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Missing ecology: integrating ecological perspectives with the social-ecological system framework

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Abstract: The social-ecological systems framework was designed to provide a common research tool for interdisciplinary investigations of social-ecological systems. However, its origin in institutional studies of the commons belies its interdisciplinary ambitions and highlights its relatively limited attention to ecology and natural scientific knowledge. This paper considers the biophysical components of the framework and its epistemological foundations as it relates to the incorporation of knowledge from the natural sciences. It finds that the mixture of inductive and deductive reasoning associated with socially-oriented investigations of these systems is lacking on the ecological side, which relies upon induction alone. As a result the paper proposes the addition of a seventh core sub-system to the social-ecological systems framework, ecological rules, which would allow scholars to explicitly incorporate knowledge from the natural sciences for deductive reasoning. The paper shows, through an instructive case study, how the addition of ecological rules can provide a more nuanced description of the factors that contribute to outcomes in social-ecological systems.

Keywords: Commons, ecology, social-ecological systems, sustainability

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1. Introduction

The social-ecological system (SES) framework is the product of many years of accumulated knowledge that incorporate the efforts of scholars working across disciplinary boundaries. Its ambitious aim is to provide a "common classificatory framework . . . (that can) facilitate multidisciplinary efforts toward a better understanding of complex SESs" (Ostrom 2009, 420). Whereas previous work showed that changes to a single variable, namely face-to-face communication, could alter outcomes in controlled laboratory environments (Ostrom et al. 1994), the next generation of commons research must address the challenge first issued by Agrawal (2001), which asks how combinations of social and ecological variables jointly affect outcomes in complex settings. The SES framework is designed to answer these types of questions by adopting a diagnostic approach that is built into its nested, partially decomposable structure (Ostrom 2007a; Ostrom and Cox 2010; Poteete et al. 2010). While the framework appears to provide a strong foundation to identify the social and institutional drivers of SES outcomes, it is unclear whether the framework is equally robust when it comes to relating biophysical characteristics and processes to ecological outcomes.

This paper explores the SES framework as it relates to the study of the biophysical or ecological components of the framework, and the extent to which it integrates knowledge from the natural sciences. It should be noted at this point that the purpose of the SES framework and this paper is not to achieve perfect congruence with ecological approaches to the study of social-ecological systems (SESs). Rather, it aims to manage the trade-offs inherent in any interdisciplinary endeavor in such a way that ecologists and social scientists can begin to meaningfully discuss social norms and property rights alongside forest succession and trophic cascades. With this in mind, the remainder of the paper is structured in the following way. Section 2 begins by tracing the development of the SES framework from its origins in the institutional analysis and development (IAD) framework. It then draws attention to the action situation as the deductive core of the framework and describes how this development has allowed scholars to link knowledge across multiple methods of inquiry. Applications of the SES framework are then considered to explore their use of the biophysical components of the framework, as well as the ways in which these attributes are tied to SES outcomes. Section 3 presents an adaptation to the framework that allows for better integration with the natural sciences that is then applied to the ecological dimension of a well-understood instructive case study – the degradation and subsequent recovery of Lake Washington. Finally, the paper concludes with a brief discussion about the use and limitations of the adapted framework.

2. Diagnosing social-ecological systems

Frameworks, theories, and models are the building blocks with which the academy develops, tests, and refines knowledge. A framework is the most abstract of the three composed of potentially relevant classes of variables and their general relationships to construct a metatheoretical language for diagnostic or prescriptive study of phenomena (Ostrom 2007b; Schlager 2007). Frameworks are used to organize study, place bounds on inquiry, and direct attention to certain attributes of the social and physical environment, but cannot in and of themselves predict or explain outcomes. Models, on the other hand, are highly formalized predictions or tests of the effects of a limited set of variables, while theories are constructed by integrating multiple models and identifying relationships among variables to predict (or explain) likely outcomes (Schlager 2007). In other words, a framework explains little other than identifying some attributes of a system as potentially influential, organizes them to advance systematic investigation and provides a common language with which to compare theories. Models answer questions about mechanisms that operate to produce outcomes under certain specific conditions, and theories answer questions about a larger universe of mechanisms that lead to outcomes under more variable conditions.

2.1. Frameworks for the study of social-ecological systems

The SES framework is one of many adaptations of the institutional analysis and development (IAD) framework developed in recent years (i.e. Anderies et al. 2004; Blomquist et al. 2010; Clement 2010) to advance the diagnostic capacity of scholarly investigations of SESs. Clement (2010) contends that the IAD framework, with its emphasis on collective action at the local level, fails to account for the role of power, history, and environmental discourses in shaping local policies and subsequent environmental outcomes. As such, the article proposes that the gaps between official policies and environmental outcomes can be explained by explicitly incorporating classes of variables that account for the large-scale politico-economic contexts that influence power relations, and discourses that shape environmental policies and social constructions of resource users (Benjaminsen et al. 2009). While the "politicised" framework makes an important contribution in linking institutional approaches to political ecology (Armitage 2007), it fails to resolve underlying ontological and epistemological differences, or recognize the dynamic and networked nature of action situations (McGinnis 2011b).

Another adaptation that is fully compatible with the IAD framework, and is often considered to be a precursor of the SES framework, is the robustness framework (Anderies et al. 2004). The robustness framework, as we are labeling it, is so-called because of its emphasis on the robustness of SESs. Robustness is generally defined as "the maintenance of some desired system characteristics despite fluctuations in the behavior of its component parts or its environment" (Carlson and Doyle 2002). It shares some similarities with resilience, although Anderies et al. (2004) argue that the two are distinct enough to warrant a preference for robustness as the primary, or most desirable, social-ecological outcome. The robustness framework defines an SES as consisting of four components: a resource, resource users who use said resource, public infrastructure, and public infrastructure providers. Unlike the SES framework, the robustness framework explicitly includes disturbances as an element in the framework, as one type of input into SESs and as an interaction between the components of an SES. The robustness framework has been applied to cases using mixed methods to suggest that institutional arrangements designed to cope with regular or expected disturbances may increase the vulnerability of groups to less frequent or novel shocks (Anderies 2006; Cifdaloz et al. 2010). However, like other frameworks designed for the study of SESs, the robustness framework has yet to achieve widespread adoption to constitute a consistent and systematic research program. Nonetheless given the likelihood of significant and widespread future disturbance due to climate change and the need for adaptive governance, the potential value of the robustness framework is immense.

2.2. Building knowledge with the SES framework

The IAD and SES frameworks are fairly unique among frameworks developed for the study of public policy in their explicit attempt to link knowledge across multiple methods of inquiry (Poteete et al. 2010). Whereas most frameworks seek to build knowledge mostly through inductive methods and case-based reasoning, the SESs' diagnostic approach embodies a mixed epistemology of case-based and rule-based reasoning that leverages the advantages while offsetting some of the weaknesses of each (Cox 2011). Case-based reasoning is associated with induction and methods such as regression, experiments, or comparative study. Rule-based reasoning, on the other hand, uses knowledge about the facts of a case (i.e. the social and biophysical context) to predict or explain outcomes on the basis of one or more rule statements (i.e. mechanisms) that link those facts to an outcome (Cox 2011). Rule statements, as mentioned previously, are often the product of inductive research, but can also emerge from formal models (Gordon 1954; Becker 1968) and other less formal, yet highly influential descriptive and deductive accounts of phenomena (Hardin 1968). Consideration of the works cited points to both the greatest strength of rule-based reasoning in clearly and concisely predicting or explaining outcomes and greatest weakness in that these explanations rely upon a simplified reality that often bears little resemblance to the one in which we live. Nonetheless, rule-based reasoning can greatly aid scholars in their attempts to study aspects of SES problems such as heterogeneous preferences (Ahn et al. 2003) and learning (Brock and Carpenter 2007), and enjoys a place of prominence in the SES framework's action situation.

The action situation is a critical feature of the SES framework that structures rule-based reasoning on the basis of social institutions in the form of rules, norms, and shared strategies (Crawford and Ostrom 2005; Ostrom 2005, 2011a; McGinnis 2011a). Figure 1 depicts the action situation at the center of the six tier-one components of the SES framework that interact to define the attributes of the situation. Figure 2 zooms in on this action situation to reveal the deductive core of the SES framework in the form of seven rules: boundary, position, choice, information, aggregation, scope, and payoff (Crawford and Ostrom 2005). The rules specify what actions must, must not, or may be taken given certain conditions,

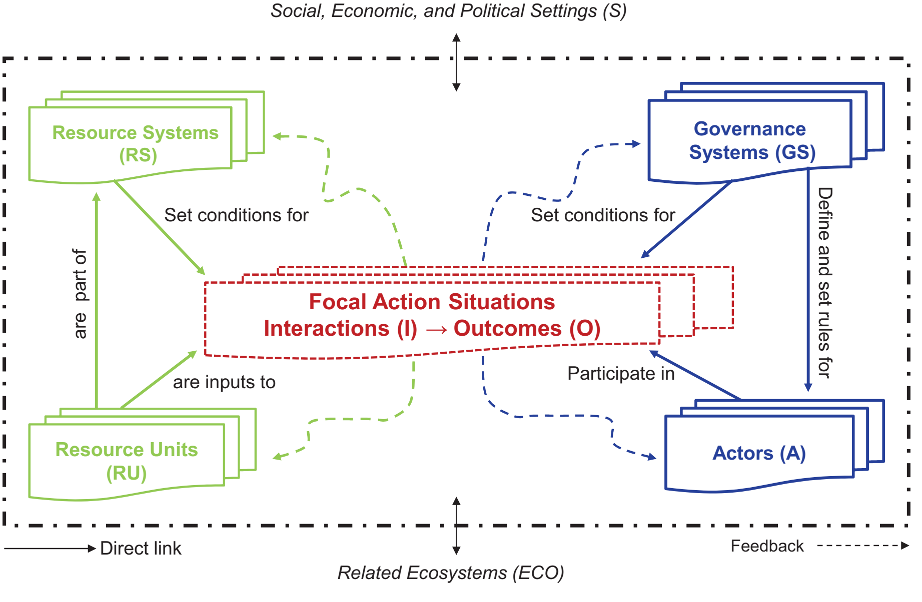

Figure 1: The action situation as the rule-based reasoning core of the SES framework (based on McGinnis and Ostrom forthcoming).

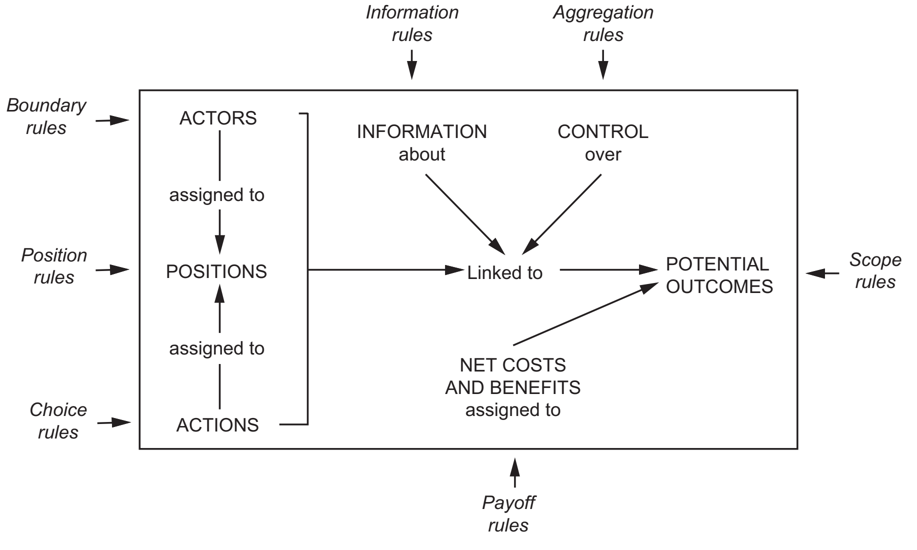

Figure 2: Social institutions for rule-based reasoning in the SES framework (adapted from Ostrom 2005, 189).

and therefore provide a level of structure to allow for rule-based reasoning. As an example, insights about the origin of social preferences allowed Ostrom and Cox (2010, 457) to apply rule-based reasoning and state that "with fewer actors . . . trust and reciprocity [is] more easily maintained." Thus, the action situation allows social scientists to apply rule-based reasoning based on many years of cumulative findings. The cumulative body of natural scientific knowledge is, however, formally absent from the SES framework, leaving the identification of biophysical causes of an outcome solely to case-based methods of reasoning.

2.3. Applications of the SES framework

The SES framework has been used sparingly as an analytical tool since its introduction in 2007, with several studies taking more of an instructive approach (Ostrom 2009; Ostrom and Cox 2010; Cox 2011; Basurto and Nenadovic 2012). Nevertheless, it has been applied to diverse settings including the study of forests (Fleischman et al. 2010), fisheries (Basurto and Ostrom 2009; Gutierrez et al. 2011; Cinner et al. 2012), water and irrigation (Madrigal et al. 2011; Ostrom 2011b), and even nature-based tourism (Blanco 2011). This section explores how these studies have approached causation when applying the framework, and their use of the biophysical components of the framework (i.e. RU and RS attributes in Table 1).

The reviewed studies include a variety of methodological approaches including both large and small-n, meta-analysis and field research, as well as quantitative

Table 1: Second-tier attributes in the SES framework, with the addition of a seventh core subsystem: ecological rules (ER) (adapted from McGinnis and Ostrom forthcoming)

<table>
<tr><td rowspan="9">Ecological rules (ER)
*ER1 Physical rules *ER2 Chemical rules *ER3 Biological rules</td><td colspan="2">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.</td></tr>
<tr><td>Resource Systems (RS)</td><td>Governance Systems (GS)</td></tr>
<tr><td>RS1 – Sector (e.g. water, forests, pasture, fish)
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</td><td>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</td></tr>
<tr><td>Resource Units (RU)</td><td>Actors (A)</td></tr>
<tr><td>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</td><td>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</td></tr>
<tr><td colspan="2">Action Situations: Interactions (I) ⟶ Outcomes (O)</td></tr>
<tr><td>Activities and Processes:</td><td>Outcome Criteria:</td></tr>
<tr><td>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</td><td>O1 – Social performance measures (e.g. efficiency, equity, accountability, sustainability)
O2 – Ecological performance measures (e.g. overharvested, resilience, biodiversity, sustainability)
O3 – Externalities to other SESs</td></tr>
<tr><td colspan="2">Related Ecosystems (ECO)
ECO1 – Climate patterns. ECO2 – Pollution patterns. ECO3 – Flows into and out of focal SES.</td></tr>
</table>

and comparative studies. The large-n quantitative studies (Gutierrez et al. 2011; Madrigal et al. 2011; Cinner et al. 2012) inherently use inductive case-based methods of reasoning to identify the causes of SES outcomes. Of the three studies, only one identifies the contribution of a biophysical attribute, while another presumably controls for biophysical variation through case selection. Blanco

(2011) applies case-based methods to identify common features of successful nature-based tourism initiatives using two existing meta-analyses. In it, she finds several biophysical correlates of success, including the geographical location of the resource system (RS9), quality of human-constructed facilities (RS4), and the non-consumptive value (RU4) of the surrounding landscape. Finally, the remaining three studies adopt mixed epistemologies, although they do so differently. Fleischman et al. (2010) apply case-based methods of reasoning to identify common features of successful responses to disturbance, and then compare those with variables associated with unsuccessful responses in five intentional forest communities in Indiana. Whereas biophysical factors are identified in relation to the cause of disturbances, none are cited as contributing to a successful response. Ostrom (2011b) begins with case-based reasoning in her reanalysis of an irrigation study from 1911 to identify characteristics of (relatively) successful governance systems in the Western Plains and then uses rule-based reasoning to relate those characteristics to different patterns of behavior. While the article emphasizes the social aspects of these systems, she also draws upon the initial study (Coman 1911) to suggest that some failures could be linked to particularly challenging soil and climate conditions. Basurto and Ostrom's (2009) study differs in that they begin with a deductive account of the incentive structure of resource users to enter collective-choice situations and create new operational rules. The resulting logic is then applied to three benthic fisheries where 13 characteristics of each SES are identified. Case-based reasoning was then used to find that, in addition to several social factors, smaller resource systems (RS3) and higher levels of predictability (RS7) were associated with successful self-organization. Overall, the applications of the framework demonstrate the use of multiple methods and epistemologies. Case-based reasoning tends to predominate in the literature, leaving rule-based reasoning to either guide research ex ante, or provide greater depth ex post.

The general absence of biophysical characteristics in the CPR literature (Agrawal 2003) appears to have continued in the SES framework. In the selected studies, biophysical attributes account for a maximum of about one-third of the total, while they are omitted entirely in others. Those that are reported also tend to be ones that have already received the most attention in the CPR literature, including: resource unit mobility (Schlager et al. 1994; Giordano 2003), resource system productivity (Wade 1994), clarity of resource system boundaries (Ostrom 1990; Cox et al. 2010), and size of the resource system (Wade 1994; Chhatre and Agrawal 2008). Furthermore, these variables are considered only as they relate to the action situation and subsequent human decisions, ignoring the potential contribution of biophysical processes. This point is made quite clearly in two studies related to benthic fisheries in Mexico. The first, discussed above, focuses on user incentives to engage in self-organization using the SES framework (Basurto and Ostrom 2009). The second, a simulated model of the same benthic fisheries, abandoned the framework to incorporate density-dependence and carrying capacity to their study of benthic sustainability (Basurto and Coleman 2010). As a result, they found that in some cases institutional weaknesses could be mitigated when found in a resource system with higher carrying capacities. This example provides a perfect illustration of the ecological shortcomings of the framework in its inability to incorporate simple and generally accepted ecological rules. While the authors could have attempted to integrate their model with the SES framework, their choice speaks to problems in incorporating ecological knowledge within the confines of the framework.

3. Integrating ecological knowledge with the SES framework

This section presents an adaptation to the SES framework that would allow for deductive ecological reasoning. It then applies the revised framework to an instructive case – the decline and recovery of Lake Washington.

The three primary branches of the natural sciences – namely physics, chemistry, and biology – have each accumulated a large body of knowledge that can help describe and identify critical features of the natural world that influence SES outcomes. Physics – with its emphasis on matter, motion, and energy – can be used to structure deductive models that inform our understanding of the greenhouse effect (Cox et al. 2000), light penetration in aquatic systems (Arhonditsis and Brett 2005), and human consumption of primary production from global fisheries (Pauly and Christensen 1995). Chemistry – with its focus on the properties and interactions of organic and inorganic matter – can point to important features of SESs that affect nutrient availability (Arhonditsis and Brett 2005), critical life processes such as photosynthesis and respiration (Hall 1979), and the bioaccumulation of toxins in aquatic food webs (Gobas 1993). Biology – as a study of living things at different levels of aggregation (i.e. individuals, populations, communities) – can also illuminate important features of resources and resource systems that may be overlooked in a case-based approach. For instance, the species composition of forest communities can be understood through biogeographic principles of dispersal that point to the limiting effects of climate and geographic barriers (Gaston 2009) or patterns of forest succession that alter resource system propertiesto facilitate or inhibit the establishment of secondary species (Connell and Slatyer 1977; Finegan 1984). Optimal foraging models can be used to deductively estimate the use of space by mobile species according to the distribution of resources in a landscape (Pyke et al. 1977). In a final example that incorporates more recent findings, natural selection can explain how the characteristics of resource-harvesting technologies and practices can influence the traits of wild populations by preferentially removing individuals based on their size, health, or other characteristic (Conover and Munch 2002; Darimont et al. 2009).

The laws, theories, and principles discussed above represent only a small fraction of natural scientific knowledge that could enhance the diagnostic capacity of the SES framework. But as of yet, there is no systematic way to incorporate such knowledge in the SES framework, belying somewhat its interdisciplinary ambitions. Thus, we propose the addition of a seventh core subsystem, "ecological rules" (abbreviated ER), in Table 1 to capture the laws, theories, and principles developed in the natural sciences. These are broadly broken down into the three dominant traditions: physics, chemistry, and biology.

The explicit inclusion of ecological rules in the SES framework serves multiple purposes. First, it creates an opportunity for rule-based reasoning on the basis of the cumulative knowledge of the natural sciences to enhance the diagnostic capacity of the framework. The study of the social aspects of CPRs has advanced considerably because scholars have been able to link deductive formal modeling to experiments and case studies (Poteete et al. 2010). In fact, Anderies (2002) argues that in the context of agent-based models, human beings and non-human resources can both be understood in a general sense as agents whose actions (or properties) are governed by rules. Thus it seems reasonable that the ecological side of the SES framework could benefit from a similar link. However, precautionary caveats lead to the second, and at least equally important, reason for explicitly incorporating ecological rules: identifying underlying assumptions. The addition of ecological rules as a seventh core subsystem of the SES framework forces scholars to explicitly identify the physical and ecological assumptions that underlie their ultimate conclusions. For instance, in a model that explores the interplay of social and ecological factors in an artisanal fishery, Bueno and Basurto (2009) rely upon a density-dependent survival rate (ER3, in the SES framework in Table 1) to conclude that incremental increases in harvesting levels (I1) can have major implications for the resilience of a resource stock (O2). While density-dependence is a fairly reasonable assumption and is clearly identified in this case, the conclusions hold if and only if this assumption holds. Thus, in addition to the ability to draw conclusions from a single case, the explicit identification of the ecological rule facilitates scholarly review, and would presumably allow for rapid reinterpretation of results in light of future ecological research.

3.1. The decline and recovery of Lake Washington

Lake Washington is a fairly large freshwater lake adjacent to the Seattle metropolitan area that covers approximately 88 square kilometers with an average depth of 33 m. Like many lakes in the 20th century, Lake Washington experienced a transformation from its natural oligotrophic state to a eutrophic state as a result of increased nutrient loading from domestic sewage (Edmondson et al. 1956). The lake first began to show evidence of this change in the mid-1950s when the traditional phytoplankton community was joined by a large population of "nuisance" cyanobacteria. At the time, the lake was receiving approximately 24,000 m^3 (6.3 million gallons) of treated sewage per day (Edmondson 1970). This number peaked in 1963 to around 75,000 m^3 (19.8 million gallons) per day and was accompanied by additional indicators of eutrophication, such as higher concentrations of phytoplankton, chlorophyll a, and a general decline in water transparency. However, by 1969, all sewage effluent was diverted to Puget Sound, a major inlet of the Pacific Ocean, and the indicators returned to pre-1955 levels in the matter of a few years (Edmondson and Lehman 1981).

The story of Lake Washington's decline and subsequent recovery appears to present a nearly ideal case of successful collective action in response to recognition of an environmental problem and its source. Ecologists working at the University of Washington and a subsection of public interests independently began to note concerns about the status of the lake and the potential relationship with sewage effluent (Edmondson 1991). It was not until these two groups united in 1956 that their concerns gained the attention of the general public and policymakers. In March of 1958, a public referendum was held that rejected a fairly ambitious, comprehensive, and expensive program of sewage diversion, watershed management, and other infrastructural adjustments. However, a revised, stripped-down proposal that focused almost exclusively on sewage diversion gained approval in September of that same year, ultimately leading to the recovery of the lake (Edmondson 1991).

Applying rule-based reasoning to the SES and emphasizing the social dimension, the combination of: (A7) scientific and local knowledge of the SES, (A2) socioeconomic attributes of actors, and (GS6) collective-choice rules that provided for public referenda led to (RS4) a diversion of human-constructed sewage facilities, and ultimately (O2) the ecological recovery of the lake. While this explanation seems to provide a structured and reasonable account for the changes that took place in Lake Washington, it fails to explain critical enabling conditions about the underlying ecology of the lake that contributed to the observed effect of sewage diversion. The following section takes a step back from the case of Lake Washington to briefly outline approximately 50 years of research on eutrophication in freshwater lakes, before returning to diagnose the ecological factors associated with Lake Washington's recovery.

3.1.1. Eutrophication of freshwater lakes

Lake eutrophication has been studied extensively by natural scientists seeking to understand the physical, chemical, and biological predictors of a water-quality problem that can lead to significant costs related to health, business, and environmental services (Carpenter et al. 1999; Dodds et al. 2008). A highly influential set of studies undertaken in what is now known as the Experimental Lakes Area of Northern Ontario provided compelling evidence that pointed to the dominant influence of phosphorus on eutrophication (Schindler 1974). It was found that in many cases the growth of phytoplankton is regulated from the bottom-up and is strongly correlated with the concentration of bioaccessible phosphorus (Edmondson 1970; Schindler 1974; Carpenter et al. 1999). While other studies have demonstrated relationships between eutrophication via nitrogen enrichment (Goldman 1988) or a trophic cascade response to a decline in piscivorous fish (Shapiro and Wright 1984), the conventional wisdom is that the productivity of most lakes is limited by phosphorus (Schindler 1977; Carpenter et al. 1999).

Thus, the remainder of this section will focus on phosphorus, the attributes and simplified mechanisms that govern its concentration in the water column and lead to the growth of phytoplankton.

In general, phosphorus enters the photic zone of the lake from either (1) external loading via rivers, runoff, atmospheric exchange, and human-constructed facilities or (2) internal loading of sedimentary phosphorus (Carpenter et al. 1999). External loading via rivers and runoff is largely influenced by land-use in the surrounding watershed with urbanization and agricultural uses tending to increase phosphorus loading (Schindler 2006). Sewage and wastewater is another external source of phosphorus inputs that was especially concentrated around the middle of the 20th century when phosphorus-based cleaning products were in heavy use (Schindler 2006). Thus, the first ecological rule that influences the likelihood of lake eutrophication can be understood through simple chemical mass-balance (ER2) equations that co-vary with system inputs.

Internal loading, on the other hand, is more complex and involves a number of potential physical, chemical, and biological processes. To begin, internal loading depends upon the phosphorus pool stored in lake sediments from past external loading (Søndergaard et al. 2003; Genkai-Kato and Carpenter 2005). The annual contribution to this pool can be roughly calculated as [inputs – outflow – Δ lakeP] (Edmondson and Lehman 1981), which highlights the importance of outflow and cumulative contributions to the pool when loading has persisted for an extended period of time. Once the pool has been established, it can be released back into the water column via a variety of pathways that include (1) wind-induced resuspension (Jones and Welch 1990), (2) temperature-mediated chemical and biological processes (Jensen and Andersen 1992), (3) bioturbation by benthic invertebrates or fish (Fukuhara and Sakamoto 1987), (4) reduction of iron ions under anoxic conditions that release bound P (Carpenter et al. 1999; Penn et al. 2000), (5) iron-hydroxides that form under high pH and limit phosphorus binding (Koski-Vähälä and Hartikainen 2001), and (6) the ratio of iron to phosphorus in the sediments (Søndergaard et al. 2003). Many years of research on eutrophication in lakes has led to the general conclusion that deep, cold lakes with short water residence times (or conversely rapid flushing) are less susceptible to eutrophication via internal loading (Dillon 1975; Carpenter et al. 1995, 1999).

Deep lakes are less susceptible to internally driven eutrophication for a variety of reasons. First of all, as depth increases, phosphorus stored in the sediments is less likely to be resuspended by wind events (Jones and Welch 1990). This is governed by the transfer of energy, a concept generally associated with physics, from the wind to the water column leading to physical disturbance (ER1) at the sedimentary interface which varies with the depth of the water column. Depth can also influence the trophic status of a lake by limiting the relative size of the photic zone where phytoplankton growth can occur, acting as a biological limit (ER3) on populations. On the other hand, depth is also associated with larger hypolimnetic volumes which dilutes (ER2) phosphorus released from the sediments before mixing with the phytoplankton in the photic zone (Genkai-Kato and Carpenter

2005). Higher temperatures are also positively correlated with eutrophication via a variety of temperature-mediated (ER2) chemical and biological phosphorus release processes (Gomez et al. 1998; Søndergaard et al. 2003). The most common process involves chemical release of phosphorus via the reduction of iron ions under anoxic conditions (Søndergaard et al. 2003). Finally, flushing – the rate at which water passes through a water body – generally forms an inverse relationship with the likelihood of lake eutrophication (Vollenweider 1975). As flushing rates (ER1) increase the fraction of phosphorus available for phytoplankton growth or stored in the sediments for possible future internal loading tends to decline as larger quantities flow out of the focal lake system.

3.1.2. Applying the revised SES framework to Lake Washington

Table 2 applies the SES framework to the ecology of Lake Washington and compares the relative diagnostic capacities of the existing case-based approach with the revised framework that allows for rule-based reasoning. The cases are drawn from a longitudinal study of Lake Washington reported in Edmondson and Lehman (1981) prior to and after sewage diversion. The attributes are subdivided into three main concepts: (1) the outcomes as captured by the trophic status of the lake and attributes of the system generally associated with (2) external and (3) internal loading. The system attributes are presented as ecologists would generally describe them and assigned to a tier-two component of the SES framework. While there was a good fit for many of these attributes, others lacked a clear match and were ultimately placed where the conceptual tension appeared smallest. For instance, temperature was assigned to productivity (RS5) as variation in temperature is generally expected to correspond to the productivity of a system, although this clearly makes assumptions regarding its effect. Alternatives such as climate patterns (ECO1) were rejected as in this case temperature is an attribute of the focal lake system. Flows between systems (ECO3) are used to account for the movement of phosphorus to and from the focal lake ecosystem, and clearly defines sediment dynamics as a separate, but related SES. Table 2 also identifies whether a particular attribute would be associated with the recovery of Lake Washington using case-based (*) and/or rule-based (**) reasoning, and if applicable briefly describes how the rule links the attribute to the recovery of Lake Washington.

The trophic status of Lake Washington (O2) improved significantly from 1962 to 1970, and ultimately recovered entirely around 1973 (Edmondson and Lehman 1981). The only independent variable to exhibit significant variation across the two time periods is the amount of point source phosphorus inputs from sewage. Thus the case-based approach successfully identifies what is generally accepted as the proximal cause of recovery – the diversion of this sewage from the lake. However, as Carpenter et al. (1999) point out, there were additional features of the lake that made it particularly likely to recover once sewage inputs were eliminated that can be identified via rule-based reasoning.

Table 2: Application of the SES framework to Lake Washington

Concept	Attribute	Prediversion (1962)	Postdiversion (1970)	Ecological Rule(s)	Explanation of effect
Outcome	O2 Trophic status	Eutrophic	Mesotrophic	–	–
External loading	RS4 Point source nutrient inputs	High	Absent*/**	ER2 Mass balance	Elimination of point source inputs reduces quantity of phosphorus in the lake
	ECO3 River and runoff inputs	Moderate	Moderate	–	–
	ECO3 Atmospheric inputs	Low	Low	–	–
Internal loading	A3 Duration of loading	Short	Short**	ER2 Mass balance	Short period of enrichment reduces the quantity of phosphorus available for internal loading
	RS5 Temperature	Cold	Cold**	ER2 Temperature mediation	Cold temperatures slow sedimentary phosphorus release processes
	RS3 Depth of lake	Deep	Deep**	ER1 Physical mixing	Increased depth insulates sedimentary phosphorus from wind-induced physical release
				ER2 Dilution	Depth increases the relative volume of the hypolimnion which dilutes phosphorus released from sediments
				ER3 Limiting factor: size of photic zone	Depth reduces the volume of the lake in which phytoplankton growth can occur
	ECO3 Outflow	High	High**	ER1 Flushing	High flushing rates transport phosphorus from the lake
	ECO3 Sedimentation	High	High	–	–

Note: Measurement of attributes is based on data presented in Edmondson and Lehman (1981). *indicates case-based reasoning, **indicates rule-based reasoning.

These additional factors include its depth (RS3) and temperature (RS5), the rate at which water flows (ECO3) out of the focal lake system, and the relatively short period of external nutrient enrichment (A3). Collectively these variables act to limit phytoplankton growth via a variety of pathways that mostly relate to the concentration of phosphorus in the photic zone of the lake. First, rapid flushing (ER1) limits phytoplankton growth by transporting water and associated nutrients such as phosphorus out of the lake system. Next the quantity of phosphorus (ER2) stored in the lake's sediments and thus available for potential release via internal loading is limited by the relatively short period of nutrient enrichment and the aforementioned outflows. The depth (RS5) of the lake serves to insulate phosphorus stored in sediments from physical, mostly wind-related release processes (ER1), while also reducing phosphorus concentrations via hypolimnetic dilution (ER2), and limiting the relative volume of the photic zone (ER3) in which phytoplankton growth can occur. Finally, cold temperatures slow the rate (ER2) at which a wide range of mostly detrimental chemical and biological processes take place. Overall, as can be seen, application of case-based reasoning identifies only one of five important ecological attributes of the SES that led to the recovery of Lake Washington, while ecological rules developed from prior research provide a more nuanced account of the recovery of Lake Washington.

The SES framework, as introduced by Ostrom (2007) is a diagnostic tool that aims to confront complexity by building cumulative knowledge concerning the effects of SES attributes, particularly those related to governance, under different social-ecological conditions. Most instructive applications have focused on diagnosis through decomposition wherein knowledge accumulates by integrating findings regarding SES attributes, and sub-attributes thereof (Ostrom and Cox 2010). However, the diagnosis of complex SESs is also confronted by a multiple-variable problem wherein a wide range of variables and their interactions jointly influence SES outcomes (Agrawal 2003). The addition of ecological rules to the framework enhances its ability to diagnose a larger set of attributes associated with the outcome of an environmental problem, in this case eutrophication. Given well-known problems of method in the study of SESs (Agrawal 2003; Young et al. 2006), ecological rules may provide an additional tool with which to cope with complexity. Ecological rules may also advance diagnosis by directing attention to relevant ecological attributes of SESs or simply place bounds on the expected external validity of socially-oriented findings (i.e. within the context of deep, cold lakes with high outflow).

Finally, with respect to decomposition and the nomenclature of SES attributes the preceding analysis of Lake Washington organized all attributes of the SES, and relevant ecological rules at the second tier of the SES framework and did not make further use of its nested structure. This reflects the general absence of clear instructions for decomposition of SES tier-two attributes or even operational definitions of these same attributes. Thus, all are assigned to the relevant tier-two attribute of the framework, while ecological rules reflect their general level of association with physics (ER1), chemistry (ER2), and biology (ER3). As should be clear from the descriptions, there is a non-trivial measure of overlap between the branches of natural scientific inquiry and it appears much work remains to be done to develop the overall nested conceptual map that is a cornerstone of the SES framework (Ostrom and Cox 2010). Thus, as this process unfolds it may be found that some of the attributes or ecological rules identified in this research are better understood as sub-attributes in the broader universe of SES cases.

4. Conclusions

The SES framework is a testament to the long and dedicated career of Elinor Ostrom and promises to provide the foundation for many more years of research. Nevertheless, its origin in institutional analysis underscores its attention to the social components and relative lack thereof to important ecological characteristics of SESs. Given that studies of human behavior in the commons were able to advance quite quickly by adopting a multiple-methods approach (Poteete et al. 2010), it seems likely that studies of SESs would benefit by incorporating opportunities for ecological deduction. The addition of a seventh core subsystem, which we have attempted to capture with the term "ecological rules," begins to provide a systematic way to capture and apply this type of knowledge and diagnose SESs in a more complete manner. For instance, reliance on induction alone would have overlooked several important variables that contributed to the recovery of Lake Washington, and asks scholars to essentially reinvent the wheel despite the existence of a well-established body of knowledge from more than 50 years of research. Lake Washington recovered from a short period of heavy external loading as a result of sewage diversion and because it was simply the type of lake that would respond to such a change (Carpenter et al. 1999). Other lakes, by virtue of one or more unfavorable ecological characteristics, would have failed to recover from the elimination of sewage inputs, even if they managed to successfully organize, as a result of their particular ecological conditions. Nevertheless, there are dangers with an overreliance on deduction when they become pathologies that undermine the very outcomes they are meant to support (Holling and Meffe 1996). The use of ecological rules can, however, aid scholars by adding depth to their studies, identify important ecological features, and avoid attributing success or failure to the social aspects of a set of cases when there are theoretically relevant ecological differences.

To conclude, we have argued that natural science warrants an equal place alongside institutional analysis in this common framework, and that its addition may help overcome some of the worst pathologies by forcing scholars to explicitly acknowledge the assumptions that underlie their findings. But the growing field of sustainability science is inexorably problem-driven and many of the important questions it asks are rooted in questions of individual and group-level choices, learning, cooperation, and interorganizational arrangements that have little to do with underlying ecological processes. Thus, the modified framework presented in this paper should be seen as a tool explicitly designed to confront questions of sustainability that are rooted in biophysical processes and their interaction with the choices that emerge from social processes. With additional refinements and hopefully contributions from natural scientists, the framework may finally move us a step closer to overcoming the "dialog of the deaf" (Agrawal and Ostrom 2006) in the pursuit of social and ecological sustainability.

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