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COMPLEXITY AND SUSTAINABILITY OF SOCIAL-ECOLOGICAL SYSTEMS

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The contemporary world faces the destruction of many core resources, including ocean fisheries, biodiverse ecosystems, and tropical forests, as well as the threat of major climate change. Analyzing the sustainability of social-ecological systems (SESs) is a challenging task because they are complex, adaptive systems (Norberg and Cumming 2008; Berkes and Folke 1998; Gunderson and Holling 2002). Simon describes complex systems as being "arranged in levels, the elements at each lower level being subdivisions of the elements at the level above. Molecules are composed of atoms, atoms of electrons and nuclei, electrons and nuclei of elementary particles. Multi-celled organisms are composed of organs, organs of tissues, tissues of cells" (2000:753).

Thus, what is considered to be a *whole* system at one level is usually one part of a system at another level. Koestler's term for such subassemblies is *holons*, which "may be applied to any stable sub-whole in an organismic or social hierarchy [that] displays rule-governed behaviour and/or structural Gestalt constancy" (1973:291). Koestler urged scientists not to reduce systems to a simple sum of their elementary parts because characteristics of a higher level emerge from the particular combination of variables at a lower level. On the other hand, a holon can be "dissected" and represented as a tree where the holons are nodes of the tree, and the lines connecting them "the channels of communication, control, or transportation, as the case may be" (1973:291).

A core challenge facing scientists who want to understand why some SESs are sustainable over time and others collapse is how to dissect complex systems into composite holons at different spatial and temporal scales. Dissecting a complex whole requires knowledge about how subsystems are related (Levin 1992). Disciplines that study relevant parts of an SES, however, use different frameworks, languages, and theories to analyze their parts of the complex whole. Development of a common framework and language to solve this "Tower of Babel" problem is an essential, long-term effort toward developing better understanding of complex SESs.

In 2007, with the help of several SES scholars, I developed the initial, multitier framework for analyzing SESs shown in Figure 1 (Ostrom 2007). The framework can be thought of as a holon that is dissected into six first-tier subsystems that represent focal SESs to be analyzed. Examples of focal SESs include the lakes in northern Wisconsin (Brock and Carpenter 2007), forests around the world (Chhatre and Agrawal 2008), and ocean fisheries (Clark 2006). Each focal SES can be further dissected into tiers to study various aspects of the system. An initial second tier of the framework is presented in Table 1. Which second-tier, third-tier, fourth-tier, or deeper variables are relevant for analysis depends on the particular questions under study.

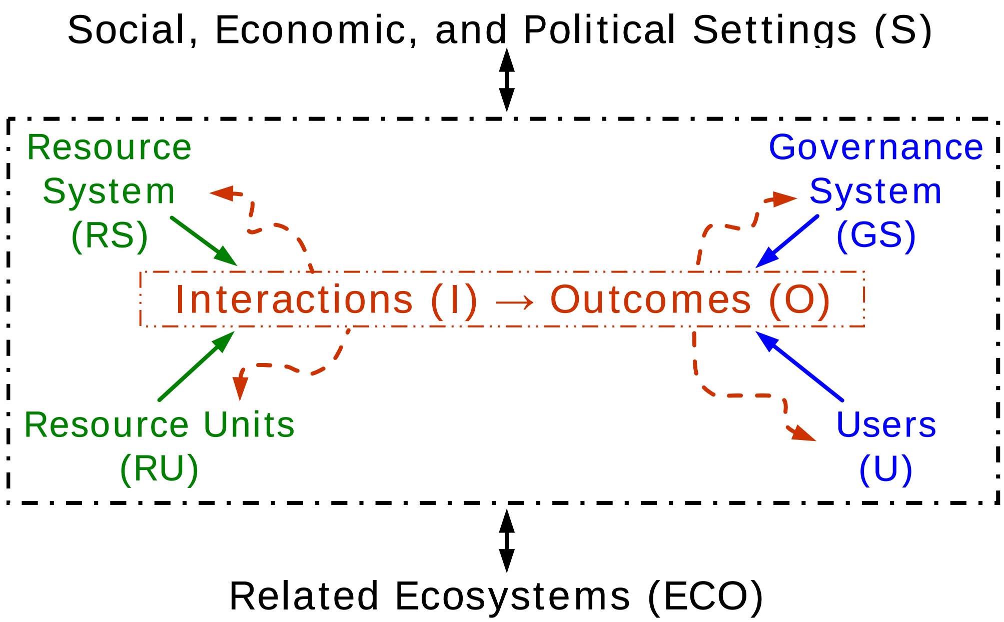

Figure 1. A Multitier Framework for Analyzing a Social-Ecological System (Straight arrows represent direct causal links; curved arrows represent feedbacks.)

Table 1. Second-Tier Variables in Framework for Analyzing a Social-Ecological System

Social, Economic, and Political Settings (S) S1- Economic development. S2- Demographic trends. S3- Political stability. S4- Government resource policies. S5- Market incentives. S6- Media organization.	
Resource System (RS)	Governance System (GS)
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	GS1- Government organizations GS2- Non-government organizations GS3- Network structure GS4- Property-rights systems* GS5- Operational rules GS6- Collective-choice rules* GS7- Constitutional rules GS8- Monitoring & sanctioning processes
Resource Units (RU)	Users (U)
RU1- Resource unit mobility RU2- Growth or replacement rate RU3- Interaction among resource units RU4- Economic value RU5- Size RU6- Distinctive markings RU7- Spatial & temporal distribution	U1- Number of users* U2- Socioeconomic attributes of users U3- History of use U4- Location U5- Leadership/entrepreneurship* U6- Norms/social capital* U7- Knowledge of SES/mental models* U8- Dependence on resource* U9- Technology used*
Interactions (I) → Outcomes (O)	
I1- Harvesting levels of diverse users* I2- Information sharing among users I3- Deliberation processes I4- Conflicts among users* I5- Investment activities I6- Lobbying activities I7-Self-organization of U*	O1- Social performance measures (e.g., efficiency, equity, accountability) O2- Ecological performance measures* (e.g., overharvested, resilience, diversity) O3- Externalities to other SESs
Related Ecosystems (ECO) ECO1- Climate patterns. ECO2- Pollution patterns. ECO3- Flows into and out of focal SES.	

*Subset of second-tier variables thought to affect self-organization.

Source: Adapted from Ostrom (2007:15183).

The complexity of this multitier framework offends some researchers. Social scientists have sought to develop simple theoretical models to analyze and prescribe solutions for avoiding destruction of key resources. The widespread appeal of Hardin's (1968) model of the commons is its simplicity. Hardin made a universal prediction of unsustainable harvesting and a simple policy prescription to impose either government or private property. Hardin's model is, however, too simple! Its predictions are empirically supported in the field and experimental laboratories when the people involved are unknown to each other and cannot communicate (Ostrom et al. 1994). Large numbers of self-organized systems do exist and sustain resource systems at relatively low costs. When simple plans to impose government or private property have been enacted by authorities, overuse of resources rather than reductions have frequently resulted (NRC 1986, 2002).

Although substantial joint benefits can be generated, changing the governance system of an open-access commons is costly in time and effort and in the loss of lucrative, short-term harvesting. Extensive empirical studies using a diversity of research methods have demonstrated that users frequently (but not always) make these investments and sustain their own commons over long periods of time (see citations in Poteete et al. 2009). To explain this behavior requires a more complex theory of human behavior (Camerer 2003; Fehr and Gächter 2002). Using behavioral theory, a theory of self-organization predicts that when the perceived benefits of revising and abiding by new rules exceed the perceived costs of this effort for a winning coalition of users, they will self-organize; otherwise, they will continue overharvesting (Ostrom 2001).

The theoretical prediction is clear. However, obtaining accurate and reliable measures of the benefits and costs perceived by users of an SES is extremely difficult. Given the extensive work of scholars focused on explaining collective-action outcomes related to natural resources, considerable consensus now exists about a subset of second-tier variables (starred in Table 1) that affect whether users will self-organize to avoid the continuance of open access (Baland and Platteau 2000; NRC 2002; Wade 1994; Gibson et al. 2005; Ostrom et al. 1994).

The second-tier RS variables related to increased likelihood of self-organization (I7) include

> **Size of resource system (RS3):** The RS is sufficiently small, given communication and transportation technologies in use, that the users can acquire accurate knowledge about the boundaries and dynamics of the system. Spatial extent also affects the costs of defining reasonable boundaries and monitoring them over time.

Productivity of system (RS5): The productivity of the RS has not been exhausted nor is it so abundant that no need exists to organize. Self-organization is likely to occur only after users observe some scarcity.

Predictability of system dynamics (RS7): The system dynamics are sufficiently predictable that users can estimate what would happen under alternative rule regimes. This is also an important variable for public officials who may have acquired management responsibilities for a resource of a particular type in a region (Wilson et al. 2007).

The important second-tier U variables include

Number of users (U1): Researchers have found a curvilinear relationship between the number of users and I7. Very small groups are frequently unable to undertake some of the needed activities while the transaction costs faced by very large groups discourage self-organization.

Leadership (U5): Some users have entrepreneurial skills of organizing and local leadership as a result of prior organization for other purposes or learning from neighbors. Given the complexity of many field settings, users face a difficult task in evaluating how diverse variables affect expected benefits and costs over time.

Norms/social capital (U6): Users share norms and trust one another to keep agreements and use reciprocity in their relationships with one another. When social capital is high, users face lower transaction costs in reaching agreements and lower costs of monitoring and sanctioning one another over time.

Knowledge of the social-ecological system (U7): Users share common knowledge of relevant SES attributes and how their own actions affect each other. Asymmetric private information about heterogeneous assets may adversely affect the willingness of users to agree to limit their own harvesting. Users are more likely to agree on rules whose operation they understand from prior experience, than on rules that are introduced by external authorities and are new to their experience.

Dependence on resource (U8): Users are dependent on the RS for a major portion of their livelihood. If users do not obtain a major part of their income from a resource, the high costs of organizing and maintaining a self-governing system may not be worth their effort. Users with many attractive options may discount future income from a particular resource by simply “mining” it and moving on to other resources, like “roving bandits” (Berkes et al. 2006).

Many variables related to the governance system (GS) are also important, but empirical studies identify that having autonomy to make one’s own rules—a third-level variable—is extremely important (Haller and Merten 2008).

Autonomy to make own operational rules (GS6a): Users have autonomy at the collective-choice level to make some or all of their operational rules. A group with little autonomy may find that those who disagree with locally developed rules seek contacts with higher-level officials to undo the local agreements. With the legal autonomy to make their own rules, users face substantially lower costs in defending their own rules against other authorities and other users (Basurto and Ostrom 2008).

Individual studies identify further variables that have been conducive or obstructive to self-organization in specific settings. Efforts are underway by scholars in the US and Europe to revise and expand the SES framework presented here. Our aims are to further enhance cumulative knowledge about the likelihood of successful self-organization and gain a better understanding of where and what types of government policies are needed to enhance sustainability. Other questions related to sustainability will utilize variables not yet integrated into the framework, but the intention is to continue working to make the framework as general as possible. Understanding the effect of deforestation on climate change or studying the impact of severe climate events on coastal areas, for example, requires a different set of variables from those needed to understand self-organization. The advantage of a common framework is that research across disciplines and questions can cumulate more rapidly and increase the knowledge we all need related to the sustainability of complex SESs.

Investigating factors that affect the likelihood of self-organization is a broad question and the list of variables that have been identified as conducive to users solving commons problems themselves are also quite general. Scholars interested in how specific rules affect incentives, behavior, and outcomes face still more complex questions to be addressed by a deeper tier of variables than whether self-organization is likely. The variety of rules identified in the field is immense, as would be expected if rules are intended to cope with the characteristics of complex systems. Research has identified seven types of operational rules (GS7) (Ostrom 1986; Painter 1991), and each third-level variable has multiple fourth-level attributes. For example, at least 27 boundary rules and 112 authority rules are used in practice as well as large numbers of position, aggregation, scope, information, and pay-off rules (Ostrom 1999).The diversity of rules found in practice is distressing to analysts who wish to prescribe optimal rules rather than to understand how specific rules work in combination in a particular environment and not in other environments. Prescriptions of blueprints for large territories have caused some of the failures of broad, externally imposed government ownership (Pritchett and Woolcock 2003).

While it is not possible, given the complex, nested system involved, to identify specific rules that work effectively across diversely structured SESs, a general set of design principles associated with long-term sustainability of self-organized systems has been identified (Ostrom 1990). A recent meta-analysis of over 100 studies that examined whether positive effects of regimes are consistent with the design principles found that less than 10% negatively evaluated the usefulness of these principles for explaining sustainability of self-organized SESs (Arnold et al. 2009). Thus, sustainability of complex SESs is characterized by the effects of diverse, specific characteristics of RSs, RUs, GSs, and Us on I7; but, at the same time, it is possible to develop useful general theories related to underlying governance systems consistent with general design principles. A core task for future research on sustainability is learning how to dissect and harness complexity, rather than eliminating it (Axelrod and Cohen 2001).

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