A framework to analyze the robustness of social-ecological systems from an institutional perspective

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Abstract

What makes social-ecological systems robust? In this paper we look at the institutional configurations that affect the interactions among resources, resource users, public infrastructure providers, and public infrastructures. We propose a framework that helps to identify potential vulnerabilities of social-ecological systems to disturbances. All of the linkages among the components of this framework can fail and thereby reduce the robustness of the system. We posit that the link between resource users and public infrastructure providers are a key variable affecting the robustness of social-ecological systems that has frequently been ignored in the past. We illustrate the problems caused by a disruption in this link. We then briefly describe the design principles originally developed for robust common-pool resource institutions since they appear to be a good starting point for the development of design principles for more general social-ecological systems and do include the link between resource users and public infrastructure providers

keywords: institutions, social-ecological systems, resilience, robustness

Introduction

Over the past century, growing human influences on biophysical processes have led to many perceived environmental problems. A typical response has been to improve our understanding of the underlying biophysical process about which decisions must be made, and thus reduce the uncertainty decision-makers must face. This is a difficult task. A degree of irreducible uncertainty always exists about how the dynamics of coupled social and ecological processes unfold. This fact suggests that rather than asking how society can better "manage" ecological resources, we ought to be asking "What makes social-ecological systems robust?"

The concept of robustness is well developed in engineering where it refers to the maintenance of system performance either when subjected to external, unpredictable perturbations, or when there is uncertainty about the values of internal design parameters (Carlson and Doyle, 2002). Robust design often involves a trade-off between maximum system performance and robustness. A "robust" system will typically not perform as efficiently with respect to a chosen set of criteria than its non-robust counterpart. However, the robust system's performance will not drop of as rapidly as its non-robust counterpart when confronted with external disturbance or internal stresses.

Resilience, a similar concept to robustness that has been developed in ecology (Holling, 1973), measures the amount of change or disruption that is required to transform a system from being maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures. Resilience is an appealing concept and it is tempting to extend it to Social Ecological Systems (Berkes et al., 1998). However, resilience can be difficult to apply to systems in which some components are concsiously designed (Carpenter et al. 2001). More recent developments in resilience theory emphasize adaptive capacity, and coupled cycles of change that interact across several scales (Gunderson and Holling, 2002). These ideas are useful in a descriptive sense, but are less useful for studying designed systems. How does one design for adaptive capacity? What is the cost of adaptive capacity? Robustness, on the other hand, emphasizes the cost benefit trade-offs associated systems designed to cope with uncertainty. As such, robustness is a more appropriate concept when trying to understand how SESs can deal with disruptions. However, we do not abandon the concept of resilience. For example, one approach to enhance the robustness of a SES would be to focus on governance that enhances the resilience of an ecosystem configuration that produces a desirable bundle of goods and services. The important point is to recognize both the designed and self-organizing compenents of a SES and to study how they interact.

Given the previous discussion, it seems natural to extend the idea of robustness to a social-ecological system. However, it is difficult in practice. In engineered systems, defining a performance index is straight-forward. Engineered systems are frequently relatively simple, controllable, and better understood than ecological or social systems. Even complex engineered systems that are composed of many subsystems, like a jet airplane, have relatively complete blueprints that can be used when diagnosing a problem and engaging in repair. SESs are never fully designed or controllable, nor are they amenable to the definition of one simple, easily measurable performance index such as output value minus input costs. In this sence, fully engineered systems and SES's provide examples at different ends of the spectrum of systems with both designed and self-organizing subcomponents and levels of uncertainty. In the former, the majority of subsystems are designed (airplane components), very few subsystems self-organize (pressure drop over an airfoil), and uncertainty is low (mostly eliminated by wind tunnel experiments and prototype testing). In the later, the majority of components are self orgainizing (ecological systems, social networks), very few are designed (rules of interaction), and uncertainty is high (experimentation is difficult or impossible). despite these difficulties, the idea of enhancing the robustness of social-ecological systems is appealing in the present context of rapid change and increasing uncertainty at and across various scales. the first step is developing a framework to study the robustness of social ecological systems and then to posit broad design principles for robust social ecological systems that may be improved with further research.

Any such framework must address three issues: 1) the maintenance of cooperation and potential for collective action within the social system, 2) ecological systems are dynamic, as are the rules of the games that agents play amongst themselves, and 3) ecological systems can occupy multiple stable states and move rapidly between them. The first of these issues has become a well developed field in the last three decades The conditions under which cooperation is maintained or will evolve has been the focus of field researchers, game theorists and experimental economists for some time (e.g. Axelrod, 1984; Ostrom, Gardner, and Walker, 1994; Bowles and Gintis, 2003). However, this work focuses on resource users and their actions when payoffs are constant over time, i.e. the resource base is static. Dynamic or differential game theory allows the incorporation of the second issue into models of strategic interaction. Dynamic games have been applied to dynamic resource management issues (e.g. Clark, 1990; Mäler et al., 2003) but here the focus is to determine optimal strategies and the assessment of the effectiveness of economic instruments toward achieving them. Little attention has been paid to the institutional context, It is simply assumed that the necessary institutional and any other associated infrastructure is in place. Finally, the third issue has been addressed in several recent papers (Carpenter et al., 1999a, 1999b; Scheffer et al., 2001; Anderies et al., 2002; Janssen et al., 2004; Brock and Xapapadeas, 2004). These studies focus on management regimes that reduce the probability that a system with multiple stable states will enter, and possibly remain in, undesirable states. However, these studies do not include institutional contexts.

The innovation in this paper is to pose a framework that enables us to begin to address these three issues as they affect one another. We wish to address the resource, its users, its governance system and associated infrastructure as a coupled system. We attempt to lay the foundations for eventual theories and models. We are using the term, "framework," purposefully. A framework identifies a broad set of variables and their linkages. Within any particular framework, alternative theories are used to make broad predictions about the effect of changes in relevant variables while multiple models operationize theories using a variety of formal techniques (see Ostrom, 1999). In this paper, we first define our area of interest and characterize "robustness" in this context. We then use this framework to discuss several general themes and apply it to specific cases. Finally we provide initial directions for future research.

The Framework

How do institutional arrangements affect the robustness of social-ecological systems? Why do some systems survive in highly varying environments over time while others collapse? Which attributes of the institutions are more likely to lead to the creation of robust social-ecological systems? How do these attributes depend on the underlying ecological system? To answer these questions, we propose a "framework". The framework consists of a set of definitions and a list of attributes that are of key importance to understanding the robustness of a social ecological system. This framework is only a beginning. We present it here in order to lay the foundation for future work.

Defining a social ecological system

What is a social-ecological system (SES)? A SES is an ecological system intricately linked with and affected by one or more social systems. An ecological system can loosely be defined as an interdependent system of organisms or biological units. Social simply means "tending to form cooperative and interdependent relationships with others of one's kind" (Merriam-Webster Online Dictionary, 2004). Broadly speaking, social systems can be thought of as an interdependent system of organisms. Thus, both social and ecological systems contain units that interact interdependently and each may contain interactive subsystems as well. We use the term, SES, to refer the subset of social systems in which some of the interdependent relationships among humans are mediated through interacting biophysical and non-human biological units. A simple example is when one fisher's activities change the outcomes of another fisher's activities *through* the interacting biophysical and non-human biological units that constitute the dynamic, living fish stock. Further, we restrict our attention to those SESs where the cooperative aspect of social systems is key, i.e. where individuals have intentionally invested resources in some type of physical and/or institutional infrastructure to cope with diverse internal and external disturbances. When social and ecological systems are so linked, the overall SES is a complex, adaptive system involving multiple subsystems as well as being embedded in multiple larger systems.

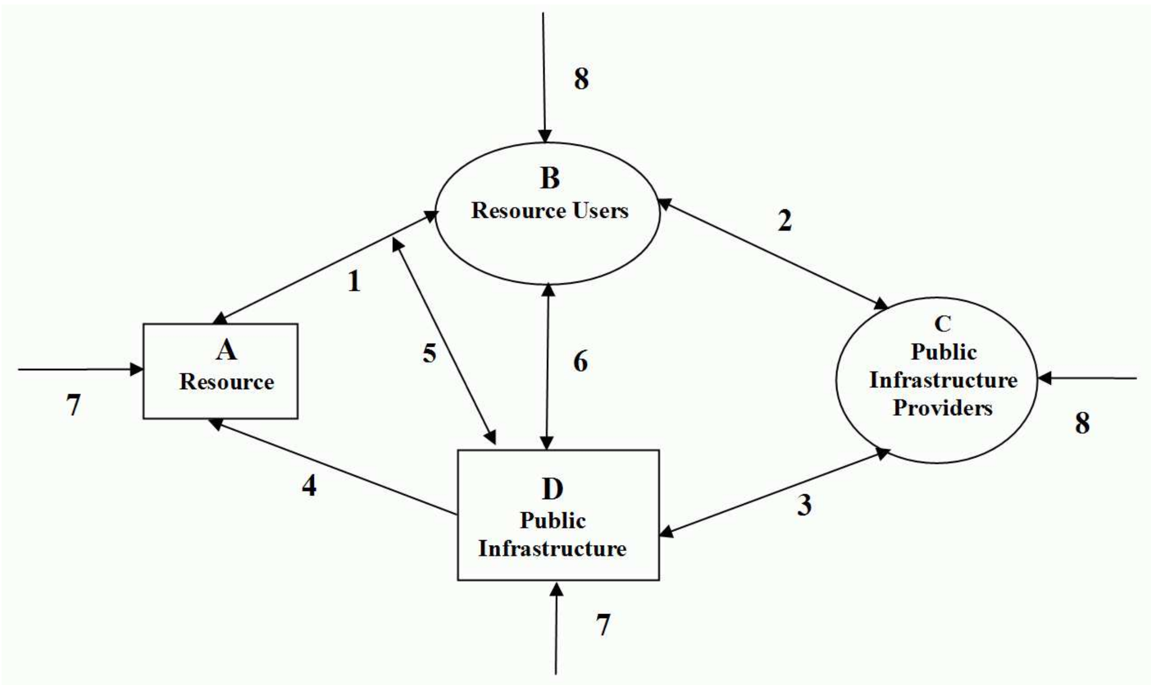

Figure 1: *A conceptual model of a social-ecological system*

Given this focus, we suggest than a minimal representation includes the elements depicted in Figure 1. Examples of the elements and their interactions are given in Tables 1 and 2. One component is a resource (*A* on Figure 1) which is used by multiple resource users.

Two components are composed of humans: the resource users (B on Figure 1), and the public infrastructure providers (C on Figure 1). There may be a substantial overlap of the individuals in B and in C or they may be entirely different individuals depending on the structure of the social system governing and managing the SES.

Entities	**Examples**	**Potential Problems**
A. Resource	Water source	Uncertainty
	Fishery	Complexity / Uncertainty
B. Resource Users	Farmers using irrigation	Stealing water, free riding on maintenance
	Fishers harvesting from in-shore fishery	Overharvesting
C. Public infrastructure providers	Executive and council of local users association	Internal conflict or indecision about which policies to adopt
	Government bureau	Information loss
D. Public Infrastructure	Engineering works	Wear out over time
	Institutional rules	Memory loss over time, deliberate cheating
External Environment	Weather, economy, political system	Sudden changes as well as slow changes that are not noticed

Table 1: *Entities Involved in Social-Ecological Systems*

Public infrastructure (D on Figure 1) combines two forms of human-made capital—physical and social (Costanza et al., 2001). Physical capital includes any engineered works such as dikes, irrigation canals, etc. By social capital we mean the rules actually used by those governing, managing and using the system and those factors that reduce the transaction costs associated with the monitoring and enforcement of these rules (Ostrom and Ahn, 2003). One example of a rule used in many self-organized SESs is rotating the role of monitor among resource appropriators. In centrally governed SESs, monitors would be employed and paid by a government agency.

In our examination of robustness, we address two types of disturbances. External disturbance can include biophysical disruptions (Arrow 7) such as floods, earthquakes, landslides, and climate change which impact the resource (A) and/or the public infrastructure (D) or socioeconomic changes (Arrow 8) such as population increases, economic change, depressions or inflations, and major political changes that impact on the resource users (B) and the public infrastructure providers (C). Internal disturbances refer to rapid reorganization of

Linkages	Examples	Potential Problems
(1) Between Resource and Resource Users	Availability of water at time of need/availability of fish	Too much or too little water / too many of uneconomic fish – too few of valued fish
(2) Between users and public infrastructure providers	Voting for providers	Indeterminacy / lack of participation
	Contributing resources	Free riding
	Recommending policies	Rent seeking
	Monitoring performance of providers	Lack of information/ free riding
(4) Between public infrastructure and resource	Impact of infrastructure on the resource level	Ineffective
(5) Between public infrastructure and resource dynamics	Impact of infrastructure on the feedback structure of the resource-harvest dynamics	Ineffective, unintended consequences
(6) Between resource users and public infrastructure	Coproduction of infrastructure itself, maintenance of works, monitoring and sanctioning	No incentives / free riding
(7) External forces on resource and infrastructure	Severe weather, earthquake, landslide, new roads	Destroys resource and infrastructure
(8) External forces on social actors	Major changes in political system, migration, commodity prices, and regulation	Conflict, uncertainty, migration, greatly increased demand

Table 2: *Linkages Involved in Social-Ecological Systems*

the ecological or social system induced by the subsystems of the ecological or social system.

Highlighting the key drivers

A part of our framework is to highlight key interactions within SESs, often overlooked in the past, that are especially important with regard to robustness. These interactions revolve around strategic interactions between agents, the rules devised to constrain the actions of agents, and the collective choice process used to generate the rules. We discuss each of these in turn.

Strategic interactions

A major focus of the past literature has been strategic interactions amongst resource users themselves and the consequences for the resource system. Classic studies by Gordon (1954) and Hardin (1968) presumed that without private ownership by individuals or a governmental unit, the temptation to over-harvest (Linkage 1) and to free ride on public infrastructure provisions would lead to the destruction of the resource base. The "property rights" solution persisted through the 1980's as the method of choice for solving common-pool resource dilemmas, one of the possible dilemmas that resource users can experience in SESs. Scholars disagreed, however, on whether this was private or government ownership. Many models presumed very simple, single species ecological systems (see, for example, Gordon, 1954). In irrigation, the presumption was that water could be delivered to farmers in known quantities following a careful marginal benefit analysis so that those farmers with the highest productivity would receive the most water and pay appropriately for the water they received (e.g., Smith, 1988).

These simple models were used to determine Maximum Sustainable Yield (MSY) and Maximum Economic Yield (MEY) and prescribe simple policies to reach the these goals. Their simplicity made them tractable and appealing to scholars searching for ways to improve the performance of SESs through the application of modeling and policy analysis. For decades, donors urged developing countries to change indigenous institutions that had existed for long periods of time because they did not conform to the prescriptions derived from the earlier models (Lansing, 1991; Mwangi, 2003; Netting, 1976, 1982).

We argue that a richer characterization is required to properly address the robustness of a SES. We must move beyond the earlier foundation focusing on just the resource users, the incongruence between individual and collective rationality, and the problem of the maintenance of cooperation (Sandler, 1992; Udéhn, 1993; Ostrom et al., 1994). For example, referring to Figure 1, there are a variety of strategic factors that may influence the interaction between resource users and the public infrastructure providers (Linkage 2 on Figure 1), public infrastructure providers and actual investment in the infrastructure (Linkage 3), resource users and the harvesting rate (Linkage 1), and potentially, between resource users and the public infrastructure (Linkage 6). Linkage 6 is rarely even addressed in most analyses of SESs since many analysts have ignored the active co-production of resource users themselves in the day-to-day operation and maintenance of a public infrastructure (but see Evans, 1997). Further, the linkages among the ecological entities (Linkages 1, 4 and 5) are also sources of fluctuations that may challenge the robustness of the overall SES at any particular point in time. In Tables 1 and 2, we present an initial overview of some of the potential problems that may exist within the four entities and eight linkages identified on Figure 1.

We know it is not possible to have one *integrated model* that captures all these potential interactions. It is important, however, to understand the broad structure of the entities and linkages in a SES and to begin to show how the games within and between entities affect the likelihood of long-term robustness. That is what we hope to illustrate in this paper and other research in progress..

Operational rules and collective-choice processes

Most institutional analyses of SESs have so far focused on either the harvesting decisions of resource users (operational processes) or the policy choices of public infrastructure providers (collective choice processes). Operational level analyses have normally assumed an exogenously fixed set of rules and then determined the appropriate incentive to maximize a social welfare objective (e.g., Clark, 1990). Such studies suggest that the operational rules need to be well-tailored to avoid overharvesting or, in the case of public infrastructure provision (e.g. irrigation systems), to avoid free riders. The resulting recommendation is frequently that the government should manage these systems through the development of rules limiting the choice sets of resource users regarding harvesting or investment. Alternatively, individual rights to resource units should be determined so that a market mechanism will allocate resources to their most valued use (see Tietenberg, 2002, for a recent review of this literature).

At the collective choice level, scholars investigate how to aggregate preferences of individual resource users over various policies, and the likely outcomes of various voting procedures given the preference structure involved. Arrow (1951) highlighted the impossibility of mapping individual preference orderings into a societal preference order. Shepsle's (1979, 1989) work showed how institutions may solve some of these problems by empowering some actors and demoting others. McKelvey's chaos theorem asserts that (a) when there is more than one dimension to a policy, the social preference ordering is likely to be intransitive, and (b) by manipulating the agenda, the public infrastructure providers can choose anything! (McKelvey, 1976, 1979). That is, group choice becomes completely unpredictable again and, what is perhaps worse, subject to strategic manipulation by a smart agenda-setter.

We argue that the operational and the collective choice levels must be analyzed *together* in order to assess the robustness of SESs. Thus, the main aspect of the framework shown in Figure 1 that we wish to examine first in this paper is the linkage between the operational level (resource users), and the collective choice level (public infrastructure provision). Depending on the precise implementation of the institutional rules, conflicts between the resource users and the public infrastructure providers may exist since there may be a mismatch between the costs and benefits. For example, the resource users may not be willing to pay a tax if the public infrastructure providers do not invest in and maintain a public infrastructure of benefit to the resource users.

Robustness in SESs

Given our characterization of the main components of a SES and the key drivers, we can now define robustness more precisely. By robustness we mean "the maintenance of some desired system characteristics despite fluctuations in the behavior of its component parts or its environment" (Carlson and Doyle, 2002: 2,538). Unfortunately, what kinds of system failure should be measured are not very clearly defined for SESs (Carpenter et al., 2001). To examine robustness, one must minimally address: (1) What is the relevant system?, (2) What are the desired system characteristics?, and (3) When does the collapse of one part of a SES, imply that the entire system loses its robustness? For example, when a particular ecological system collapses, but the social system continues to function due to its ability to adapt and use alternative resources, is that system robust? Or, does the entire system lose its robustness due to the robustness of the social component?

Within SESs, this difficulty of interpretation is a problem of defining the appropriate scale of analysis. For example, a small scale (or short time scale) resource might collapse in order to maintain desired functions at a larger scale (or longer time scale). An example is the transformation of mangroves and rice fields into intensive shrimp aquaculture in Thailand and Vietnam, which is unsustainable, but argued to be required as a (short time scale) stepping stone for the industrial development (long term stability) of these countries (Lebel et al., 2002). Another example is peat mining in Holland during mainly the 17^{th} century to meet the demand for fuel in Dutch cities (Westbroek, 2002). Swamps were drained in order to mine the peat. It is interesting to note that the characteristic Dutch landscape of waterways, polders, and dikes is nowadays viewed as nature, but was actually a swamp before the peat mining industry started a few centuries ago.

Since we explicitly analyze SESs, we distinguish between the collapse of a *resource* or an undesirable transformation of the resource (e.g. a fishery or a water distribution system that is no longer productive), and the collapse or loss of robustness of the *entire system*. We require that *both* the social and ecological systems collapse before we define a SES as being collapsed, and thus implicitly define our scale of analysis (or system boundary) as to include the human social system and *all* ecological systems from which it extracts goods and services.

For example, social systems that reward innovation can be robust to many external shocks, as long as it innovates quickly enough. As Anderies (2003) shows in a recent paper, however, such innovation can make the eventual collapse of a larger-scale system more extreme. Unless a society can manage to organize around principles other than "replacement technologies," its eventual collapse is likely. Are such SESs robust? We would argue that they are, in respect to a certain time scale. As time progresses and problems become more complex, the probability increases that society will eventually fail to cope with a shock. Eventually, a "collapse" event is triggered, after which reorganization occurs on a very large scale (Holling's r-K phase followed by <Omega>) (Holling, 1986).

In summary, we will argue that a SES is robust if it prevents the ecological systems upon which it relies from moving into a new domain of attraction that cannot support a human population, or induces a transition that causes long-term human suffering. We might argue that the ability of a social system (B and C in Figure 1) to persist in the face of an ecological collapse is a sign that that system has a low adaptive capacity in relation to that ecological resource. Rather than looking for social changes to prevent the collapse of a resource base and transform to a lower use of the resource, the social system maintains itself and looks for another resource to exploit. Eventually, we hope to be able to offer some useful suggestions for how to avoid this sequential destruction of natural resources.

Applying the Framework: Designing for Robustness

In this section we apply the framework to highlight aspects of robust designs for SESs. Through the discussion of general examples, we highlight examples of vulnerabilities that reduce the robustness of SESs and reflect on Ostroms's (1990) design principles for common-pool resource institutions. These principles were based on extensive fieldwork, extensive reviews of case study literature, and the growing theoretical literature on institutions. The cases varied from small, self-contained systems of homogeneous resource users to complex systems organized in modern economies where the resource users were linked to public infrastructure providers through a variety of mechanisms. Instead of focusing on specific rules, the effort turned to identifying underlying design principles that characterized robust common-pool resource institutions. No assertion was made that those crafting these institutions were intentionally using the design principles, but rather that robust systems could be characterized as meeting a large number of these principles. The design principles identified at that time are listed in Table 3.

One of the limitations of the original design principles is the lack of imbedding of ecological dynamics (Brown, 2003). Future versions of the design principles should address mechanisms related to the match between the spatial and temporal dynamics of ecological and social systems, like, for instance, those that sustain institutional and ecological memory (Berkes et al. 1998). Several aspects of the case studies that follow highlight the importance of the close linkage between the biophysical and social components of these systems. However, our analysis just scratches the surface of this important issue that deserves significant future research effort.

The cases

Many examples exist of complex interactions between the components of a SES. Many are farmer organized irrigation systems, such as those of Bali (Lansing, 1991), the zanjeros of the Philippines (Siy, 1982), and of Spain (Maass and Anderson, 1986). These are examples of long-lived, "robust" irrigation SESs. The Hohokam, on the other hand, provides an example of a long-lived irrigation SES that eventually collapsed (Bayman, 2001). Other examples come from managed fisheries, forests, and dike systems. Some of these are long-lived and remain robust, e.g. the Dutch water boards (Kaijser, 2002), the lobster fisheries in Maine (Acheson, 2003), or the Hatfield Forest (Rackham, 1988), while others were long-lived yet did collapse, e.g. early Mesopotamian civilization, the lowland Mayas (Tainter, 1988), Chacoan culture (Mills, 2002), Mesa Verde (Lipe, 1995), the northern cod fisheries (Finlayson and McCay, 1998) and the customary marine system of the Tonga (Malm, 2001). Other SESs have not been long-lived and have been rapidly destroyed, e.g. the Aral Sea (Glantz, 1999). Still others never seem to get organized in the first place and experience substantial overuse and mismanagement, such as the oyster fishery of Chesapeake Bay (McHugh, 1972), or the irrigation systems of Ghana (Webb, 1991).

Our objective is not to characterize the robustness of each of these cases in detail in

1. *Clearly Defined Boundaries*
   The boundaries of the resource system (e.g., irrigation system or fishery) and the individuals or households with rights to harvest resource units are clearly defined.

2. *Proportional Equivalence between Benefits and Costs*
   Rules specifying the amount of resource products that a user is allocated are related to local conditions and to rules requiring labor, materials, and/or money inputs.

3. *Collective-Choice Arrangements*
   Most individuals affected by harvesting and protection rules are included in the group who can modify these rules.

4. *Monitoring*
   Monitors, who actively audit bio-physical conditions and user behavior, are at least partially accountable to the users and/or are the users themselves.

5. *Graduated Sanctions*
   Users who violate rules-in-use are likely to receive graduated sanctions (depending on the seriousness and context of the offense) from other users, from officials accountable to these users, or from both.

6. *Conflict-Resolution Mechanisms*
   Users and their officials have rapid access to low-cost, local arenas to resolve conflict among users or between users and officials.

7. *Minimal Recognition of Rights to Organize*
   The rights of users to devise their own institutions are not challenged by external governmental authorities, and users have long-term tenure rights to the resource.

For resources that are parts of larger systems:

8. *Nested Enterprises*
   Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprises.

Table 3: *Design principles derived from studies of long-enduring institutions for governing resources. Source: based on Ostrom (1990: 90)*

this article. Rather, we look for commonalities. Each case includes a common-pool ecological resource that has two characteristics (Ostrom et al., 1994): 1) it is costly to devise physical (e.g. fences) and institutional (e.g. boundary rules) means of excluding potential beneficiaries, and 2) one person can withdraw valued "resource units" (e.g. water, fish, CPU time) from the system for the given infrastructure at a particular point in time that cannot be used by others. When exclusion is difficult and consumption is subtractive, resource users face incentives to over-harvest, free ride on the provisional infrastructure, and shirk on maintenance, unless institutions are crafted, monitored, and enforced that counteract these incentives. What can we learn about general robust design principles from these cases?

The simplest type of case

The simplest case of the linkage between B and C (the operational and collective choice levels discussed above) would be a small group with relatively homogeneous interests in which each agent acts both as a resource user and as an infrastructure provider. Further, if there is no medium of exchange other than labor and goods, cooperation in constructing and maintaining infrastructure must be undertaken by transparent means. An example might be a small irrigation system where the farmers meet once a year to decide how many days they will work to repair and maintain the canal and how they will monitor each others' use of the flow of water from the system (see Tang, 1992; Lam, 1998; Ostrom, 1992). If all farmers are required to be present for a work day to maintain a canal, it is easy to detect non-cooperation. This is also the group that decides on the rules for allocating water and these rules need to be relatively easy to understand, monitor, and enforce. So, in such a system, the resource users are also involved in collective choice and impose upon themselves harvesting rules and investment requirements. Such rules then tend to be perceived by resource users as legitimate and tend to be followed without high costs of monitoring and enforcement. If such systems experience little external challenges, they can sustain themselves for very long eras. Some long-lived irrigation systems in Asia (Coward, 1979, 1980; Siy, 1982) were examples of this kind of extremely simple SES until the end of the last century.

Although SESs consisting of small homogeneos groups of resource users can function for long periods of time, they are not immune to new disturbances. Challenges for the continuation of these SESs come from outside the system, like new technologies, new job opportunities, new media of exchange. Our framework can be useful to understand the impact of such challenges, which we will illustrate with some examples below.

In the case where the actors at the operational and collective choice levels are roughly the same individuals, the system is likely to persist in an environment with a stable disturbance regime. Because the SES is well adapted to this stable disturbance regime, however, it might not be robust to challenges coming from outside the system. An example might be the construction of a new road. The population in the system may decline due to better opportunities elsewhere, leading to declining investments in maintenance and a resulting decay of the SES. On the other hand, the population might increase due to immigration or accelerated natural growth (e.g. a decline in the death rate due to better health care, the option to import food in periods of scarcity, etc.) which may threaten the SES. More resource users may harvest from the resource, challenging the rule makers at the collective choice level to develop new and better ways to allocate resource units. It also might provide more labor and investments in the public infrastructure to increase the carrying capacity of the system (Fox, 1993; Leach and Fairhead, 2000).

With a larger population size it becomes more likely that specialization of tasks will occur. A subset of resource users may now become public infrastructure providers. As long as there is a strong social embedding of public infrastructure providers within the community of resource users, networks of control and monitoring may be strong, and the system might persist for a long time. The irrigation system of Bali is an example. Temple priests act as public infrastructure providers by giving advice, maintaining knowledge, and ensuring coordination (Lansing, 1991). The public infrastructure providers are closely related with the resource users since the priests are family members of the resource users. When the Indonesian government imposed the Green Revolution to increase rice production, the robustness of the Bali irrigation system was seriously challenged. The bureaucrates from the Indonesian government lacked an understanding of the system. The introduction of new rules and infrastructure (artificial fertilizers and new rice varieties) and ignorance of indigenous rules resulted in water shortages and pest outbreaks (Lansing, 1991).

Changes in the economic opportunities in a region may also challenge a SES. When all resource users heavily depend on the resource, they are more likely to follow rules and contribute time and effort to co-producing infrastructure. Baker (forthcoming) analyzes a set of 39 farmer managed irrigation systems in Himalchal Pradesh, India, where some farmers using an irrigation system begin to obtain significant off-farm income. Baker finds that their valuation of some of the resources and their own time changed substantially. For some SESs the resource was thus reduced to marginal economic importance. The cost of the work required to maintain those irrigation systems exceeded benefits generated and these systems collapsed, while others with higher continuing economic value reorganized their rules and continued as robust SESs.

Just the introduction of money as a medium of exchange can by itself be an important disturbance. When labor is the primary medium of exchange, investment in public infrastructure is easy to monitor. Further, resource users can easily see where this input is allocated. If, for example, the public infrastructure providers request resource users to build them beautiful homes, resource users can object on the grounds that such activity does not contribute to their irrigation system. If money is involved, it is more difficult to monitor both the tax paying efforts of resource users and the rent allocation of the public infrastructure providers.

More complex types of cases

Beyond the case of small, homogeneous groups involved in a pattern of mutual reciprocity to produce an obvious collective benefit, the picture becomes more difficult. The more the composition of the resource users and the participants in the public infrastructure provision differ, the more complex incentive structures become. In an extreme case, when there is no overlap, the public infrastructure provider has an incentive to engage in rent seeking by imposing high taxes on the resource users while not investing in public infrastructure. In this case the public infrastructure providers do not depend on the SES, and may act as a "roving bandit," extracting wealth with little regard for the future (Olson, 1993). Multiple variations exist between these two extremes:

- The public infrastructure providers might be (elected) representatives from the population of resource users. Since they also benefit from the resource there is an incentive to invest in public infrastructure. However, problems with rent seeking and lobbying may lead to little investment reaching public infrastructure. It is therefore important how Link 2 is implemented, such that public infrastructure providers experience the consequences when resource users are not satisfied with their decisions.

- Resource users and public infrastructure providers may posess different information sets. Resource users may have more local knowledge about the resource dynamics, while the public infrastructure providers have better knowledge of larger scale processess. Public infrastructure providers might generate harvesting rules without sufficient understanding of the resource dynamics, thus generating unintended consequences. An example is the collapse of the northern Cod. Government scientists used a scientific model of the fishery and highly aggregated data to assert that the amount of fish being harvested was within the MSY, while the fishers argued from the size of the fish in their nets that the fishery was in grave danger (Finlayson and McCay, 1998). Others argue that the politicians and bureaucrates were biased when choosing which scientific information to include in the decision making (Spurgeon, 1997). Direct observation of the diverse dimensions of the state of the resource is often not possible by public infrastructure providers in complex SESs. Public infrastructure providers may derive information about the functioning of the resource in different ways. For example, from resource users who directly experience the flow from the resource (Link 1) and may provide the information to the resource users (Link 2), which may include various reasons of miscommunication. Public infrastructure providers may also employ scientists or others who study the resource (Link 5), and report back to the public infrastructure providers (Link 3). Again the indirect way of deriving information may lead to translation error.

- Heterogeneity in the benefits resource users derive may exist. Some may benefit from the public infrastructure and others do not. Nonbeneficiaries may refuse to pay tax. The Aral Sea is an extreme example of heterogeneity. Farmers upstream benefited from the irrigation infrastructure, but those dependent of the ecological services of the Aral Sea witnessed the disappearance of their resource system. In more complex SESs, the boxes in the framework consist of a diversity of agents who may have conflicting goals and attributes.

- The public infrastructure provider behaves as a stationary bandit, who has some incentive to invest in improvements because he will reap some return from those improvements (Olson, 1993). Therefore the public infrastructure provider has the incentive to invest in the public infrastructure to maximize his or her long-term tax revenues without regard for the welfare of resource users.

In some cases, relatively robust local SESs have been seriously challenged by a lack of understanding of public infrastructure providers, of how they operate, and why an effective linkage between the resource users and the public infrastructure providers is so essential. An intriguing example is from Taiwan, where the weakening of Link 2 led to a weakening of Links 3 and 6. In Taiwan, a set of seventeen Irrigation Associations have been responsible for the operation and maintenance of a large number of Taiwan's irrigation systems. The Irrigation Associations were corporations organized by the farmers, who paid fees to their local Irrigation Association. The Irrigation Association, in turn, took substantial responsibility for the day-to-day maintenance and operation of local canals, while the Government of

Taiwan undertook responsibility for the construction and operation of the larger irrigation works. Thus, the Irrigation Associations acted as local public infrastructure providers that were linked to a larger-scale public infrastructure provider. The Irrigation Associations have repeatedly been acclaimed as major contributors to efficient irrigation in the country and thus to substantial agricultural development (Levine, 1977; Moore, 1989; Lam, 1996).

Taiwan, like other countries whose economies are less and less dependent on agriculture and more dependent on industrial and service industries, has been trying to find ways of adjusting a variety of economic policies. Further, the rural population still has a significant vote and national politicians have been vying for support in the rural areas. In the early 1990s, politicians argued that farmers faced hard times and could not make a decent living. "The government, argued these politicians, should not burden the farmers with irrigation fees. In 1993, after much political negotiation, the government agreed to pay the irrigation fees on behalf of the farmers" (Lam, 2003: 8). As it turned out, both major national parties supported the cancellation of irrigation fees as no one wanted to be seen as being against the farmers, even though many of the officials familiar with irrigation expressed substantial concern about the long-term consequences.

The cancellation of the fee has had substantial and unexpected adverse consequences. Farmers are much less likely to volunteer for work activities, to pay voluntary group fees, or to pay much attention to what is happening on the canals and in the ecological environment around them, as they had done earlier (Wade, 1995). As one Irrigation Association official expressed it: "The problem facing irrigation management at the field level is not simply a matter of finding one or two farmers to serve as local group leaders, the more serious challenge is that nowadays fewer and fewer farmers have good knowledge of their own systems and understand how to engage with one another in organizing collective action" (quoted in Lam, 2003: 12). Maintenance of the systems has declined precipitously. The cost of water has been increasing rather than decreasing. Thus, systems that had been robust for long periods of time have largely been destroyed by an effort "to help" the resource users by changing Link 2 between the users and the public infrastructure providers. The problem of misunderstanding what makes a SES robust can lead to public policies that undermine the more successful SESs.

Design principles for robustness

We do not wish to argue that the only robust SESs are small-scale common-pool resources in remote locations serving a homogeneous community without market opportunities or access to a commonly-used medium of exchange (see Dietz et al. 2003). We started with the example of how operational and collective-choice situations may be robustly linked as the "simplest" possible example of a relatively robust system. In such a simple SES, it is easy to understand why the system can be robust over very long periods: the resource users and the public infrastructure providers are the same individuals who observe each other's behavior and the impact of these actions on the resource on a daily basis. They solve their internal problems through reciprocity and trust based on reputation and repeated interactions over an indefinite time horizon (Ostrom, 1998). Such systems may collapse rather rapidly, however, when large biophysical or socioeconomic disturbances occur.

The design principles of Ostrom (1990) were developed with robustness in mind. However, Ostrom used the definition of Shepsle (1989), and studied whether the institutions were robust or in institutional equilibrium. To enhance the robustness of SESs, it might be desirable to have institutions which are not persistent but may change as social and ecological variables change. Ostrom (1990, p. 58) mentioned that "appropriators designed basic operational rules, created organizations to undertake the operational management of their CPRs, and modified their rules over time in light of past experience accoding to their own collective-choice and constitutional-choice rules". This statement illustrates a situation in which a social system adapts to an ecological systems whose dynamics do not change over time. Ecological dynamics may change, and institutions may need to adapt to this change in order to sustain the robustness of the SES. We do not yet know in detail what the design principles for robustness of SES are., However, we will breifly discuss aspects of the original design principles that suggest they are a good starting point.

We now return to the principles listed in Table 3. Why would these design principles enhance robustness in SESs? Clearly defining boundaries (Principle 1) helps to identify who should receive benefits and pay costs. If these are not well defined, resource users are less willing to trust one another and the public infrastructure providers. Assigning a rough proportionality between the benefits a resource user obtains and his or her contributions to the public infrastructure (Principle 2) is considered a fair procedure in most social systems (Isaac et al. 1991). Decisions that are considered fair reduce the chance that the resource users will try to challenge, avoid, or disrupt the policies of the public infrastructure provider.

Decisions by local users to establish harvesting and protection rules (Principle 3) enable those with the most information and stakes in a system to have a major voice in regulating use. This principle emphasizes the importance of Link 2 in Figure 1. Further, rules that most of the resource users themselves establish are better known, understood, and perceived as being legitimate.

The first three principles together help solve core problems associated with free riding and subtractability of use. They do not by themselves necessarily improve the robustness of a SES because rules made to solve these problems are not self-enforcing. Thus, monitoring (Principle 4), graduated sanctioning (Principle 5), and conflict-resolution mechanisms (Principle 6) as part of public infrastructure provide continuous mechanisms for invoking and interpreting rules and finding ways of assigning sanctions that increase common knowledge and agreement. These principles, taken together can be thought of as a feedback control for resource use. They transform information about the state of the system into actions that influence the system. However, the constraints imposed by rules are not like the constraints imposed by the physical infrastructure. Whether resource users follow the rules depends on their perception of legitimacy and whether the rules are monitored and enforced. Thus, given that agents do not possess perfect information about the state of the system and actions of other agents, the SES can become fragile from within due to conflicts over the interpretation of rules, whether certain agents have indeed broken a rule, and the nature of the appropriate punishment. Without regular access to low cost and rapid conflict resolution mechanisms to mediate this internal noise, the common understanding about what rules mean can be lost. Graduated sanctions preserve a sense of fairness by allowing flexible punishment when there is disagreement about rule infractions. Without these mechanisms the incentives to over-harvest and free ride may again dominate strategic behavior.

Recognizing the formal rights of users to do the above (Principle 7) prevents those who want to evade local systems from claiming a lack of legitimacy. In addition, nesting a set of local institutions into a broader network of medium- to larger-scale institutions helps to ensure that larger-scale problems are addressed as well as those that are smaller. Institutions that have failed to sustain resources tend to be characterized by very few of these design principles, and those that are characterized by a few of the principles are fragile.

We expect that more systematic analyses of the robustness of SESs will provide design principles concerning how communities deal with ecological dynamics at various scales. Such principles will include, for example, sustaining memory, adapting rules when ecological conditions change, maintaining institutional diversity, or experimenting systematically with alternative institutional configurations.

Conclusion

We have presented an initial framework for the analysis of robustness of SESs. Our framework is useful for scholars from diverse disciplines as a method for analyzimng the internal dynamics within the components of a SES and the important links among the components. The design principles that originally were developed to understand robust, but simple, common-pool resources are, we think, a good starting point for developing further design principles of robust but more complex SESs. Given that multiple scholars have independently examined their relevance of these design principle for explaining the difference between sustainably versus unsustainably managed SESs, we have some confidence in starting here (Guillet, 1992; Abernethy and Sally, 2000; de Moor et al., 2002; Kaijser, 2002). We will undertake more research on the robustness of linked SESs. We plan to build a dynamic systems model of a SES, for example, that enables us to examine specific rules that are used in linking *A, B, C,* and *D* in Figure 1. We will ask which rules tend to protect the system from the perverse non-cooperative incentives that exist within *B* and *C*, as well as in the linkages between them. We also want to examine what rules protect SESs from particular types of external disturbances (*E).* We think several types of formal models will be useful tools for examining the internal mechanisms of the four entities as these affect their linkages. Rule-based computational models can be used to analyze which conditions of SES configuration are robust (Anderies, 2002; Janssen, 2002).

In this paper we have made some modest steps in what might become an exciting journey to understand how institutional arrangements affect the robustness of SESs. We hope that the proposed framework will function as a valuable roadmap on this journey.

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