Social-Ecological Systems. *Annual Review of Environment and Resources* 30(1):441–473.
- Folke, C., L. Pritchard, F. Berkes, J. Colding, and U. Svedin. 2007. The problem of fit between ecosystems and institutions: Ten years later. *Ecology and Society* 12(1):30.
- Fonseca, M., and V. Solis. 2005. Pesca artesanal y participación en conservación de recursos marino-costeros. IN Gobernabilidad en las zonas marino-costeras. *Ambientales* 30:44–51.
- Förster, J., J. Barkmann, R. Fricke, S. Hotes, M. Kleyer, S. Kobbe, D. Kübler, C. Rumbaur, M. Siegmund-Schultze, R. Seppelt, J. Settele, J. H. Spangenberg, V. Tekken, T. Václavík, and H. Wittmer. 2015. Assessing ecosystem services for informing land-use decisions: a problem-oriented approach. *Ecology and Society* 20(3):art31.
- Fox, H. E., M. B. Mascia, X. Basurto, A. Costa, L. Glew, D. Heinemann, L. B. Karrer, S. E. Lester, A. V Lombana, R. S. Pomeroy, C. A. Recchia, C. M. Roberts, J. N. Sanchirico, L. Pet-soede, and A. T. White. 2012. Reexamining the science of marine protected areas : linking knowledge to action. *Conservation Letters* 5:1–10.
- Franke, R. H., and J. D. Kaul. 1978. The Hawthorne experiments: First statistical interpretation. *American Sociological Review* 43:623–643.
- Frey, U. J., and M. Cox. 2015. Building a Diagnostic Ontology of Social-Ecological Systems.

- International Journal of the Commons* 9(2):595–618.
- Frey, U. J., and H. Rusch. 2013. Using Artificial Neural Networks for the Analysis of Social-Ecological. *Ecology and Society* 18(2).
- Fujiie, M., Y. Hayami, and M. Kikuchi. 2005. The conditions of collective action for local commons management: The case of irrigation in the Philippines. *Agricultural Economics* 33(2).
- Fujitani, M., A. Mcfall, C. Randler, and R. Arlinghaus. 2017. Participatory adaptive management leads to environmental learning outcomes extending beyond the sphere of science. *Science Advances*(June):1–12.
- Fung, A., and E. O. Wright. 2001. Deepening democracy: innovations in empowered participatory governance. *Politics and Society* 29(1):5–41.
- Fusch, P. I., and L. R. Ness. 2015. Are We There Yet? Data Saturation in Qualitative Research. *The Qualitative Report* 20(9):1408–1416.
- Gadgil, M., F. Berkes, and C. Folke. 1993. Indigenous knowledge for biodiversity conservation. *Ambio* 22(2-3):151–156.
- Galaz, V., P. Olsson, T. Hahn, C. Folke, and U. Svedin. 2008. *The Problem of Fit among Biophysical Systems, Environmental and Resource Regimes, and Broader Governance Systems: Insights and Emerging Challenges. Institutions and Environmental Change.*
- Gibson, R. B. 2006. Sustainability assessment: basic components of a practical approach. *Impact Assessment and Project Appraisal* 24(3):170–182.
- Glaser, M., W. Baitoningsih, S. C. a Ferse, M. Neil, and R. Deswandi. 2010a. Whose sustainability? Top-down participation and emergent rules in marine protected area management in Indonesia. *Marine Policy* 34(6):1215–1225.
- Glaser, M., U. Berger, and R. Macedo. 2003. Local vulnerability as an advantage: Mangrove forest management in Pará state, North Brazil under conditions of illegality. *Regional Environmental Change* 3(4):162–172.
- Glaser, M., A. Breckwoldt, R. Deswandi, I. Radjawali, W. Baitoningsih, and S. C. A. Ferse. 2015. Of exploited reefs and fishers - A holistic view on participatory coastal and marine management in an Indonesian archipelago. *Ocean and Coastal Management* 116:193–213.
- Glaser, M., P. Christie, K. Diele, L. Dsikowitzky, S. Ferse, I. Nordhaus, A. Schlüter, K. Schwerdtner Mañez, and C. Wild. 2012. Measuring and understanding sustainability-enhancing processes in tropical coastal and marine social–ecological systems. *Current Opinion in Environmental Sustainability* 4(3):300–308.
- Glaser, M., and K. Diele. 2004. Asymmetric Outcomes: Assessing the biological, economic and social sustainability of a mangrove crab fishery, *Ucides cordatus* (Ocypodidae), in North Brazil. *Ecological Economics* 49(3):361–373.
- Glaser, M., and B. Glaeser. 2012. The Social Dimension in the Management of Social-Ecological Change. in H. Kremer and J. Pinckney, editors. *Integrated Management of Estuaries and Coasts*. Elsevier, Munich.

- Glaser, M., and B. Glaeser. 2014. Towards a framework for cross-scale and multi-level analysis of coastal and marine social-ecological systems dynamics. *Regional Environmental Change* 14(6):2039–2052.
- Glaser, M., G. Krause, R. S. Oliveira, and M. Herazo-Fontalvo. 2010b. Mangroves and People: A Social-Ecological System. Pages 307–388 in U. Saint-Paul and H. Schneider, editors. *Mangrove dynamics and management in North Brazil*. Ecological. Springer Berlin Heidelberg.
- Glaser, M., and R. da Silva Oliveira. 2004. The prospects for co-management of mangrove ecosystems on the North Brazilian coast – Whose rights, whose duties and whose priorities? *Natural Resources Forum* 28:224–233.
- Görg, C., H. Keune, E. Primmer, and C. Schleyer. 2015. Good Governance. in M. Potschin and K. Jax, editors. *OpenNESS Ecosystem Service Reference Book*. EC FP7 Grant Agreement no. 308428.
- Görg, C., J. H. Spangenberg, V. Tekken, B. Burkhard, D. Thanh Truong, M. Escalada, K. Luen Heong, G. Arida, L. V. Marquez, J. Victor Bustamante, H. Van Chien, T. Klotzbücher, A. Marxen, N. Hung Manh, N. Van Sinh, S. (Bong) Villareal, and J. Settele. 2014. Engaging Local Knowledge in Biodiversity Research: Experiences from Large Inter- and Transdisciplinary Projects. *Interdisciplinary Science Reviews* 39(4):323–341.
- Graham, N. a J., D. R. Bellwood, J. E. Cinner, T. P. Hughes, A. V. Norstr??m, and M. Nystr??m. 2013. Managing resilience to reverse phase shifts in coral reefs. *Frontiers in Ecology and the Environment* 11:541–548.
- Graham, N. A. J., S. Jennings, M. A. MacNeil, D. Mouillot, and S. K. Wilson. 2015. Predicting climate-driven regime shifts versus rebound potential in coral reefs. *Nature* 518(7537):94–97.
- Green, R. H. 1979. *Sampling Design and Statistical Methods for Environmental Biologists*. Wiley, Chichester.
- Grêt-Regamey, A., B. Weibel, F. Kienast, S.-E. Rabe, and G. Zulian. 2014. A tiered approach for mapping ecosystem services. *Ecosystem Services* 13:16–27.
- de Groot, R. S., R. Alkemade, L. Braat, L. Hein, and L. Willemsen. 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity* 7(3):260–272.
- Grorud-Colvert, K., S. E. Lester, S. Airamé, E. Neeley, and S. D. Gaines. 2010. Communicating marine reserve science to diverse audiences. *Proceedings of the National Academy of Sciences of the United States of America* 107(43):18306–11.
- Gruby, R. L., N. J. Gray, L. M. Campbell, and L. Acton. 2015. Toward a Social Science Research Agenda for Large Marine Protected Areas. *Conservation Letters* 9(June):153–163.
- Guariguata, M. R., P. Cronkleton, A. E. Duchelle, and P. A. Zuidema. 2017. Revisiting the “cornerstone of Amazonian conservation”: a socioecological assessment of Brazil nut exploitation. *Biodiversity and Conservation*.

Part 4: Synthesis and conclusions

- Guevara, L. E. T., A. Schlüter, and M. C. Lopez. 2016. Collective action in a tropical estuarine lagoon : adapting Ostrom's SES framework to Ciénaga Grande de Santa Marta. *International Journal of the Commons* 10(1):1–29.
- Gunderson, L. H., and C. S. Holling. 2002. *Panarchy: understanding transformations in systems of humans and nature*. Island Press.
- Gurney, G. G., J. Cinner, N. C. Ban, R. L. Pressey, R. Pollnac, S. J. Campbell, S. Tasidjawa, and F. Setiawan. 2014. Poverty and protected areas: An evaluation of a marine integrated conservation and development project in Indonesia. *Global Environmental Change* 26(1):98–107.
- Gutiérrez, N. L., R. Hilborn, and O. Defeo. 2011. Leadership, social capital and incentives promote successful fisheries. *Nature* 470(7334):386–9.
- Hadorn, G. H., D. Bradley, C. Pohl, S. Rist, and U. Wiesmann. 2006. Implications of transdisciplinarity for sustainability research. *Ecological Economics* 60:119–128.
- Haines-Young, R., and M. Potschin. 2010. The links between biodiversity, ecosystem services and human well-being. Pages 110–139 in D. G. Raffaelli and C. L. J. Frid, editors. *Ecosystem Ecology: a new synthesis*. Cambridge University Press, Cambridge.
- Haines-Young, R., and M. Potschin. 2012. *Common International Classification of Ecosystem Services (CICES): Consultation on Version 4, August-December 2012*. EEA Framework Contract No.
- Haines-Young, R., and M. Potschin. 2014. The ecosystem approach as a framework for understanding knowledge utilisation. *Environment and Planning C: Government and Policy* 32(2):301–319.
- Halim, A. 2001. Grouper Culture: An Option for Grouper Management in Indonesia. *Coastal Management* 29(September 2015):319–326.
- Halpern, B. S. 2014. Making marine protected areas work. *Nature* 506(167):7–8.
- Halpern, B. S., M. Frazier, J. Potapenko, K. S. Casey, K. Koenig, C. Longo, J. S. Lowndes, R. C. Rockwood, E. R. Selig, K. a. Selkoe, and S. Walbridge. 2015. Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature Communications* 6(JANUARY):7615.
- Hardin, G. 1968. The Tragedy of the Commons. *Science* 162:1243–1248.
- Hauck, J., C. Görg, R. Varjopuro, O. Ratamäki, J. Maes, H. Wittmer, and K. Jax. 2013. “Maps have an air of authority”: Potential benefits and challenges of ecosystem service maps at different levels of decision making. *Ecosystem Services* 4:25–32.
- Hearn, A. 2008. The rocky path to sustainable fisheries management and conservation in the Galápagos Marine Reserve. *Ocean & Coastal Management* 51(8-9):567–574.
- Heinmiller, T. 2009. Path dependency and collective action in common pool governance. *International Journal of the Commons* 3(1):131–147.
- Hertz, T., and M. Schlüter. 2015. The SES-Framework as boundary object to address theory

- orientation in social–ecological system research: The SES-TheOr approach. *Ecological Economics* 116:12–24.
- Hicks, C. C., A. Levine, A. Agrawal, X. Basurto, J. Sara, C. Carothers, S. Coulthard, J. Donatuto, K. Norman, M. R. Poe, K. S. Martin, and S. Phillip. 2016. Engage key social concepts for sustainability. *Science* 352(April):38–40.
- Hileman, J., P. Hicks, and R. Jones. 2016. An alternative framework for analysing and managing conflicts in integrated water resources management (IWRM): linking theory and practice. *International Journal of Water Resources Development* 32(5):675–691.
- Hill, M. O., and H. G. Gauch. 1980. Detrended correspondence analysis: An improved ordination technique. *Vegetatio* 42(1-3):47–58.
- Hinkel, J., P. W. G. Bots, and M. Schluter. 2014. Enhancing the Ostrom social-ecological system framework through formalization. *Ecology and Society* 19(3):51.
- Hinkel, J., M. E. Cox, M. Schlüter, C. R. Binder, and T. Falk. 2015. A diagnostic procedure for applying the social-ecological systems framework in diverse cases. *Ecology and Society* 20(1).
- Holling, C. S., and G. K. Meffett. 1996. Command and Control and the Pathology of Natural Resource Management. *Conservation Biology* 10(2):328–337.
- Hoogesteger, J. 2015. Normative structures, collaboration and conflict in irrigation; a case study of the Pillaro North Canal Irrigation System, Ecuadorian Highlands. *International Journal of the Commons* 9(1).
- Horan, R. D., E. P. Fenichel, K. L. S. Drury, and D. M. Lodge. 2011. Managing ecological thresholds in coupled environmental-human systems. *Proceedings of the National Academy of Sciences of the United States of America* 108(18):7333–7338.
- Hornidge, A.-K. 2012. “Knowledge” in Development Discourse. A Critical Review. Pages 21–54 in A.-K. Hornidge and C. Antweiler, editors. *Environmental Uncertainty and Local Knowledge. Southeast Asia as a Laboratory of Global Ecological Change*.
- Hox, J., and H. Boeijs. 2005. Data Collection, Primary vs. Secondary.pdf.
- Hunt, L. M., S. G. Sutton, and R. Arlinghaus. 2013. Illustrating the critical role of human dimensions research for understanding and managing recreational fisheries within a social-ecological system framework. *Fisheries Management and Ecology* 20(2-3).
- Huong, T. T. T., and F. Berkes. 2011. Diversity of resource use and property rights in Tam Giang Lagoon, Vietnam. *International Journal of the Commons* 5(1):130–149.
- Hurlbert, S. H. 1984. Pseudoreplication and the design of ecological field experiments. *Ecological Monographs* 54(2):187–211.
- ICMBio. 2012. RESERVE MANAGEMENT PLAN Extractive Marine Reserve CAETÉ-Taperaçu (PA). Chico Mendes Institute for Biodiversity Conservation, Bragança.
- IFRI. 2013. International Forestry Resources and Institutions (IFRI) network: research methods. www.ifriresearch.net.

- IPCC. 2007. *Contribution of Working Groups I,II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.
- Islam, M. S., A. Milstein, M. A. Wahab, A. H. M. Kamal, and S. Dewan. 2005. Production and economic return of shrimp aquaculture in coastal ponds of different sizes and with different management regimes. *Aquaculture International* 13(6):489–500.
- Jacobs, S., B. Haest, T. de Bie, G. Deliège, A. Schneiders, and F. Turkelboom. 2013. Biodiversity and Ecosystem Services. Pages 29–40 in S. Jacobs, N. Dendoncker, and H. Keune, editors. *Ecosystem Services*. Elsevier, Amsterdam, Boston, Heidelberg, London, New York, Oxford, Paris, San Diego, San Francisco, Singapore, Sydney, Tokyo.
- Janssen, M. A., J. M. Anderies, and J. C. Cardenas. 2011. Head-enders as stationary bandits in asymmetric commons: Comparing irrigation experiments in the laboratory and the field. *Ecological Economics* 70(9):1590–1598.
- Jentoft, S. 2000. Legitimacy and disappointment in fisheries management. *Marine Policy* 24(2):141–148.
- Jentoft, S. 2004. Institutions in fisheries: What they are, what they do, and how they change. *Marine Policy* 28(2):137–149.
- Jentoft, S. 2005. Fisheries co-management as empowerment. *Marine Policy* 29(1):1–7.
- Jentoft, S., and B. J. McCay. 1995. User participation in fisheries management: Lessons drawn from international experiences. *Marine Policy* 19(3):227–246.
- Jentoft, S., B. J. McCay, and D. C. Wilson. 1998. Social theory and fisheries co-management. *Marine Policy* 22(4-5):423–436.
- Jerneck, A., L. Olsson, B. Ness, S. Anderberg, M. Baier, E. Clark, T. Hickler, A. Hornborg, A. Kronsell, E. Lövbrand, and J. Persson. 2010. Structuring sustainability science. *Sustainability Science* 6(1):69–82.
- Jones, P. J. S., W. Qiu, and E. M. De Santo. 2013. Governing marine protected areas: Social–ecological resilience through institutional diversity. *Marine Policy* 41:5–13.
- Jordan, A., and D. Russel. 2014. Embedding the concept of ecosystem services? The utilisation of ecological knowledge in different policy venues. *Environment and Planning C: Government and Policy* 32(2):192–207.
- Kajikawa, Y., F. Tocoa, and K. Yamaguchi. 2014. Sustainability science: the changing landscape of sustainability research. *Sustainability Science* 9(4):431–438.
- Kanwar, P., C. Koliba, S. Greenhalgh, and W. B. Bowden. 2016. An Institutional Analysis of the Kaipara Harbour Governance Network in New Zealand. *Society and Natural Resources* 29(11).
- Kappelle, M. 2016. *Costa Rican Ecosystems*. The University of Chicago Press.
- Karrasch, L., T. Klenke, and J. Woltjer. 2014. Linking the ecosystem services approach to social preferences and needs in integrated coastal land use management – A planning approach. *Land Use Policy* 38:522–532.

- Kasanoski, D. S. 2016. Bolsa verde: benefício social e incentivo à conservação ambiental? Universidade de Brasília.
- Kates, R. W. 2011. What kind of a science is sustainability science? *Proceedings of the National Academy of Sciences of the United States of America* 108(49):19449–50.
- Kates, R. W., and T. M. Parris. 2003. Long-term trends and a sustainability transition. *Proceedings of the National Academy of Sciences of the United States of America* 100(14):8062–7.
- Kelly, R. P., A. L. Erickson, L. A. Mease, W. Battista, J. N. Kittinger, and R. Fujita. 2015. Embracing thresholds for better environmental management. *Philosophical Transactions of the Royal Society B: Biological Sciences* 370(1659).
- Kenter, J. O., R. Bryce, M. Christie, N. Cooper, N. Hockley, K. N. Irvine, I. Fazey, E. O'Brien, J. Orchard-Webb, N. Ravenscroft, C. M. Raymond, M. S. Reed, P. Tett, and V. Watson. 2016. Shared values and deliberative valuation: Future directions. *Ecosystem Services* This issue(October):358–371.
- Kenter, J. O., M. S. Reed, M. Everard, K. N. Irvine, E. O'Brien, C. Molloy, R. Bryce, E. Brady, M. Christie, A. Church, and T. Collins. 2014. *Shared, plural and cultural values: A handbook for decision-makers, in UK National Ecosystem Assessment follow-on phase*. Cambridge.
- Kerkhoff, L. 2013. Developing integrative research for sustainability science through a complexity principles-based approach. *Sustainability Science*.
- van Kerkhoff, L. 2014. Developing integrative research for sustainability science through a complexity principles-based approach. *Sustainability Science* 9:143–155.
- Kittinger, J. N., E. M. Finkbeiner, N. C. Ban, K. Broad, M. H. Carr, J. E. Cinner, S. Gelcich, M. L. Cornwell, J. Z. Koehn, X. Basurto, R. Fujita, M. R. Caldwell, and L. B. Crowder. 2013. Emerging frontiers in social-ecological systems research for sustainability of small-scale fisheries. *Current Opinion in Environmental Sustainability* 5(3-4):352–357.
- Kittinger, J. N., E. M. Finkbeiner, E. W. Glazier, and L. B. Crowder. 2012. Human Dimensions of Coral Reef Social-Ecological Systems. *Ecology & Society* 17(4).
- Klein, P. G. 2009. NEW INSTITUTIONAL ECONOMICS.
- Klenk, N. L., K. Meehan, S. L. Pinel, F. Mendez, P. T. Lima, and D. M. Kammen. 2015. Stakeholders in climate science: Beyond lip service? *Science* 350:743–744.
- Klinger, D., and R. Naylor. 2012. Searching for Solutions in Aquaculture: Charting a Sustainable Course. *Annual Review of Environment and Resources* 37(1):247–276.
- Klöckner, C. A. 2013. A comprehensive model of the psychology of environmental behaviour—A meta-analysis. *Global Environmental Change* 23:1028–1038.
- Knight, A. T., R. M. Cowling, M. Rouget, A. Balmford, A. T. Lombard, and B. M. Campbell. 2008. Knowing but not doing: Selecting priority conservation areas and the research-implementation gap. *Conservation Biology* 22(3):610–617.

- Knight, A. T., A. Driver, R. M. Cowling, K. Maze, P. G. Desmet, A. T. Lombard, M. Rouget, M. A. Botha, A. F. Boshoff, J. G. Castley, P. S. Goodman, K. Mackinnon, S. M. Pierce, R. Sims-Castley, W. I. Stewart, and A. Von Hase. 2006. Designing Systematic Conservation Assessments that Promote Effective Implementation: Best Practice from South Africa. *Conservation Biology*:739–750.
- Knowlton, N., and J. B. C. Jackson. 2008. Shifting Baselines, Local Impacts, and Global Change on Coral Reefs. *PLoS biology* 6(2):0215–0220.
- Koch, V., and I. Nordhaus. 2010. Feeding Ecology and Ecological Role of North Brazilian Mangrove Crabs. Pages 265–273 in U. Saint-Paul and H. Schneider, editors. *Mangrove dynamics and management in North Brazil*. Springer.
- Koralagama, D., J. Gupta, and N. Pouw. 2017. Inclusive development from a gender perspective in small scale fisheries. *Current Opinion in Environmental Sustainability* 24:1–6.
- Krause, S. M. 2013. Pilgrimage to the Playas Surf Tourism in Costa Rica. *Anthropology in Action* 19:37–48.
- Krauss, K. W., K. L. McKee, C. E. Lovelock, D. R. Cahoon, N. Saintilan, R. Reef, and L. Chen. 2014. How mangrove forests adjust to rising sea level. *The New Phytologist* 202(1):19–34.
- Kuhn, T. 1962. *The structure of scientific revolutions*. University of Chicago Press.
- Kumazawa, T., K. Kozaki, T. Matsui, O. Saito, M. Ohta, K. Hara, M. Uwasu, M. Kimura, and R. Mizoguchi. 2014. Initial design process of the sustainability science ontology for knowledge-sharing to support co-deliberation. *Sustainability Science* 9:173–192.
- Lakatos, I. 1978. *The Methodology of Scientific Research Programmes*. Cambridge University Press, Cambridge.
- Lang, D. J., A. Wiek, M. Bergmann, M. Stauffacher, P. Martens, P. Moll, M. Swilling, and C. J. Thomas. 2012. Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustainability Science* 7(S1):25–43.
- Lange, P., P. P. J. Driessen, A. Sauer, B. Bornemann, and P. Burger. 2013. Governing Towards Sustainability—Conceptualizing Modes of Governance. *Journal of Environmental Policy & Planning* 15(3):403–425.
- Lanz, R. 2017. After the blue rush: Assessment of the sustainability of recreational fisheries in Peenemünde, Germany as part of a social-ecological system. Lund University.
- Lara, R. J., M. Cohen, and C. Szlafsztein. 2010. Drivers of Temporal Changes in Mangrove Vegetation Boundaries and Consequences for Land Use. Pages 127–142 in U. Saint-Paul and H. Schneider, editors. *Mangrove dynamics and management in North Brazil*.
- Law N° 8000. 2000. Law N° 8000. Diario Oficial La Gaceta, San Jose, Costa Rica.
- Legat, J. F. A., A. P. Legat, A. PEREIRA, and L. GÓES. 2006. Caranguejo-uçá: métodos para captura, estocagem e transporte. Embrapa Meio-Norte-Documents (INFOTECA-E).
- Leslie, H. M., X. Basurto, M. Nenadovic, L. Sievanen, K. C. Cavanaugh, J. J. Cota-Nieto, B. E. Erismang, E. Finkbeiner, G. Hinojosa-Arango, M. Moreno-Báez, S. Nagavarapu, S. M. W.

- Reddy, A. Sánchez-Rodríguez, K. Siegel, J. J. Ulibarria-Valenzuela, A. H. Weaver, and O. Aburto-Oropeza. 2015. Operationalizing the social-ecological systems framework to assess sustainability. *Proceedings of the National Academy of Sciences* 112(19):5979–5984.
- Leventon, J., B. Luuk Fleskens, B. Heleen Claringbould, B. Gudrun Schwilch, and B. Rudi Hessel. 2016. An applied methodology for stakeholder identification in transdisciplinary research. *Sustainability Science* 11(5):763–775.
- Lienhoop, N., and D. C. MacMillan. 2007. Contingent valuation: comparing participant performance in group-based approaches and personal interviews. *Environmental Values* 16:209–232.
- Liquete, C., C. Piroddi, E. G. Drakou, L. Gurney, S. Katsanevakis, A. Charef, and B. Egoh. 2013. Current Status and Future Prospects for the Assessment of Marine and Coastal Ecosystem Services: A Systematic Review. *PLoS ONE* 8(7).
- Liu, J., T. Dietz, S. R. Carpenter, M. Alberti, C. Folke, E. Moran, A. N. Pell, P. Deadman, T. Kratz, J. Lubchenco, E. Ostrom, Z. Ouyang, W. Provencher, C. L. Redman, S. H. Schneider, and W. W. Taylor. 2007a. Complexity of coupled human and natural systems. *Science (New York, N.Y.)* 317(5844):1513–6.
- Liu, J., T. Dietz, S. R. Carpenter, C. Folke, M. Alberti, C. L. Redman, S. H. Schneider, E. Ostrom, A. N. Pell, J. Lubchenco, W. W. Taylor, Z. Ouyang, P. Deadman, T. Kratz, and W. Provencher. 2007b. Coupled Human and Natural Systems. *AMBIO: A Journal of the Human Environment* 36(8):639–649.
- Liu, J., H. Mooney, V. Hull, S. J. Davis, J. Gaskell, T. Hertel, J. Lubchenco, K. C. Seto, P. Gleick, C. Kremen, and S. Li. 2015. Systems integration for global sustainability. *Science* 347(6225).
- London, S., M. L. Rojas, M. M. I. Martin, F. Scordo, M. A. H. Cisneros, M. L. Bustos, G. M. E. Perillo, and M. C. Piccolo. 2017. Characterization of an artisanal fishery in Argentina using the social-ecological systems framework. *International Journal of the Commons* 11(1).
- Loos, J., D. J. Abson, M. J. Chappell, J. Hanspach, F. Mikulcak, M. Tichit, and J. Fischer. 2014. Putting meaning back into “sustainable intensification.” *Frontiers in Ecology and the Environment* 12(6):356–361.
- López-Angarita, J., R. Moreno-Sánchez, J. H. Maldonado, and J. a. Sánchez. 2014. Evaluating Linked Social-Ecological Systems in Marine Protected Areas. *Conservation Letters* 7(3):241–252.
- Lord, T. R. 1999. A comparison between traditional and constructivist teaching in environmental science. *The Journal of Environmental Education* 30:22–27.
- Lozano, A. J. G., and J. T. Heinen. 2015. Identifying Drivers of Collective Action for the Co-management of Coastal Marine Fisheries in the Gulf of Nicoya, Costa Rica. *Environmental Management*:1–11.
- Lozano, A. J. G., and J. T. Heinen. 2016. Property relations and the co-management of small-scale fisheries in Costa Rica: Lessons from Marine Areas for Responsible Fishing in the Gulf of Nicoya. *Marine Policy* 73:196–203.

Part 4: Synthesis and conclusions

- Luederitz, C., E. Brink, F. Gralla, V. Hermelingermeier, M. Meyer, L. Niven, L. Panzer, S. Partelow, A.-L. Rau, R. Sasaki, D. J. Abson, D. J. Lang, C. Wamsler, and H. von Wehrden. 2015. A review of urban ecosystem services: six key challenges for future research. *Ecosystem Services* 14:98–112.
- Luks, F., and B. Siebenhuner. 2007. Transdisciplinarity for social learning? The contribution of the German socio-ecological research initiative to sustainability governance. *Ecological Economics* 63(2-3):418–426.
- Lynam, T., W. De Jong, D. Sheil, T. Kusumanto, and K. Evans. 2007. A review of tools for incorporating community knowledge, preferences, and values into decision making in natural resources management. *Ecology and Society* 12.
- Mace, G. M. 2014. Whose conservation? *Science* 345(6204):1558–1560.
- MacGillivray, B. H., and A. Franklin. 2015. Place as a boundary device for the sustainability sciences: Concepts of place, their value in characterising sustainability problems, and their role in fostering integrative research and action. *Environmental Science & Policy* 53:1–7.
- Macneil, M. A., and J. E. Cinner. 2013. Hierarchical livelihood outcomes among co-managed fisheries. *Global Environmental Change*.
- Madrigal, R., F. Alpízar, and A. Schlüter. 2011. Determinants of Performance of Community-Based Drinking Water Organizations. *World Development* 39(9):1663–1675.
- Mahon, N., I. Crute, E. Simmons, and M. M. Islam. 2017. Sustainable intensification – “oxymoron” or “third-way”? A systematic review. *Ecological Indicators* 74.
- Mansee, B., V. A. J. Anthonie, and B. J. Jaap. (n.d.). Sustainability of Water Resource Systems in India : Role of Value in Urban Lake Governance in Ahmedabad:1–30.
- Markus, T., H. Hillebrand, A.-K. Hornidge, G. Krause, and A. Schlüter. 2017. Disciplinary diversity in marine sciences: the urgent case for an integration of research. *ICES Journal of Marine Science* 74(4):941–954.
- Marshall, G. R. 2015. A social-ecological systems framework for food systems research: accommodating transformation systems and their products. *International Journal of the Commons* 9(2):1–28.
- Martín-López, B., E. Gómez-Baggethun, M. García-Llorente, and C. Montes. 2014. Trade-offs across value-domains in ecosystem services assessment. *Ecological Indicators* 37:220–228.
- Mascia, M. B., and C. A. Claus. 2009. A property rights approach to understanding human displacement from protected areas: The case of marine protected areas. *Conservation Biology* 23(1):16–23.
- Mausser, W., G. Klepper, M. Rice, B. S. Schmalzbauer, H. Hackmann, R. Leemans, and H. Moore. 2013. Transdisciplinary global change research: The co-creation of knowledge for sustainability. *Current Opinion in Environmental Sustainability* 5(3-4):420–431.
- MaxQDA. 2016. MaxQDA. VERBI Software, Berlin, Germany.
- McAllister, R. R., and B. M. Taylor. 2015. Partnerships for sustainability governance: a synthesis

of key themes. *Current Opinion in Environmental Sustainability* 12:86–90.

McCay, B. J., and J. M. Acheson. 1990. *The Question of the Commons: The Culture and Ecology of Communal Resources*. University of Arizona Press.

Mccord, P., J. D. Angelo, E. Baldwin, and T. Evans. 2016. Polycentric Transformation in Kenyan Water Governance : A Dynamic Analysis of Institutional and Social-Ecological Change. *Policy Studies Journal* 00(00).

McGinnis, M. D. 2011a. Networks of Adjacent Action Situations in Polycentric Governance. *Policy Studies Journal* 39(1):51–78.

McGinnis, M. D. 2011b. An Introduction to IAD and the Language of the Ostrom Workshop: A Simple Guide to a Complex Framework. *Policy Studies Journal* 39(1):169–183.

McGinnis, M. D., and E. Ostrom. 2014. Social-ecological system framework: Initial changes and continuing challenges. *Ecology and Society* 19(2).

McGreavy, B., K. Hutchins, H. Smith, L. Lindenfeld, and L. Silka. 2013. Addressing the complexities of boundary work in sustainability science through communication. *Sustainability (Switzerland)* 5:4195–4221.

McKinnon, a D., A. Williams, J. Young, D. Ceccarelli, P. Dunstan, R. J. W. Brewin, R. Watson, R. Brinkman, M. Cappel, S. Duggan, R. Kelley, K. Ridgway, D. Lindsay, D. Gledhill, T. Hutton, and A. J. Richardson. 2014. Tropical marginal seas: priority regions for managing marine biodiversity and ecosystem function. *Annual review of marine science* 6:415–37.

McMahon, K. W., M. L. Berumen, and S. R. Thorrold. 2012. Linking habitat mosaics and connectivity in a coral reef seascape. *Proceedings of the National Academy of Sciences* 109:15372–15376.

MEA. 2005. *Ecosystems and Human Well-being: General Synthesis*. Washington DC.

Meadows, D. H., D. L. Meadows, J. Randers, and W. W. Behrens. 1972. *The Limits to Growth*. Potomac Associates, New York.

Medin, D. L., and M. Bang. 2014. The cultural side of science communication. *Proceedings of the National Academy of Sciences* 111(Supplement_4):13621–13626.

Meinzen-Dick, R. 2007. Beyond panaceas in water institutions. *Proceedings of the National Academy of Sciences* 104(39):15200–15205.

Meinzen-Dick, R., K. V. Raju, and A. Gulati. 2002. What affects organization and collective action for managing resources? Evidence from canal irrigation systems in India. *World Development* 30(4):649–666.

Meyer, B. D. 1995. Natural and quasi-experiments in economics. *Journal of Business and Economic Statistics* 13:151–161.

Milcu, A. I., J. Hanspach, D. Abson, and J. Fischer. 2013. Cultural Ecosystem Services: A Literature Review and Prospects for Future Research. *Ecology and Society* 18(3):art44.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: General*

Part 4: Synthesis and conclusions

Synthesis. Washington DC.

- Miller, T. R., T. D. Baird, C. M. Littlefield, G. Kofinas, F. S. C. Iii, and C. L. Redman. 2008. Epistemological Pluralism: Reorganizing Interdisciplinary Research. *Ecology & Society* 13(2).
- Miller, T. R., B. a. Minter, and L.-C. Malan. 2011. The new conservation debate: The view from practical ethics. *Biological Conservation* 144(3):948–957.
- Miller, T. R., A. Wiek, D. Sarewitz, J. Robinson, L. Olsson, D. Kriebel, and D. Loorbach. 2013. The future of sustainability science: a solutions-oriented research agenda. *Sustainability Science*.
- Milner-Gulland, E. 2012. Interactions between human behaviour and ecological systems. *Phil. Trans. R. Soc. B* 367:270–278.
- Moberg, F. . b, and P. . Rönnbäck. 2003. Ecosystem services of the tropical seascape: Interactions, substitutions and restoration. *Ocean and Coastal Management* 46(1-2):27–46.
- Mollinga, P. P. 2010. Boundary Work and the Complexity of Natural Resources Management. *Crop Science* 50(Supplement 1):S–1–S–9.
- Mouillot, D., S. Villeger, V. Parravicini, M. Kulbicki, J. E. Arias-Gonzalez, M. Bender, P. Chabanet, S. R. Floeter, a. Friedlander, L. Vigliola, and D. R. Bellwood. 2014. Functional over-redundancy and high functional vulnerability in global fish faunas on tropical reefs. *Proceedings of the National Academy of Sciences* 111(38):13757–13762.
- Murase, A., A. Angulo, Y. Miyazaki, W. a. Bussing, and M. I. L??pez. 2014. Marine and estuarine fish diversity in the inner Gulf of Nicoya, Pacific coast of Costa Rica, Central America. *Check List* 10(6):1401–1413.
- N°35502-MAG, D. 2009. Decree N°35502-MAG. Diario Oficial La Gaceta, San Jose, Costa Rica.
- Nagendra, H., and E. Ostrom. 2014. Applying the social-ecological system framework to the diagnosis of urban lake commons in Bangalore , India. *Ecology & Society* 19(2).
- Naiga, R., M. Penker, and K. Hegl. 2015. Challenging pathways to safe water access in rural Uganda: From supply to demand-driven water governance. *International Journal of the Commons* 9(1).
- Nakandakari, A., M. Caillaux, J. Zavala, S. Gelcich, and F. Gherzi. 2017. The importance of understanding self-governance efforts in coastal fisheries in Peru: Insights from La Isilla and Ilo. *Bulletin of Marine Science* 93(1).
- Narahara, K. L. 2014. Para evitar questão: a elaboração do Plano de Utilização em uma Reserva Extrativista. in N. Esterici, H. O. Sant’ana-Júnior, and M. J. S. A. Teisserenc, editors. *Territórios socioambientais em construção na Amazônia brasileira*. HIFE (Sociologia & Antropologia), Rio de Janeiro.
- Nascimento, J. R., D. Domingues, and R. S. L. Barboza. 2015. A cadeia produtiva do caranguejo (Ucides cordatus): os desafios frente às pressões do mercado no território da Resex Marinha Caeté-Taperaçu, Bragança-Pará. *Revista Saude e Ciencia on line* 4(2):299–309.

Part 4: Synthesis and conclusions

- Nassl, M., and J. Löffler. 2015. Ecosystem services in coupled social–ecological systems: Closing the cycle of service provision and societal feedback. *Ambio* 44(8):737–749.
- Nenadovic, M., and G. Epstein. 2016. The relationship of social capital and fishers’ participation in multi-level governance arrangements. *Environmental Science & Policy* 61(April):77–86.
- Neori, A., M. Troell, T. Chopin, C. Yarish, A. Critchley, and A. H. Buschmann. 2007. The Need for a Balanced Ecosystem Approach to Blue Revolution Aquaculture. *Environment: Science and Policy for Sustainable Development* 49(3):36–43.
- Ness, B. 2013. Sustainability Science: Progress Made and Directions Forward. *Challenges in Sustainability* 1(1):27–28.
- Ness, B., E. Urbel-Piirsalu, S. Anderberg, and L. Olsson. 2007. Categorising tools for sustainability assessment. *Ecological Economics* 60(3):498–508.
- Newell, B., C. L. Crumley, N. Hassan, E. F. Lambin, C. Pahl-Wostl, A. Underdal, and R. Wasson. 2005. A conceptual template for integrative human–environment research. *Global Environmental Change* 15(4):299–307.
- Newig, J., and O. Fritsch. 2009. Environmental governance: Participatory, multi-level - And effective? *Environmental Policy and Governance* 19(3):197–214.
- Newing, H. 2011. *Conducting research in conservation: A social science perspective*. Routledge, New York, United States of America.
- Noble, B. F. 2000. Institutional criteria for co-management. *Marine Policy* 24(1):69–77.
- Nobre, D. M., D. T. Alarcon, A. Cinti, and A. Schiavetti. 2017. Governance of the Cassurubá Extractive Reserve, Bahia State, Brazil: An analysis of strengths and weaknesses to inform policy. *Marine Policy* 77(January):44–55.
- North, D. C. 1990. Institutions, Institutional Change, and Economic Performance. *Cambridge University Press* 5(1):1–153.
- Nunnally, J. C. 1967. *Psychometric theory*. McGraw-Hill, New York.
- O’Byrne, D., W. Dripps, and K. a. Nicholas. 2014. Teaching and learning sustainability: An assessment of the curriculum content and structure of sustainability degree programs in higher education. *Sustainability Science* 10(1):43–59.
- O’Neill, D. W., A. L. Fanning, W. F. Lamb, and J. K. Steinberger. 2018. A good life for all within planetary boundaries. *Nature Sustainability* 1(February):88–95.
- Oberlack, C., L. Tejada, P. Messerli, S. Rist, and M. Giger. 2016. Sustainable livelihoods in the global land rush? Archetypes of livelihood vulnerability and sustainability potentials. *Global Environmental Change* 41:153–171.
- Oberlack, C., P. L. Walter, J. Schmerbeck, and B. K. Tiwari. 2015. Institutions for sustainable forest governance: Robustness, equity, and cross-level interactions in Mawlyngbna, Meghalaya, India. *International Journal of the Commons* 9(2).
- Oliveira, M. D. V., and M. C. A. Maneschy. 2014. Territories and territorialities on the extraction

Part 4: Synthesis and conclusions

- of crabs in Pontinha de Bacuriteua, Bragança, Pará. *Boletim do Museu Paraense Emílio Goeldi. Ciências Humanas* 9(1):129–143.
- Olson, M. 1965. *Logic of collective action: Public goods and the theory of groups*. Harvard University Press.
- Olsson, L., a. Jerneck, H. Thoren, J. Persson, and D. O’Byrne. 2015. Why resilience is unappealing to social science: Theoretical and empirical investigations of the scientific use of resilience. *Science Advances* 1(4):e1400217–e1400217.
- Olsson, P., C. Folke, V. Galaz, T. Hahn, and L. Schultz. 2007. Enhancing the Fit through Adaptive Co-management : Creating and Maintaining Bridging Functions for Matching Scales in the Kristianstads Vattenrike Biosphere Reserve , Sweden. *Ecology and Society* 12(1).
- Orenstein, D. 2013. More than Language Is Needed in Valuing Ecosystem Services. *BioScience* 63(12):913–913.
- Orley, A., and D. Card. 1985. Using the longitudinal structure of earnings to estimate the effect of training programs. *The Review of Economics and Statistics* 67:648–660.
- Orth, R. J. ., T. J. B. . Carruthers, W. C. . Dennison, C. M. . Duarte, J. W. . e Fourqurean, K. L. . Heck Jr., A. R. . h Hughes, G. A. . Kendrick, W. J. . Kenworthy, S. . h Olyarnik, F. T. . l Short, M. . Waycott, and S. L. . h Williams. 2006. A global crisis for seagrass ecosystems. *BioScience* 56(12):987–996.
- Osés-Eraso, N., and M. Viladrich-Grau. 2007. Appropriation and concern for resource scarcity in the commons: An experimental study. *Ecological Economics* 63(2-3):435–445.
- Osmundsen, T. C., and M. S. Olsen. 2017. The imperishable controversy over aquaculture. *Marine Policy* 76(October 2016):136–142.
- Ostrom, E. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press, Cambridge, UK.
- Ostrom, E. 1998. A Behavioral Approach to the Rational Choice Theory of Collective Action. *American Political Science Review* 92(1):1–22.
- Ostrom, E. 2005. *Understanding Institutional Diversity*. Princeton Universty Press, Princeton, NJ, USA.
- Ostrom, E. 2007. A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences of the United States of America* 104(39):15181–7.
- Ostrom, E. 2009. A general framework for analyzing sustainability of social-ecological systems. *Science (New York, N.Y.)* 325(5939):419–22.
- Ostrom, E. 2011. Background on the Institutional Analysis and Development Framework. *Policy Studies Journal* 39(1):7–28.
- Ostrom, E., J. Burger, C. B. Field, R. B. Norgaard, and D. Policansky. 1999. Revisiting the commons: local lessons, global challenges. *Science (New York, N.Y.)* 284(5412):278–82.

Part 4: Synthesis and conclusions

- Ostrom, E., and M. Cox. 2010. Moving beyond panaceas: A multi-tiered diagnostic approach for social-ecological analysis. *Environmental Conservation* 37(4).
- Ostrom, E., R. Gardner, and J. Walker. 1994. *Rules, Games, and Common-Pool Resources*.
- Ostrom, E., J. Walker, and R. Gardner. 1992. Covenants with and without a Sword: Self-Governance Is Possible. *American Political Science Review* 86(02):404–417.
- Oviedo, A. F. P., and M. Bursztyn. 2016. The Fortune of the Commons: Participatory Evaluation of Small-Scale Fisheries in the Brazilian Amazon. *Environmental Management* 57(5).
- Pacheco Urpi, O., S. Salas, and L. Sierra Sierra. 2012. DETERMINATION OF CRITERIA AND INDICATORS FOR GOOD GOVERNANCE IN MANAGEMENT FOR THE SUSTAINABILITY OF THE FISHERY RESOURCES OF THE GULF OF NICOYA AND IN PARTICULAR OF THE COMMUNITIES OF COSTA DE PÁJAROS AND MANZANILLO. *Revista geografica de America Central*:75–102.
- Pacheco Urpí, O., S. Salas, and L. Sierra Sierra. 2013. Modelo de gestión para la sostenibilidad de los recursos pesqueros del Golfo de Nicoya, Costa Rica. *Revista Geográfica de América Central* 1(50):165–193.
- Partelow, S. 2015. Key steps for operationalizing social–ecological system framework research in small-scale fisheries: A heuristic conceptual approach. *Marine Policy* 51:507–511.
- Partelow, S. 2016. Coevolving Ostrom’s social–ecological systems (SES) framework and sustainability science: four key co-benefits. *Sustainability Science* 11(3):399–410.
- Partelow, S., and C. Boda. 2015. A modified diagnostic social-ecological system framework for lobster fisheries: Case implementation and sustainability assessment in Southern California. *Ocean and Coastal Management* 114:204–217.
- Partelow, S., A. Schlüter, H. von Wehrden, M. Jänig, and P. Senff. 2018a. A Sustainability Agenda for Tropical Marine Science. *Conservation Letters* 11(1).
- Partelow, S., P. Senff, N. Buhari, and A. Schlüter. 2018b. Operationalizing the social-ecological systems framework in pond aquaculture. *International Journal of the Commons* 12(1).
- Partelow, S., H. von Wehrden, and O. Horn. 2015. Pollution exposure on marine protected areas: A global assessment. *Marine Pollution Bulletin* 100(1):352–358.
- Partelow, S., and K. J. Winkler. 2016. Interlinking ecosystem services and Ostrom’s framework through orientation in sustainability research. *Ecology and Society* 21(3).
- Pauly, D., and D. Zeller. 2016. Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nature Communications* 7:1–9.
- Perrings, C. 2007. Future challenges. *Proceedings of the National Academy of Sciences of the United States of America* 104(39):15179–80.
- Pimm, S. L. 2007. Africa: Still the “dark continent.” *Conservation Biology* 21(3):567–569.
- Pinheiro, H. T., F. Di Dario, L. C. Gerhardinger, M. S., R. de Melo, R. L. de Moura, R. E. Reis, F. Vieira, J. Zuanon, and L. A. Rocha. 2015. Brazilian aquatic biodiversity in peril. *Science*

Part 4: Synthesis and conclusions

(New York, N.Y.) 350(6264):1–2.

Pittman, J., and D. Armitage. 2016. Governance across the land-sea interface: A systematic review. *Environmental Science and Policy* 64:9–17.

Plummer, R., and A. Hashimoto. 2011. Adaptive co-management and the need for situated thinking in collaborative conservation. *Human Dimensions of Wildlife* 16(4):222–235.

Poe, M. R., K. C. Norman, and P. S. Levin. 2014. Cultural Dimensions of Socioecological Systems : Key Connections and Guiding Principles for Conservation in Coastal Environments. *Conservation Letters* 7(June):166–175.

Polk, M. 2014. Achieving the promise of transdisciplinarity: a critical exploration of the relationship between transdisciplinary research and societal problem solving. *Sustainability Science*:439–451.

Pollnac, R. ., P. . Christie, J. E. . Cinner, T. . Dalton, T. M. . Daw, G. E. . Forrester, N. A. J. . Graham, and T. R. . McClanahan. 2010. Marine reserves as linked social-ecological systems. *Proceedings of the National Academy of Sciences of the United States of America* 107(43):18262–18265.

Pomeroy, R. S. 2012. Managing overcapacity in small-scale fisheries in Southeast Asia. *Marine Policy* 36(2):520–527.

Pomeroy, R. S., B. M. Katon, and I. Harkes. 2001. Conditions affecting the success of fisheries co-management : lessons from Asia. *Marine Policy* 25:197–208.

Pomeroy, R. S., L. M. Watson, J. E. Parks, and G. a. Cid. 2005. How is your MPA doing? A methodology for evaluating the management effectiveness of marine protected areas. *Ocean & Coastal Management* 48(7-8):485–502.

Popper, K. 1959. *The Logic of Scientific Discovery*. Routledge.

Poteete, A., M. a. Janssen, and E. Ostrom. 2010. *WORKING TOGETHER: Collective action, the Commons and Multiple Methods in Practice*. Princeton University Press.

Poteete, A., and E. Ostrom. 2004. Heterogeneity, Group Size and Collective Action: The Role of Institutions in Forest Management. *Development and Change* 35(3):435–461.

Preston, J. 2016. Paul Feyerabend. *The Stanford Encyclopedia of Philosophy*.

Pretty, J. 2003. Social Capital and the Collective Management of Resources. *Science* 302(5652):1912–1914.

Primmer, E., P. Jokinen, M. Blicharska, D. N. Barton, R. Bugter, and M. Potschin. 2015. Governance of Ecosystem Services: A framework for empirical analysis. *Ecosystem Services*:1–9.

R Core Team. 2016. R: A language and environment for statistical computing. Vienna, Austria.

Rahimi, S., S. D. Gaines, S. Gelcich, R. Deacon, and D. Ovando. 2016. Factors driving the implementation of fishery reforms. *Marine Policy* 71.

- Rahman, H. M. T., A. S. Sainte Ville, A. M. Song, J. Y. T. Po, E. Berthet, J. R. Brammer, N. G. Jayaprakash, K. N. Lowitt, A. Rastogi, G. Reed, and G. M. Hickey. 2017. A framework for analyzing institutional gaps in natural resource governance. *International Journal of the Commons* 11(2):823–853.
- Ratajczyk, E., U. Brady, J. A. Baggio, A. J. Barnett, N. Rollins, C. A. Rubinos, H. C. Shin, J. Y. David, R. Aggarwal, J. M. Anderies, and M. A. Janssen. 2016. Challenges and Opportunities in Coding the Commons: Problems, Procedures, and Potential Solutions in Large-N Comparative Case Studies. *International Journal of the Commons* 10(2):this issue.
- Raymond, C. M., I. Fazey, M. S. Reed, L. C. Stringer, G. M. Robinson, and A. C. Evelyn. 2010. Integrating local and scientific knowledge for environmental management. *Journal of Environmental Management* 91(8):1766–1777.
- Reed, M., A. Evelyn, G. Cundill, I. Fazey, J. Glass, A. Laing, J. Newig, B. Parrish, C. Prell, C. Raymond, and L. Stringer. 2010. What is Social Learning? *Ecology and Society* 15(4):r1.
- Reed, M. S. 2008. Stakeholder participation for environmental management: A literature review. *Biological Conservation* 141(10):2417–2431.
- Reyers, B., R. Biggs, G. S. Cumming, T. Elmqvist, A. P. Hejnowicz, and S. Polasky. 2013. Getting the measure of ecosystem services: a social–ecological approach. *Frontiers in Ecology and the Environment* 11(5):268–273.
- Richards, D. R., and D. a. Friess. 2015. Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012. *Proceedings of the National Academy of Sciences* 113(2):344–349.
- Richmond, R. H. ., T. . Rongo, Y. . Golbuu, S. . Victor, N. . e Idechong, G. . Davis, W. . Kostka, L. . Neth, M. . Hamnett, and E. . Wolanski. 2007. Watersheds and coral reefs: Conservation science, policy, and implementation. *BioScience* 57(7):598–607.
- Rimmer, M. A., K. Sugama, D. Rakhmawati, R. Rofiq, and R. H. Habgood. 2013. A review and SWOT analysis of aquaculture development in Indonesia. *Reviews in Aquaculture* 5(4):255–279.
- Risvoll, C., G. E. Fedreheim, A. Sandberg, and S. BurnSilver. 2014. Does Pastoralists’ participation in the management of national parks in northern Norway contribute to adaptive governance? *Ecology and Society* 19(2).
- Roberts, N. 2004. Public deliberation in an age of direct citizen participation. *The American review of public administration* 4(4):315–353.
- da Rocha, D. F., M. F. Porto, T. Pacheco, and J. P. Leroy. 2017. The map of conflicts related to environmental injustice and health in Brazil. *Sustainability Science*:1–11.
- Rocha, J., J. Yletyinen, R. Biggs, T. Blenckner, and G. Peterson. 2014. Marine regime shifts: drivers and impacts on ecosystems services. *Philosophical Transactions of the Royal Society B: Biological Sciences* 370(1659):20130273–20130273.
- Rodela, R. 2013. The social learning discourse: Trends, themes and interdisciplinary influences in current research. *Environmental Science and Policy* 25:157–166.
- Rodríguez Estrada, F. C., and L. S. Davis. 2015. Improving Visual Communication of Science

Through the Incorporation of Graphic Design Theories and Practices Into Science Communication. *Science Communication* 37(1):140–148.

Rodríguez-Robayo, K. J., and L. Merino-Perez. 2017. Contextualizing context in the analysis of payment for ecosystem services. *Ecosystem Services* 23.

Roff, G., and P. J. Mumby. 2012. Global disparity in the resilience of coral reefs. *Trends in Ecology and Evolution* 27(7):404–413.

Rova, S., and F. Pranovi. 2017. Analysis and management of multiple ecosystem services within a social-ecological context. *Ecological Indicators* 72.

Ruppert-Winkel, C., R. Arlinghaus, S. Deppisch, K. Eisenack, D. Gottschlich, B. Hirschl, M. Padmanabhan, K. Selbmann, R. Ziegler, and T. Plieninger. 2015. Characteristics , emerging needs , and challenges of transdisciplinary sustainability science : experiences from the German Social-Ecological. *Ecology & Society* 20(3).

Saint-Paul, U., and H. Schneider. 2010. *Mangrove dynamics and management in North Brazil*. Springer.

Sala, S., B. Ciuffo, and P. Nijkamp. 2015. A systemic framework for sustainability assessment. *Ecological Economics* 119:314–325.

Salas, E., E. Ross Salazar, and E. Arias. 2012. *Diagnóstico de las Áreas Marinas Protegidas y de las Áreas Marinas para la Pesca Responsable en el Pacífico Costarricense*. San Jose, Costa Rica.

Sampson, B. G. S., J. N. Sanchirico, C. A. Roheim, S. R. Bush, J. E. Taylor, E. H. Allison, J. L. Anderson, N. C. Ban, and R. Fujita. 2015. Secure sustainable seafood from developing countries: Require improvements as conditions for market access. *Science* 348(6234):504–506.

Sandker, M., B. M. Campbell, M. R. Perez, J. A. Sayer, R. M. Cowling, H. Kassa, and A. Knight. 2010. The role of participatory modeling in landscape approaches to reconcile conservation and development. *Ecology and Society* 15(13).

Sant’ana-Júnior, H. A. 2014. Projetos de desenvolvimento e a criação de reservas extrativistas: estratégias de luta de grupos sociais locais no Acre e no Maranhão. in N. Esterci, H. A. Sant’ana-Júnior, and M. J. S. Teisserenc, editors. *Territórios socioambientais em construção na Amazônia brasileira*. HIFE (Sociologia & Antropologia), Rio de Janeiro.

Santos, A. N. 2015. Fisheries as a way of life: Gendered livelihoods, identities and perspectives of artisanal fisheries in eastern Brazil. *Marine Policy* 62:279–288.

Santos, A. N., and C. Brannstrom. 2015. Livelihood strategies in a marine extractive reserve: Implications for conservation interventions. *Marine Policy* 59:44–52.

Santos, C. Z., and A. Schiavetti. 2014. Assessment of the management in Brazilian marine extractive reserves. *Ocean and Coastal Management* 93:26–36.

Santos, C. Z., and A. Schiavetti. 2017. Reservas extrativistas marinhas do Brasil: contradições de ordem legal, sustentabilidade e aspecto ecológico. *Boletim do Instituto de Pesca* 39(4):479–494.

- Santos, L. C. M., M. A. Gasalla, F. Dahdouh-Guebas, and M. D. Bitencourt. 2017. Socio-ecological assessment for environmental planning in coastal fishery areas: A case study in Brazilian mangroves. *Ocean and Coastal Management* 138:60–69.
- Saunders, C. D., A. T. Brook, and O. E. Myers. 2006. Using psychology to save biodiversity and human well-being. *Conservation Biology* 20:702–705.
- Schlager, E. 2004. Common-pool Resource Theory. Pages 145–175 *Environmental Governance Reconsidered*.
- Schlager, E., W. Blomquist, and S. Y. Tang. 1994. Mobile Flows, Storage, and Self-Organized Institutions for Governing Common-Pool Resources. *Land Economics* 70(3):294–317.
- Schlager, E., and E. Ostrom. 1992. Property-Rights Regimes and Natural Resources : A Conceptual Analysis. *Land Economics* 68(3):249–262.
- Schleyer, C., C. Görg, J. Hauck, and K. J. Winkler. 2015. Opportunities and challenges for mainstreaming the ecosystem services concept in the multi-level policy-making within the EU. *Ecosystem Services* 16:174–181.
- Schlüter, A., and R. Madrigal. 2012. The SES Framework in a Marine Setting : Methodological Lessons *. *RMM* 3:148–167.
- Schlüter, A., S. Partelow, L. E. T. Guevara, and T. Jennerjahn. 2018. Coastal commons as social-ecological systems. in B. Hudson, J. Rosenbloom, and D. Cole, editors. *Handbook of the Study of the Commons*. Routledge.
- Schlüter, A., and I. Theesfeld. 2010. The grammar of institutions: The challenge of distinguishing between strategies, norms, and rules. *Rationality and Society* 22(4):445–475.
- Schlüter, A., S. Wise, K. Schwerdtner-Máñez, G. de Moraes, and M. Glaser. 2013. Institutional Change, Sustainability and the Sea. *Sustainability* 5(12):5373–5390.
- Schneider, F., and T. Buser. 2017. Promising degrees of stakeholder interaction in research for sustainable development. *Sustainability Science*.
- Scholes, R., B. Reyers, R. Biggs, M. Spierenburg, and a Duriappah. 2013. Multi-scale and cross-scale assessments of social–ecological systems and their ecosystem services. *Current Opinion in Environmental Sustainability* 5(1):16–25.
- Scholte, S. S. K., A. J. A. van Teeffelen, and P. H. Verburg. 2015. Integrating socio-cultural perspectives into ecosystem service valuation: A review of concepts and methods. *Ecological Economics* 114:67–78.
- Scholz, R. 2011. *Environmental Literacy in Science and Society: From Knowledge to Decisions*. Cambridge University Press, Cambridge.
- Scholz, R. W., and G. Steiner. 2015a. The real type and ideal type of transdisciplinary processes: part I—theoretical foundations. *Sustainability Science*.
- Scholz, R. W., and G. Steiner. 2015b. Transdisciplinarity at the crossroads. *Sustainability Science* 10(4):521–526.

Part 4: Synthesis and conclusions

- Schoolman, E. D., J. S. Guest, K. F. Bush, and A. R. Bell. 2012. How interdisciplinary is sustainability research? Analyzing the structure of an emerging scientific field. *Sustainability Science* 7:67–80.
- Schoon, M., and S. van der Leeuw. 2015. The shift toward social-ecological systems perspectives: insights into the human-nature relationship. *Natures Sciences Sociétés* 23:166–174.
- Schröter, M., and A. P. E. van Oudenhoven. 2016. Ecosystem Services Go Beyond Money and Markets: Reply to Silvertown. *Trends in Ecology & Evolution* xx:2–3.
- Seawright, J., and J. Gerring. 2008. Case Selection Techniques in Case Study Research. *Political Research Quarterly* 61(2):294–308.
- Seppelt, R., C. F. Dormann, F. V. Eppink, S. Lautenbach, and S. Schmidt. 2011. A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. *Journal of Applied Ecology* 48(3):630–636.
- SESMAD. 2014. Social-Ecological Systems Meta-Analysis Database. <http://sesmad.dartmouth.edu/>.
- Sharma, D., I. Holmes, G. Vergara-Asenjo, W. N. Miller, M. Cunampio, R. B. Cunampio, M. B. Cunampio, and C. Potvin. 2016. A comparison of influences on the landscape of two social-ecological systems. *Land Use Policy* 57.
- Shivakoti, G. P., and E. Ostrom. 2002. *Improving irrigation governance and management in Nepal*. ICS press.
- Silva, A. C. S., C. O. Galvão, and G. N. S. Silva. 2015. Droughts and governance impacts on water scarcity: An analysis in the Brazilian semi-arid. *IAHS-AISH Proceedings and Reports*.
- da Silva, P. P. 2004. From common property to co-management: Lessons from Brazil's first maritime extractive reserve. *Marine Policy* 28(5):419–428.
- Silva-Junior, S. R. 2013. Participação e relações de poder no Conselho Deliberativo da Reserva Extrativista Marinha Caeté-Taperaçu, Bragança-PA. Universidade Federal do Pará.
- Silverman, D. 2005. *Doing qualitative research*. Sage, London.
- Silvertown, J. 2015. Have Ecosystem Services Been Oversold? *Trends in Ecology & Evolution* 30(11):641–648.
- Simonian, L. T., and M. Glaser. 2002. Extractive reserves and the question of sustainability in neotropical ecosystems. *Neotropical Ecosystems: Proceedings of the German-Brazilian workshop*:767–776.
- Soares, Denise; Gutierrez, I. 2011. Vulnerabilidad social, institucionalidad y percepciones sobre el cambio climático: un acercamiento al municipio de San Felipe, Costa de Yucatán. *Ciencia Ergo Sum* 18(3):249–263.
- Spangenberg, J. H. 2011. Sustainability science: a review, an analysis and some empirical lessons. *Environmental Conservation* 38(3):275–287.

- Spangenberg, J. H., C. von Haaren, and J. Settele. 2014. The ecosystem service cascade: Further developing the metaphor. Integrating societal processes to accommodate social processes and planning, and the case of bioenergy. *Ecological Economics* 104:22–32.
- Star, S. L., and J. R. Griesemer. 1989. Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907–39. *Social Studies of Science* 19(3):387–420.
- Steffen, W., W. Broadgate, L. Deutsch, O. Gaffney, and C. Ludwig. 2015a. The trajectory of the Anthropocene : The Great Acceleration. *The Anthropocene Review*:1–18.
- Steffen, W., K. Richardson, J. Rockström, E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, R. Stephen, W. De Vries, C. A. De Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, and M. Linn. 2015b. Planetary boundaries : Guiding human development on a changing planet. *Science*(January).
- Stemler, S. 2001. An Overview of Content Analysis. *Practical Assessment, Research & Evaluation* 7(17).
- Steneck, R. S., T. P. Hughes, J. E. Cinner, W. N. Adger, S. N. Arnold, F. Berkes, S. a Boudreau, K. Brown, C. Folke, L. Gunderson, P. Olsson, M. Scheffer, E. Stephenson, B. Walker, J. Wilson, and B. Worm. 2011. Creation of a gilded trap by the high economic value of the Maine lobster fishery. *Conservation biology : the journal of the Society for Conservation Biology* 25(5):904–12.
- Stern, P. C. 2000. Psychology and the science of human-environment interactions. *American Psychologist* 55:523–530.
- Stern, P. C. 2005. Deliberative Methods for Understanding Environmental Systems. *BioScience* 55(11):976.
- Stevenson, T. C., and B. N. Tissot. 2014. Current trends in the analysis of co-management arrangements in coral reef ecosystems: A social-ecological systems perspective. *Current Opinion in Environmental Sustainability* 7.
- Stewart-Oaten, A., W. W. Murdoch, and K. R. Parker. 1986. Environmental impact assessment: "pseudoreplication" in time? *Ecology* 67:929–940.
- Stojanovic, T., H. M. Mcnae, P. Tett, T. W. Potts, J. Reis, H. D. Smith, and I. Dillingham. 2016. The " social " aspect of social-ecological systems : a critique of analytical frameworks and findings from a multisite study of coastal sustainability. *Ecology & Society* 21(3).
- Sutinen, J. G. 1999. What works well and why: evidence from fisheries-management experiences in OECD countries. *ICES Journal of Marine Science* 56:1051–1058.
- Swann, L. 1992. A Basic Overview of Aquaculture. *Technical Bulletin Series # 102 Funding*(August):1–10.
- Swim, J., S. Clayton, T. Doherty, R. Gifford, G. Howard, J. Reser, P. Stern, and E. Weber. 2009. *Psychology and global climate change: addressing a multi-faceted phenomenon and set of challenges*. American Psychological Association, Washington D.C.
- Tàbara, J. D., and I. Chabay. 2013. Coupling Human Information and Knowledge Systems with

Part 4: Synthesis and conclusions

- social–ecological systems change: Reframing research, education, and policy for sustainability. *Environmental Science & Policy* 28:71–81.
- Taggart-Hodge, T. D., and M. Schoon. 2016. The challenges and opportunities of transboundary cooperation through the lens of the east carpathians biosphere reserve. *Ecology and Society* 21(4).
- Talley, J. L., J. Schneider, and E. Lindquist. 2016. A simplified approach to stakeholder engagement in natural resource management : the Five-Feature Framework. *Ecology and Society* 21(4).
- Talwar, S., A. Wiek, and J. Robinson. 2011. User engagement in sustainability research. *Science and Public Policy* 38(June):379–390.
- Tam, C.-L. 2015. Timing exclusion and communicating time: A spatial analysis of participation failure in an Indonesian MPA. *Marine Policy* 54:122–129.
- Tang, S. Y. 1992. *Institutions and collective action: Self-governance in irrigation*. ICS press.
- Tebet, G., M. Trimble, and R. Pereira. 2018. Using Ostrom’s principles to assess institutional dynamics of conservation : Lessons from a marine protected area in Brazil. *Marine Policy* 88(August 2017):174–181.
- TEEB. 2010. *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*. (P. Kumar, editor). Earthscan, London and Washington.
- Teisserenc, M. J. S. 2014. Atores não governamentais, relações, representações e desafios do desenvolvimento sustentável (na Amazônia brasileira). in N. Esterçi, H. A. Sant’ana-Júnior, and M. J. S. Teisserenc, editors. *Territórios socioambientais em construção na Amazônia brasileira*. HIFE (Sociologia & Antropologia), Rio de Janeiro.
- Tengö, M., E. S. Brondizio, T. Elmqvist, P. Malmer, and M. Spierenburg. 2014. Connecting diverse knowledge systems for enhanced ecosystem governance: The multiple evidence base approach. *Ambio* 43(5):579–591.
- The White House. 2015. Incorporating Natural Infrastructure and Ecosystem Services in Federal Decision-Making. <https://www.whitehouse.gov/blog/2015/10/07/incorporating-natural-infrastructure-and-ecosystem-services-federal-decision-making>.
- Thiel, A., M. E. Adamseged, and C. Baake. 2015. Evaluating an instrument for institutional crafting: How Ostrom’s social-ecological systems framework is applied. *Environmental Science and Policy* 53.
- Thies-Albrecht, O. 2016. Spatial and Temporal Dispersal of the *U. cordatus* crab fishery in mangroves near Bragança, Northern Brazil: Fishers as optimal foragers and resulting management applications. University of Bremen, Germany.
- Le Tourneau, F.-M., and B. Beaufort. 2017. Exploring the boundaries between individual and collective land use management in a CPR system : the PAE Chico Mendes (Acre , Brazil). *International Journal of the Commons* 11(1):1–27.
- Trimble, M., and F. Berkes. 2015. Towards adaptive co-management of small-scale fisheries in Uruguay and Brazil: lessons from using Ostrom’s design principles. *Maritime Studies* 14(1).

- Troell, M., R. L. Naylor, M. Metian, M. Beveridge, P. H. Tyedmers, C. Folke, K. J. Arrow, S. Barrett, A.-S. Crépin, P. R. Ehrlich, Å. Gren, N. Kautsky, S. a. Levin, K. Nyborg, H. Österblom, S. Polasky, M. Scheffer, B. H. Walker, T. Xepapadeas, and A. de Zeeuw. 2014. Does aquaculture add resilience to the global food system? *Proceedings of the National Academy of Sciences* 111(37):13257–13263.
- Trumbo, J. 1999. Visual Literacy and Science Communication. *Science Communication* 20(4):409–425.
- Turnhout, E., C. Waterton, K. Neves, and M. Buizer. 2013. Rethinking biodiversity: from goods and services to “living with.” *Conservation Letters* 6(3):154–161.
- Underdal, A. 2010. Complexity and challenges of long-term environmental governance. *Global Environmental Change* 20(3):386–393.
- United Nations. 2012. *Back to our Common Future: Sustainable Development in the 21st Century (SD21) project. Back to our Common Future: Sustainable Development in the 21st Century (SD21) project.*
- US NRC. 2008. *Public Participation in Environmental Assessment and Decision Making.* Washington D.C.
- Vadjunec, J. M., and D. Rocheleau. 2009. Beyond forest cover: Land use and biodiversity in rubber trail forests of the chico mendes extractive reserve. *Ecology and Society* 14(2).
- Vaske, J. J., and M. P. Donnelly. 1999. A value-attitude-behavior model predicting wildland preservation voting intentions. *Society and Natural Resources.*
- Vedeld, T. 2000. Village politics: Heterogeneity, leadership and collective action. *Journal of Development Studies* 36(5):105–134.
- Villamayor-Tomas, S., A. Thiel, S. Villamayor-Tomas, F. D. Fleischman, I. P. Ibarra, and F. van Laerhoven. 2014. From Sandoz to Salmon: Conceptualizing resource and institutional dynamics in the Rhine watershed through the SES framework. *International Journal of the Commons* 8(2).
- Vogt, J. M., G. B. Epstein, S. K. Mincey, B. C. Fischer, and P. Mccord. 2015. Putting the “ E ” in SES : unpacking the ecology in the Ostrom social-ecological system framework. *Ecology and Society* 20(1).
- Voinov, A., and E. J. B. Gaddis. 2008. Lessons for successful participatory watershed modeling: A perspective from modeling practitioners. *Ecological Modelling* 216:197–207.
- Wade, R. 1994. *Village Republics: Economic Conditions for Collective Action in South India.* ICS Press, Oakland.
- Walker, B., and D. Salt. 2006. *Resilience thinking: sustaining ecosystems and people in a changing world.* Island Press, Washington, Covelo, London.
- Wang, M., and M. Lu. 2015. Tilapia polyculture: a global review. *Aquaculture Research* 47(8):1–12.
- Wanyonyi, I. N., A. Wamukota, S. Mesaki, A. T. Guissamulo, and J. Ochiewo. 2016. Artisanal

Part 4: Synthesis and conclusions

- fisher migration patterns in coastal East Africa. *Ocean and Coastal Management* 119:93–108.
- Weber de Morais, G. 2016. Governance of Marine Protected Areas in Costa Rica: stability and change of institutions. Jacobs University.
- Weber de Morais, G., A. Schlüter, and M. Verweij. 2015. Can institutional change theories contribute to the understanding of marine protected areas? *Global Environmental Change* 31:154–162.
- White, A. T., P. Christie, H. D’Agnes, K. Lowry, and N. Milne. 2005. Designing ICM projects for sustainability: Lessons from the Philippines and Indonesia. *Ocean and Coastal Management* 48(3-6 SPEC. ISS.):271–296.
- Whitney, C. K., N. J. Bennett, N. C. Ban, E. H. Allison, D. Armitage, J. L. Blythe, and M. Jenn. 2017. Adaptive capacity: from assessment to action in coastal social-ecological systems. *Ecology and Society* 22(2).
- Wiek, A., J. Harlow, R. Melnick, S. van der Leeuw, K. Fukushi, K. Takeuchi, F. Farioli, F. Yamba, A. Blake, C. Geiger, and R. Kutter. 2014. Sustainability science in action: a review of the state of the field through case studies on disaster recovery, bioenergy, and precautionary purchasing. *Sustainability Science*.
- Wiek, A., and D. Iwaniec. 2013. Quality criteria for visions and visioning in sustainability science. *Sustainability Science* 9(4):497–512.
- Wiek, A., B. Ness, P. Schweizer-Ries, F. S. Brand, and F. Farioli. 2012. From complex systems analysis to transformational change: a comparative appraisal of sustainability science projects. *Sustainability Science* 7(S1):5–24.
- Wilcox, C., E. Van Sebille, and B. D. Hardesty. 2015. Threat of plastic pollution to seabirds is global, pervasive, and increasing. *Proceedings of the National Academy of Sciences of the United States of America* 112(38):11899–11904.
- Williams, K. W., and H.-S. Tai. 2016. A multi-tier social-ecological system analysis of protected areas co-management in Belize. *Sustainability (Switzerland)* 8(2).
- Williams, S. L., N. Janetski, J. Abbott, S. Blankenhorn, B. Cheng, R. E. Crafton, S. O. Hameed, S. Rapi, and D. Trockel. 2014. Ornamental Marine Species Culture in the Coral Triangle: Seahorse Demonstration Project in the Spermonde Islands, Sulawesi, Indonesia. *Environmental Management* 54(6):1342–1355.
- Wilson, K. A., and E. A. Law. 2016. How to Avoid Underselling Biodiversity with Ecosystem Services: A Response to Silvertown. *Trends in Ecology & Evolution* xx(2014):2014–2015.
- Winkler, K. J., and K. A. Nicholas. 2016. More than wine : Cultural ecosystem services in vineyard landscapes in England and California. *Ecological Economics* 124:86–98.
- Wolff, M. 2015. From sea sharing to sea sparing - Is there a paradigm shift in ocean management? *Ocean and Coastal Management* 116:58–63.
- Wollenberg, E., L. Merino, A. Agrawal, and E. Ostrom. 2007. Fourteen years of monitoring community-managed forests: learning from IFRI’s experience. *International Forestry*

Part 4: Synthesis and conclusions

Review 9(2):670–684.

Wong-Parodi, G., and B. H. Strauss. 2014. Team science for science communication. *Proceedings of the National Academy of Sciences* 111:13658–13663.

Woodroffe, C. D., K. Rogers, K. L. McKee, C. E. Lovelock, I. A. Mendelssohn, and N. Saintilan. 2016. Mangrove Sedimentation and Response to Relative Sea-Level Rise. *Annual Review of Marine Science* 8(1):243–266.

World Bank. 2013. *Fish to 2030: Prospects for fisheries and aquaculture. Agriculture and environmental services discussion paper.*

World Bank. 2015. World Bank lending groups. <http://data.worldbank.org/about/country-and-lending-groups>.

World Bank. 2016. World Bank: Indonesia. <https://data.worldbank.org/country/indonesia>.

Worm, B., E. B. Barbier, N. Beaumont, J. E. Duffy, C. Folke, B. S. Halpern, J. B. C. Jackson, H. K. Lotze, F. Micheli, S. R. Palumbi, E. Sala, K. a Selkoe, J. J. Stachowicz, and R. Watson. 2006. Impacts of biodiversity loss on ocean ecosystem services. *Science (New York, N.Y.)* 314(5800):787–90.

Worm, B., R. Hilborn, J. K. Baum, T. A. Branch, J. S. Collie, C. Costello, M. J. Fogarty, E. A. Fulton, J. A. Hutchings, S. Jennings, O. P. Jensen, H. K. Lotze, P. M. Mace, T. R. McClanahan, C. Minto, S. R. Palumbi, A. M. Parma, D. Ricard, A. A. Rosenberg, R. Watson, and D. Zeller. 2009. Rebuilding Global Fisheries. *Science* 325(5940):578–585.

Yandle, T., D. S. Noonan, and B. Gazley. 2016. Philanthropic Support of National Parks: Analysis Using the Social-Ecological Systems Framework. *Nonprofit and Voluntary Sector Quarterly* 45.

Ye, Q. 2014. Building resilient power grids from integrated risk governance perspective: A lesson learned from china's 2008 Ice-Snow Storm disaster. *European Physical Journal: Special Topics* 223(12).

Yeakel, K. L., A. J. Andersson, N. R. Bates, T. J. Noyes, A. Collins, and R. Garley. 2015. Shifts in coral reef biogeochemistry and resulting acidification linked to offshore productivity. *Proceedings of the National Academy of Sciences* 112:14512–14517.

Yin, R., T. Liu, S. Yao, and M. Zhao. 2013. Designing and implementing payments for ecosystem services programs: Lessons learned from China's cropland restoration experience. *Forest Policy and Economics* 35.

Zscheischler, J., and S. Rogga. 2015. Transdisciplinarity in land use science – A review of concepts, empirical findings and current practices. *Futures* 65:28–44.

Zurba, M., and M. Trimble. 2014. Youth as the inheritors of collaboration: Crises and factors that influence participation of the next generation in natural resource management. *Environmental Science and Policy* 42:78–87.

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Appendix A. Carbon emissions from flights for the RECODE project.

Person	Country	Purpose	From	Via	Via	To	Emissions (~Tons CO ₂ e)* https://www.carbonfootprint.com/
Stefan	Indonesia (Lombok)	Field work	Frankfurt	Dubai	--	Lombok	1.83
Paula	Indonesia (Lombok)	Field work	Bremen	Amsterdam	Jakarta	Lombok	1.83
Achim	Indonesia (Lombok)	Field work	Bremen	Jakarta	--	Lombok	1.83
Stefan	Brazil	Field work	Dusseldorf	Sau Paulo	--	Belem	1.35
Sofia	Brazil	Field work	Dusseldorf	Sau Paulo	--	Belem	1.35
Stefan	Costa Rica	Field work	Bremen	Amsterdam	Panama City	San Jose	1.5
Anne	Costa Rica	Field work	Bremen	Amsterdam	Panama City	San Jose	1.5
Vignesh	Costa Rica	Field work	Bremen	Amsterdam	Panama City	San Jose	1.5
Achim	Costa Rica	Field work	Bremen	Amsterdam	Panama City	San Jose	1.5
Isis	Germany	Study visit	San Jose	Frankfurt	--	Bremen	1.5
Stefan	Canada	IASC conference	Bremen	Amsterdam	Calgary	Edmonton	1.1
Stefan	Norway	Winter school	Hamburg	Stockholm	--	Bodo	0.3
Stefan	USA	SESYNC workshop	Dusseldorf	--	--	Baltimore	1
Stefan	Tenerife	EU Cost workshop	Dusseldorf	Madrid	--	Tenerife	0.44
Stefan	Sweden	Resilience conference	Bonn	--	--	Copenhagen	0.09
						Total	18.62