

# DESIGN PRINCIPLES FOR ROBUSTNESS OF INSTITUTIONS IN SOCIAL-ECOLOGICAL SYSTEMS

by

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## **Abstract**

What makes social-ecological systems robust? In this paper we look at the institutional configuration that affect the interactions between resource, resource users, public infrastructure providers and public infrastructure. The framework we propose helps us to identify potential vulnerable parts of a social-ecological system to internal disturbances. Especially the tentions between resource users and public infrastructure providers are key in potential robustness of the social-ecological system. Design principles orginally developed for robust common-pool resource institutions seem to be a good starting point for the development of design principles for more general social-ecological systems.

## **INTRODUCTION**

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? What 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? These are the main questions addressed in this paper. We address these questions by examining a particular class of social-ecological systems (SEs).

The SEs of relevance to this paper are (1) complex systems composed of biophysical and social components and (2) systems where individuals have self-consciously invested resources in some type of physical and institutional infrastructure that affects the way the system functions over time in coping with diverse external disturbances and internal problems. In other words, humans have designed *some parts* of the overall SES. The design effort may have occurred at one time period in the past, or design may have occurred over time as feedback generates information

about how the SES is operating and participants in multiple positions try to improve the operation of the system—at least from their perspective.

Many of our examples will come from irrigation systems which typify the type of SES of interest to us. In an irrigation system, a hydrological cycle is affected by building physical capital in the form of dikes, head-works, canals, and regulatory intakes so as to increase the availability and reduce variability of water supplies to farmers when they need it most. Usually, another form of infrastructure exists—a form of social capital—in the rules that have been constituted so as to change the behavior of the individuals using the irrigation system. The physical infrastructure affects when and how much water flows through the system. The institutional infrastructure affects how much water is allocated to each farmer and the resources that the farmer must invest in the operation of the system. The physical and institutional infrastructure affects the likelihood that the SES will last a long time in a particular environment that is subject to external disturbances. Creating any particular type of infrastructure, however, is no guarantee that the SES will be robust under all conditions that it may face.

Our effort to begin to understand how complex SESs may or may not be robust over time, is also of relevance to the study of managed fisheries, forests, and computer networks in addition to irrigation systems. In all cases of interest here, the ecological resource is a common-pool resource that is characterized by two characteristics (Ostrom, Gardner, and Walker, 1994): First, it is costly to devise physical (e.g., fences) and institutional (e.g., boundary rules) ways of excluding potential beneficiaries. Second, one person can withdraw valued “resource units” (e.g., water, fish, CPU time) from the finite supply that a system can make available given the infrastructure as it exists at any particular point in time. Resource users face incentives that can lead to overuse and lack of maintenance unless institutions are crafted, monitored, and enforced that counteract these incentives. Crafting these institutions, however, occurs in settings characterized by still other incentives that can lead to unsustainable outcomes.

During the history of mankind, impressive examples of complex SESs have existed for hundreds, or even for a thousand years or more that have survived many types of disturbances. These include the irrigation systems of Bali (Lansing, 1991), of the Philippines (Siy, 1982), and of Spain (Maass and Anderson, 1986); the Dutch water boards (Kaijser, 2002), the lobster fisheries in Maine (Acheson, 2003), or the Hatfield Forest (Rackham, 1988). On the other hand, there are numerous examples of rapid destruction of SESs such as the Northern cod fisheries (Finlayson and McCay, 1998) and the Aral Sea (Glantz, 1999). There are also examples of complex social-ecological systems that existed for a long period but have collapsed after long stability, such as early Mesopotamian civilization, the lowland Mayas (Tainter, 1988), the Hohokam (Bayman, 2001), Chacoan (Mills, 2002), Mesa Verde (Lipe, 1995), and the customary marine system of the Tonga (Malm, 2001). Further, some SESs have had substantial difficulty in getting organized in the first place and have faced a recent history of substantial overuse and mismanagement, such as the Oyster fishery of Chesapeake Bay (McHugh, 1972), or irrigation systems in Ghana (Webb, 1991).

## COMPONENTS OF A SOCIAL-ECOLOGICAL SYSTEM

In order to analyze the robustness—or any other attribute of a complex SES—one needs a general framework that identifies the relevant parts of such a system and how they are linked. In Figure 1, we present the elements of such a framework. We identify five “entities” that are normally involved in SESs that are based on common-pool resources (A on Figure 1) utilized by groups of individuals over time (Table 1). Two of these entities are composed of humans. These are the resource users (B on Figure 1), who are the population of those harvesting from resource, and the public infrastructure providers (C on Figure 1), who receives monetary taxes or contributed labor and makes policies regarding how to invest these resources in the construction, operation and maintenance of a public infrastructure. There may be a substantial overlap in 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.

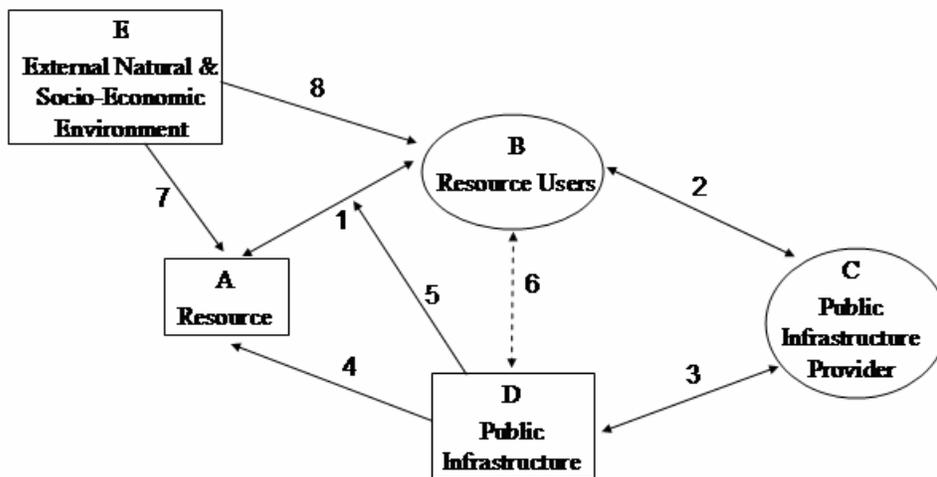


Figure 1: A conceptual Model of a Social-Ecological System

Table 1: Entities Involved in Social-Ecological Systems

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 inshore 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
E. External Environment	Weather, economy, political system	Sudden changes as well as slow changes that are not noticed

The public infrastructure (*D* on Figure 1) combines two forms of human-made capital—physical capital and social capital (see Ostrom and Ahn, 2003; Costanza et al., 2001). The physical capital includes a variety of engineered works and the social capital includes the rules actually used by those governing, managing and using the system that create opportunities and constraints in the action-outcome linkages available to participants. The social capital also includes the monitoring and enforcement of these rules, the way individuals have learned to work together, and various investments in research and development that may be undertaken to keep the system operating over time in a changing environment.

The resource (*A* on Figure 1) is most frequently a biophysical system or a form of natural capital that has been transformed for use by *B* through the efforts of *C* to invest in *D*. (In fully engineered systems such as a computer network or a highway system, the distinction between *D* and *A* may not be needed, but we will focus in this paper on the problem of achieving robustness related to ecological systems that have not been constructed entirely by humans. If one is going to examine robustness or resilience, one needs to include external disturbances (*E* on Figure 1) which can include biophysical disruptions including floods, earthquakes, landslides, and climate change which impact on *A* or socioeconomic changes including population increases, change in economic opportunities, depressions or inflations, and major political changes that impact on *B*.

## ROBUSTNESS OF A SOCIAL-ECOLOGICAL SYSTEMS

Resilience and robustness are frequently used as equivalent or similar concepts. In this paper, we use the term “robustness” because we are focusing on partly designed systems rather than strictly evolved systems. By robustness of a system, 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). How to determine if a SES is robust and what kinds of system failure should be measured are not very well defined for SESs.

To examine the robustness of a system, one must minimally address the questions: (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, mean that the entire system loses its robustness? In other words, when an ecological system (the resource in Figure 1) collapses, but the social system continues to function due to adaptability of the social actors to derive resources elsewhere, did just a part of the SES collapse, or does one evaluate the entire system as losing its robustness?

Within social or ecological systems this difficulty of interpretation occurs when systems are analyzed at different scales. From a large-scale perspective, a local scale resource might collapse in order to maintain desired functions at a larger scale. Many social systems that were based on an agricultural economic base have allowed irrigation systems to collapse when the region has converted to an entirely different economic system (for an excellent example of these issues, see Berkes, Folke, and Colding, 1998). 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 stepping stone for industrial development of these countries (Lebel et al., 2002). Another example is peat mining in Holland during mainly the 17<sup>th</sup> century to meet the demand for fuel in the Dutch cities (Westbroek, 2002). It is interesting to note that the characteristic Dutch landscape of waterways, polders, and dikes is nowadays viewed as nature, but was a swamp before the peat mining industry started a few centuries ago.

Since we explicitly analyze SESs, we distinguish between a 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*. A resource might collapse and the resource users and the public infrastructure providers might continue to generate desired outcomes by substituting another stream of valued goods. Thus, *both* the social and ecological system requires a collapse before we define a SES to have lost its robustness. With robustness, we refer to the ability of a SES to remain in its social and/or ecological domain of attraction on a particular time scale. A system may be robust during one time period and not in another. We recognize that this is a controversial way of viewing the question.

Thus, the idea of the maintenance of a social system through an environmental collapse brings a time dimension into our definition of robustness. In fact, a social system that generates and rewards innovation can be robust to many external shocks, as long as it innovates quickly enough. However, as Anderies (2003) has discussed in a recent paper, such innovation can make the eventual collapse of a larger system more extreme. Unless society can manage to organize around principles other than “replacement technologies,” it is likely they will all eventually collapse. Are such SES’s robust? We would argue that they are, on a certain time scale. This time scale is defined by the suite of replacement technologies available. As time progresses, and the problems that society faces become more complex, the probability increases that society will come up short on dealing 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).

One of the interesting questions is whether some linked SESs generate internal feedbacks that make them more prone to paint themselves into a corner. How does this depend on the nature of the resource base? For example, the Hohokam built a huge irrigation network to feed themselves in an arid environment. Perhaps the need to mobilize labor and maintain the system induced a rigid social structure between the public infrastructure providers and resource users that made the system brittle and unable to deal with change. It may not have been a catastrophic environmental event that caused them to collapse. However, the social arrangements that were driven by the society's need to cope with the environment made it collapse from within.

In summary, we will argue that a SES is robust if it prevents the ecological system 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. Because a social system can persist in one time frame, however, does not mean it will last forever. It is likely that all social systems will find themselves eventually in a domain where collapse will occur. We might argue that the ability of a social system (*B* and *C*) to persist in the face of an ecological collapse is a sign that that system has low adaptive capacity in relation to that ecological resource. Rather than looking for social changes to prevent the collapse of a resource base, the social system maintains itself and looks for another resource to exploit. We hope eventually to be able to offer some useful suggestions for how to avoid this sequential destruction of natural resources.

## **THE GAMES WITHIN AND BETWEEN THE COMPONENTS OF A SOCIAL-ECOLOGICAL SYSTEM**

If the only problems that challenged a complex designed SES came from external disturbances (*E* on Figure 1), addressing the question of how institutional arrangements affect the robustness of SESs would be easier. The fluctuations within internal entities and the links between are as important (and, sometimes more important) in assessing how institutions affect the robustness of linked social-ecological systems as are external disturbances. A variety of games are played among the resource users and among the participants in the process of providing the public infrastructure. Further, games are played in regard to the linkages among resource users and the public infrastructure providers (Linkage 2 on Figure 1), the public infrastructure providers and the investments made in the infrastructure (Linkage 3), the harvesting rate from the resource (Linkage 1), and potentially, the linkage 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 five entities and eight linkages identified on Figure 1.

Table 2: Linkages Involved in Social-Ecological System

<b>Linkages</b>	<b>Examples</b>	<b>Potential Problems</b>
(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
(3) Between public infrastructure providers and public infrastructure	Building initial structure	Over- or under-invest
	Regular maintenance	Shirking
	Monitoring and enforcing rules	Cost / corruption
(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	Severe weather, earthquake, landslide	Destroys resource and infrastructure
(8) External forces on resource users	Major changes in political system, economic prices, new roads, and infrastructure	Conflict, uncertainty, out-migration, greatly increased demand

A major focus of the past literature that has analyzed the problem of sustaining common-pool resources over time has examined the games played by resource users themselves and how they may affect and be affected by the resource system. Classic studies by Gordon (1954) and Hardin (1968) presumed that unless the resource was owned either by individual resource users or a governmental unit, the temptation to overharvest from the resource (Linkage 1) and to free ride on the provision of resources needed by the public infrastructure provider to invest in the infrastructure (Linkage 2) would lead itself to the destruction of the resource.

In other words, there was a presumption into the 1980s that there was “one best way” of governing a common-pool resource. Scholars disagreed, however, on whether the best solution was private ownership or government ownership (i.e. whether a Coasian or Pigouvian approach was best in practice.). Many of these models presumed a very simple ecological system such as a single species fishery model (with no age structure) in which the only factor affecting the availability of fish in the next time period was the harvesting effort (and total fish biomass) in the

past period (see, for example, Gordon, 1954). Clark (1990) discusses several problems associated with the simplifying assumptions made in these models.

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).

With these simple models of the ecological system, it was possible to define a Maximum Sustainable Yield (MSY) and a Maximum Economic Yield (MEY) and simple policies to reach the latter goal. The simplicity of the earlier models 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 of SESs (Lansing, 1991; Mwangi, 2003; Netting, 1976, 1982).

As scholars have tried to develop more realistic models of ecological systems, there has been a lot of challenge to the idea that there could be “one best way” to govern and manage the diversity of common-pool resources that exist in the world (see National Research Council, 2002). Not only do the models of the ecological system need to include more of the important aspects of the complexity of these systems, eventually, we need to understand the patterns of behavior within the entities and across the linkages shown in Figure 1. We know it is not possible to have one *integrated model* of an *individual* organism that includes ALL of the important linkages among such essential “entities” as the heart, lungs, brain, and skeletal system. We do use skeletal charts or frameworks of organisms and models of the working parts, but we cannot put all of that complexity into a single model. It is a major accomplishment to understand how each system works, how they are linked, and where problems in one part generate problems in other parts. Similarly, it is not possible to have a single, integrated model of all of the entities and their linkages shown in Figure 1. 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 do in this paper.

## **LINKING OPERATIONAL AND COLLECTIVE-CHOICE PROCESSES**

Most institutional analysis of SESs have so far focused on either the day-to-day harvesting decisions of resource users at an operational level or the policy choices of public infrastructure providers at a collective choice level. Those focusing on the operational level assume a fixed set of rules and determine the appropriate incentive to maximize long term harvest, or other social welfare objectives (e.g., Clark, 1990). The insights from those studies suggest that the rules and incentives need to be well-tailored to avoid overharvesting. If the operational-level analysis focused on the maintenance of a public infrastructure, such as for irrigation systems, the incentives need to be well-tailored to avoid free riding of the resource users on the provision of public infrastructure. As mentioned above, the resulting picture of studies focusing on the operational level is that the government should manage these systems so as to limit the choice sets of resource users regarding how much to harvest or to invest. Alternatively, the presumption

is made that individual rights to resource units should be determined so that a market mechanism can be used to allocate resources to their most valued use (see Tietenberg, 2002, for 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) showed that for a society with at least three options and two members, there exists no social choice function, which transforms the set of preference orders, one for each individual, into a global societal preference order. Shepsle's (1979, 1989) work showed how institutions may solve some of these problems. Institutions achieve this hardly nimble feat by empowering some actors and demoting others. By doing so equilibrium outcomes become possible. 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 exist since there may be a mismatch between the costs and benefits. The resource users may not be willing to pay a tax if the public infrastructure providers do not invest in public infrastructure that will benefit the resource users.

## THE SIMPLEST CASE

The simplest case of the linkage between *B* and *C* would be that the resource users and public infrastructure providers are a small group of the same actors who have relatively homogeneous interests. Further, if there is no medium of exchange generally accepted in the economy 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 supposed to be present for a work day to maintain a canal, it is hard to hide the fact that one farmer did not cooperate! 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 on themselves harvesting rules and investment requirements. If such systems experience little external challenges they can sustain themselves for a very long time. 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.

In the case where the actors of the operational and the collective choice level are identical, the system might persist in an environment with a stable disturbance regime. However, because they are well adapted to this stable disturbance regime, they might not be robust to a number of challenges coming from outside the system. Construction of a new road might have, for example,

many unintended consequences. 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. decline death rate due to better health care, the option to import food in periods of scarcity, etc.). Such population growth may threaten the SES in different ways. More resource users may harvest from the resource. This would challenge 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 in line with population growth.

With a larger population size it becomes likely that specialization of tasks occurs. A number of resource users now become public infrastructure providers. As long as there is a strong social embedding of those public infrastructure providers within the community of resource users, networks of control and monitoring might 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.

Inflow of people from outside the SES can have major consequences when there are no clear rules for who is eligible to be a resource user. In various SESs, one needs to be living in a SES for certain generations in order to be accepted to be a member. Lobster gangs in Maine are such an example (Acheson, 1988, 2003).

Changes in economic opportunities in a region may challenge a SES. If the public infrastructure provider was organized in an era when all resource users were heavily dependant on the resource, the users would be more likely to participate in decisions related to the provider and to co-produce the upkeep of the infrastructure. As Baker (forthcoming) analyzes for a set of 39 farmer managed irrigation systems in Himalchal Pradesh, India, however, when some farmers using an irrigation system begin to obtain significant off-farm income, their valuation of the resource and of their time may change substantially. Instead of the resource being the major source of household sustenance, the resource may now only be of marginal importance. And the days of work that are requested by the provider to maintain the system may be far more costly to members of a household.

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. You take roll at each maintenance day and you know whether people have shown up or not. Further, resource users can easily see where this input is allocated. If the public infrastructure providers want the resource users to build them a beautiful home, they can say “No, that does not contribute to our 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. With money as the medium of exchange the public infrastructure providers may shift some of it from investing in the irrigation system to investing in their new house or a Swiss bank account. This is more difficult for the resource users to see.

## MORE COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

As soon as one introduces changes in the assumptions of a small, homogeneous group involved in a pattern of mutual reciprocity to produce an obvious benefit for all, 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 might become to sustain the SES. In the extreme case, when there is no overlap, the public infrastructure provider has an incentive to rent seek by requiring high taxes from the resource users, and not invest in the public infrastructure. This may lead to a collapse of the system. Since the public infrastructure provider does not depend on the SES, it may act as a roving bandit, who will confiscate wealth with little regard for the future, (Olson, 1993)

There are multiple variations between these two extremes:

- The public infrastructure providers might be (elected) representatives from the population of resource users. Since they are part of the actors who also benefit from the resource they may want to invest in the public infrastructure, but problems with rent seeking and lobbying may lead to tax revenues not being invested in public infrastructure.
- There might be a difference in information available to resource users and public infrastructure providers. Resource users may have more local knowledge about the resource dynamics, while the public infrastructure providers know how much tax is collected and where it is spent. (This relates to the problem of accounting in the recent scandals in the USA.) The public infrastructure providers might decide on harvesting rules without an accurate understanding of the resource dynamics, thus generating unintended consequences. An example is the collapse of the Northern Cod, where the governmental 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).
- Heterogeneity in the benefits resource users derive may exist. Some may benefit from the public infrastructure and the others do not. Nonbeneficiaries may refuse to pay tax. The Aral Sea is an extreme example of heterogeneity. Farmers upstream benefited from irrigation infrastructure, but those dependent of the ecological services of the Aral Sea witnessed the disappearance of their resource system.
- 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 operated and why an effective linkage between the resource users and the public infrastructure providers is so important. An intriguing example is from Taiwan, where the weakening of Link 2 has led to a weakening of Links 3 and 6. In Taiwan, a set of 17 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 has undertaken 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: 7-8). As it turned out, both major national parties supported the cancellation of irrigation fees as no one wanted to be seen as against the farmer, even though many of the officials familiar with irrigation expressed substantial concern about the long-term consequences.

The cancellation of the fee has had substantially adverse consequences. Farmers are much less likely to volunteer 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 earlier done (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 been declining precipitously and the cost of water supply has been increasing rather than decreasing. Thus, systems that have been robust for a long period 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 ROBUST, COMPLEX SOCIAL-ECOLOGICAL SYSTEMS**

We do not wish to argue that the only robust SESs are very small-scale common-pool resources located in remote locations serving a homogeneous community without market opportunities or access to a commonly-used medium of exchange. 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 of time so long as external disturbances are not too large or erratic. 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 dilemma problems by adopting strategies of reciprocity

with individuals who trust each other based on reputation and interaction over an indefinite time horizon (Ostrom, 1998). Such systems may collapse rather rapidly, however, when large biophysical or socioeconomic disturbances occur.

More than a decade ago, Elinor Ostrom (1990) put forth a series of design principles which she thought, on the basis of doing a lot of fieldwork, reading extensive case study literature, and familiarity with the growing theoretical literature on institutions, characterized robust, common-pool resource institutions. These varied from small, self-contained systems of homogenous resource users to complex systems organized in modern economies where the resource users were linked to public infrastructure providers through a variety of mechanisms. Systems were characterized as robust using Kenneth Shepsle's (1989) concept of institutional robustness. Shepsle considered a system to be robust if it was long-living *and* the operational rules had been devised and modified over time according to a set of collective choice rules (which themselves might be modified more slowly over time within a set of constitutional-choice rules, which were modified, if at all, very infrequently). Among the many systems that met these criteria, the specific operation and collective choice rules that were observed varied dramatically from one SES to another. Thus, the particular harvesting and provision rules could not be used as the foundation for assessing robustness.

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 using the design principle self-consciously, but rather than those systems that were robust could be characterized as meeting a large number of these principles. The design principles identified at that time are listed in Table 3.

Table 3: Design Principles Derived from Studies of Long-Enduring Institutions for Governing Sustainable Resources

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.

*Source:* Based on Ostrom (1990: 90).

Why would these design principles help a SES, in line with our framework, become robust? 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 as they never know when strangers may take advantage of the reciprocity the resource users have built up over time to overexploit the resource. Assigning a rough proportionality between the benefits a resource user obtains and the costs the user contributes to the public infrastructure provider for the public infrastructure (Principle 2), is considered a fair procedure in most social systems. When decisions are considered fair, there is less 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 stake in a system to have a major voice in regulating use. 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. However, they do not by themselves necessarily improve the robustness of a SES because rules made to solve these problems are not, however, 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 state. However, the constraints imposed by rules are not like the constraints

imposed by the physical infrastructure. Under most normal weather conditions, water flows in a constructed channel in a predictable way. Whether farmers follow the rules in regard to the amount of water they extract or the amount of resources they contribute to the public infrastructure provider, 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 as to the interpretation of rules, whether certain agents have indeed broken a rule, and the nature of the appropriate punishment. Even then, conflicts can occur as to the interpretation of rules and without regular access to low cost and rapid conflict resolution mechanisms mediate this internal noise in the system by reinforcing, the common understanding about what rules mean. Graduated sanctions preserve a sense of fairness by allowing flexible punishment when there is disagreement about rule infractions. Without these mechanisms the incentives to overharvest 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 some, but not most, of the principles are fragile.

Systems such as the *zanjeras* of Northern Philippines (Coward, 1979; Siy, 1982); the *Thulo Kulo* irrigation system of Nepal (Laitos et al., 1986; Martin, 1986; Martin and Yoder, 1983); the 1,000 year old irrigation system of the *Huerta of Valençia* (Maass and Anderson, 1986); and contemporary users of groundwater basins underlying the Los Angeles metropolitan area (Blomquist, 1992); differ greatly in regard to surface characteristics but all have resource users linked to public infrastructure providers and to public infrastructures in a manner consistent with the design principles. The *zanjeras* could be called communal system as landless laborers can acquire use-rights to land and water. The *Thulo Kulo* irrigation system approaches a strictly private system given that each farmer has separable land and water rights. The *Huerta of Valencia* forbids the separation of water rights from the land being served while no necessary relationship exists between ownership of land and water in the southern California groundwater basins where a vigorous market for water rights without their attachment to the ownership of land.

Potential additional design principles need to be defined for the ability of resource users to express their demand to public infrastructure, knowledge transfer between resource users and public infrastructure providers, accountability of investments by public infrastructure, and effects of public infrastructure on resource.

## CONCLUSION

We feel somewhat confident about the validity of the design principles as being associated with robust SESs given that multiple scholars have independently examined their relevance for explaining the difference between systems that have sustainably managed and harvested from a diversity of resources over time (de Moor, Shaw-Taylor, and Warde, 2002; Kaijser, 2002). We

contemplate undertaking considerably more research on the robustness of linked SESs. We would like, for example, to begin building a dynamic systems model of a SES that would enable us to examine what are some of the specific rules that could be used in linking *A*, *B*, *C*, and *D* in Figure 1 so as to protect the system from external disturbance (*E*), as well as protecting the system from the perverse incentives that exist within *B* and within *C* and in the linkages between them and the public infrastructure and resource. We think several types of formal models will be useful tools for examining the internal mechanism of the five entities as these affect their linkages. Rule-based computational model can be used to analyze which conditions of SES configuration are robust (Anderies, 2002; Janssen, 2002). We also plan to undertake a systematic comparison of case studies of long-living SESs. At the moment, we are developing a coding scheme that may make it possible to perform systematic analysis of case studies.

In this paper we 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.

### **Acknowledgements**

Paper to be presented at the IASCP Northern Polar Regional Meeting, Anchorage, Alaska, August 17-21, 2003. An earlier version of this paper was presented at the workshop on "The Robustness of Coupled Natural and Human Systems," Santa Fe Institute, Santa Fe, NM, May 16-18, 2003. We gratefully acknowledge support from the Center for the Study of Institutions, Population, and Environmental Change at Indiana University through National Science Foundation grant SES0083511, from the Resilience Alliance through a grant from the James S. MacDonnell Foundation, and from the Workshop in Political Theory and Policy Analysis through a grant from the MacArthur Foundation. We greatly benefited from discussions with Ed Araral, Bobbi Low, Vincent Ostrom, Carl Simon, Brian Walker, and James Wilson, and the helpful editing of Patty Zielinski.

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