3b2 Version Number : 7.51c/W (Jun 11 2001)
File path : p:/Santype/Journals/Taylor&Francis/Usnr/v20n4/usnr216061/usnr216061.3d
Date and Time : 6/1/07 and 17:08

Society and Natural Resources, 20:1–16

ISSN: 0894-1920 print/1521-0723 online
DOI: 10.1080/08941920601161320

Robustness of Social-Ecological Systems to Spatial and Temporal Variability

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Some social-ecological systems (SESs) have persisted for hundreds of years, remaining in particular configurations that have withstood a variety of natural and social disturbances. Many of these long-lived SESs have adapted their institutions to the particular pattern of variability they have experienced over time as well as to the broader economic, political, and social system in which they are located. Such adaptations alter resource use patterns in time and/or space to maintain the configuration of the SESs. Even well-adapted SESs, however, can become vulnerable to new types of disturbances. Through the analysis of a series of case studies, we begin to characterize different types of adaptations to particular types of variability and explore vulnerabilities that may emerge as a result of this adaptive process. Understanding such vulnerabilities may be critical if our interest is to contribute to the future adaptations of SESs as the more rapid processes of globalization unfold.

Keywords disturbances, institutions, resilience, robustness, social-ecological system, variability

Received 10 May 2004; accepted 19 May 2006.

We gratefully acknowledge support from the National Science Foundation (grants SES0083511 and BCS 0527744), from the Resilience Alliance through a grant from the James S. MacDonnell Foundation, and from the MacArthur Foundation. Furthermore, we greatly benefited from the participants at seminars in Santa Fe, Bloomington, Montreal, Oaxaca, Fairbanks, Bonn, the reviews of anonymous reviewers, and discussions with Ed Araral, Bobbi Low, Vincent Ostrom, Carl Simon, Brian Walker, and James Wilson, and helpful editing by Patty Lezotte.

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Various local and regional social-ecological systems (SESs) (by which we refer to a *particular* group of people, a *particular* set of resources, and a *particular* set of institutions that operate together, as carefully defined later) have existed for more than a century by adapting their institutions to local natural variability (Berkes and Folke 1998). Examples of such adaptations include institutional arrangements associated with transhumance and irrigation systems, both of which mediate environmental variation. Some of these long-lived SESs are presently experiencing difficulty in continuing to function due to the changing nature of the variability they face. How did these SESs adapt to the natural variability they faced in earlier times? Why are they becoming more vulnerable now? Have these SESs become vulnerable because they became too highly adapted to a particular type of variability in the past? In this article, we provide a modest attempt to identify a research strategy for addressing these questions.

These questions are interesting in their own right, but have broad implications as well. These implications have two interrelated parts. First, national and international interventions in small-scale SESs do not always lead to desired outcomes (Gibson et al. 2005; Ostrom et al. 2002). Many explanations exist as to why national governments choose to intervene in the first place, and why they are so often unsuccessful. One compelling argument has been put forth by Scott (1998). He argues that states seek to sedentarize mobile people and regularize the way they interact with resources in order "to make a society legible, to arrange the population in ways that simplified the classic state functions of taxation, conscription, and prevention of rebellion" (Scott 1998, 2). There is no doubt that this "ordering" of social interactions has many benefits. As Scott points out, however, any "ordering" of society from above is necessarily schematic since it "ignores essential features of any real, functioning social order (Scott 1998, 6). Important local knowledge and practices are necessarily lost when national governments attempt to "regularize" interactions between people and nature without a solid knowledge base of the diverse ecological and social conditions faced.

There is abundant evidence that large-scale interventions in local SESs have frequently been counterproductive (Feeny et al. 1990). It is also clear that small-scale governance regimes that incorporate local knowledge, have clear rules that are enforced, and rely on high levels of trust frequently perform well (Ostrom 1990; Ostrom et al. 2002). Herein lies the second aspect of the broader implications of the questions just outlined. Preserving well-functioning small-scale SESs to manage ecological resources may be as important for the future as preserving biodiversity. The reason for this importance is that preserving institutional diversity maintains a rich set of solutions of social systems adapting to ecological contexts. At the same time, the process of globalization has aspects similar to the "regularization" processes associated with states. Thus, globalization processes can be in direct conflict with the maintenance of local SESs (Young et al. in press), such as the sequential exploitation of marine resources (e.g., sea urchins) (Berkes et al. 2006). Thus, it is essential to understand how local SESs become vulnerable as the context in which they operate changes with an increasingly globalized world. All institutional solutions to resource problems should be considered to be relatively "temporary fixes." All SESs are potentially vulnerable to new disturbances in their environment. This article attempts to address this important issue.

Foundations: SESs, Variability, Disturbance, Scale, and HOT

Resilience and Robustness

The concepts of robustness, resilience, and adaptation to variability are receiving more attention in the literature regarding the interaction of social and ecological systems in highly uncertain environments (Gunderson and Holling 2002; Berkes et al. 2003). A core idea emerging from resilience theory is that complex systems such as SESs organize around continuous change. Components of this change are the processes of increasing connections across several scales and the locking up of resources that then cause the system to become susceptible to a collapse initiated by a minor disturbance (Holling 1986). Related concepts developed by Carlson and Doyle (2002) suggest that systems subjected to a particular type and degree of variability may become highly optimized to tolerate this variability (this characteristic of adaptive systems is referred to as highly optimized tolerance or HOT). In so doing, however, the system may become more brittle and susceptible to changes that may occur in the type and degree of variability to which it has become highly adapted or to new types of disturbances. Put another way, systems cannot be robust to all types of variability and disturbances. Complex systems must trade off the capacity to cope with some types of variability to become robust to others. This process of trading off among different sets of feedbacks is apparent in both the idea of resilience and of highly optimized tolerance (HOT).

The ideas of resilience and robustness have developed in ecology and engineering, respectively. Both can be applied when analyzing the persistence of SESs (Anderies et al. 2004). We use these concepts to help explain several well-documented, long-term studies to address our central question of why some long-lived SESs persist in the face of change and why some do not. This requires that we identify for each case the particular type of variability to which the social-ecological system have adapted, the nature of these adaptations, and the vulnerabilities that may arise. We may then extract some general themes that may help in maintaining SESs that are becoming increasingly embedded in the modern global economy. Before embarking on this journey, we clarify our use of the terms SES, variability, disturbance, and scale, and provide additional background for the concept of HOT systems.

Social-Ecological Systems

The social-ecological systems (SESs) of relevance to this article are systems composed of biophysical and social components where (1) individuals have self-consciously invested time and effort in institutional infrastructure (and, in some cases, physical infrastructure) that affects the pattern of outcomes (e.g., patterns of resource use and their distribution within the population) achieved over time in coping with diverse external disturbances and internal problems, and (2) these components are embedded in a network of relationships among smaller and larger components. 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, more likely, the design may have developed over time as feedbacks generated information about how the SES was operating.

Based on these feedbacks, participants in various positions have then tried to improve the performance of the system—at least from the perspective of those who invest heavily to keep the system operational over time. Whether the performance of the system is a success or a failure is subject to the interpretations of those involved in the SESs. We are not imposing a measure of success or failure. Rather, we are suggesting that attempts to improve the performance of the system from outside may undermine its ability to cope with change and maintain its structure and function. Some changes might have been experienced as improvements in the short term, but subsequently reduced the resilience of the system. A typical example is the suppression of forest fires, which led to accumulation of fuel for large intensive fires (Holling 1986; Reiners, 2006).

SESs frequently involve groups of resource users who are linked to each other and to multiple resources that occur across multiple scales through multilevel governance arrangements (for an extended discussion of the concept of a SES, see Anderies et al. 2004). Given the complexity of these systems and the spatial and temporal changes that affect their structure and performance, many scholars have written fascinating case studies about them (see Acheson 2003; Netting 1981; Lansing 1991; Glick 1970; and others cited later). There is, however, a need to generalize some of the insights from case studies by developing more coherent and useful frameworks, theories, and models that enable scholars and policymakers to better understand complex, multilevel, multiscale systems.

We emphasize "multilevel" and "multiscale" because they characterize attributes that are often critical organizing features in many SESs. In the discussion that follows, we use *multilevel* to refer to nested, human organizational structures that operate at several levels. Operational decisions are made on a daily basis within the context of a set of rules, created at a collective-choice level, which in turn were created at a constitutional-choice level (Ostrom 2005). We use *multiscale* to refer to ecological/biophysical processes that operate at several geographic and temporal scales and are often linked across these scales (Gibson et al. 2000).

Multilevel and multiscale systems are far more complex to study and understand than even the most complex single-level or single-scale system. Nonetheless, it is important for researchers interested in resources to begin to explore how variously structured multilevel and multiscale systems enhance or detract from the capabilities of SESs to persist over the long run. Several recent studies that have examined the persistence and performance of irrigation systems (Baker 2005; Lam 2005; Lansing 1991), pastoral systems (Chakravarty-Kaul 1998; Netting 1981, 1982), and inshore fisheries (Acheson 2003; Wilson 2002) over extended time periods are particularly useful for the insights they bring to an analysis of the robustness of systems that operate at multiple levels and multiple scales.

Variability and Disturbances

SESs face both predictable and well-understood variation as well as unpredictable temporal and spatial variation of social and natural variables. In both cases, the "objective" of the SES is to maintain flows of desired ecosystem goods and services within some tolerable bounds. If the flows move outside these bounds, human suffering may occur. Systems can become attuned to either type of variation, and in so doing may become vulnerable through a robustness trade-off. Typical variations are regular and continuous, like temperature and precipitation. On the other hand, some variations are unexpected and discrete. These disrupt ecosystems, communities, and population structures. Those events are called disturbances (White and

Pickett 1985). Ecologists tend to focus on natural variability and disturbances, like climate variability, fire, floods, hurricanes, and insect and disease outbreaks. Within SESs, we broaden the original ecological definition to include a broader range of disturbances and variability, such as changes in regulations concerning property rights or subsidies, the autonomy of local resource users to govern a local resource, the preferences of producers or consumers, local commodity prices and wage rates, transportation costs between producers and markets (e.g., creation of paved roads), fluctuations of commodity prices on the global market, and so on.

Adaptation

Adaptation to variability may occur over many generations by experimentation and learning and, as a consequence, may lead to the development of specialized institutions. Such adaptations refer to highly optimized complex systems that are robust within a certain range and type of variability, but may be fragile to changes in these patterns of variability (Carlson and Doyle 2002). We hypothesize that many long-term SESs have developed a highly optimized tolerance (HOT) reaction to a particular type of variability, but are now vulnerable to regime changes caused by many contemporary social-economical processes.

As described later, various long-lived SESs have adapted their institutions to the variability they have experienced over space and time as well as to the broader economic, political, and social systems in which they are located. Such adaptations may lead to patterns of resource use in time and/or space that maintain a particular configuration of the SESs as long as the disturbances experienced are similar in type and extent to those experienced in the past. The mixture of private and common property rights that enable the movement of livestock over large areas (Netting 1981, 1982; Smith 2000; Chakravarty-Kaul 1998; Agrawal 1999) is an example of an institutional arrangement that expressly addresses the multiple geographic scales of the underlying resource system. Another example of an adaptation to disturbances is the switching of institutional rules to be used in an irrigation system depending on the level of precipitation (Maass and Anderson 1986). This switching of rules is not expressed at multiple scales, but rather at multiple levels of decision making as an adaptation to droughts.

Any complex SES that suffers periods of low resource availability typically attempts to develop infrastructure—either physical or institutional—that enables it to cope with adverse conditions. If a group of irrigators can build a dam, that physical infrastructure stores water from good years to be used in bad years. Agricultural systems have built storage facilities to spread the consumption of harvest in good years so that some are available in bad years. If physical infrastructure is not suitable, or beyond technical or economic reach, various rule systems are developed that switch regimes for allocating resources. In good years, looser rules are used that do not require strict monitoring. In bad years, stringent rules are used to allocate a much smaller supply to users, depending on what is considered a fair and efficient system, given local values.

We may distinguish two classes of adaptations. First, people have developed institutions over time, intentionally or not, to spread resource-use intensity over space and/or time in accordance with particular variability regimes. This might include seasonal movement of cattle, or seasonal permissions to harvest from a resource (a multiscale issue). We may view such systems as being in a stable periodic cycle. We show later that disrupting this stable cycle may make the system vulnerable to collapse.

The second class of adaptations is characterized by those directed at managing discrete disturbances like droughts, cyclones, and price fluctuations. Systems in which resources are not mobile (e.g., irrigated agriculture) are especially vulnerable to such disturbances. Resource user groups have developed diverse responses allowing them to recover after a disturbance. To cope with disturbances, they have themselves developed technical solutions like dams and irrigation systems. This physical infrastructure and the associated institutional arrangements (rules that guide and constrain human action, as explained in Ostrom 2005) enable the system to remain within a stable configuration when it is challenged by a disturbance. Feedbacks from efforts to tailor responses to particular types of disturbances can increase vulnerability of the system. For example, dikes are suitable for a particular range of water-flow variability. Changes in water-flow regimes may cause dikes to become too wet or too dry, leading in both cases to a collapse of the dike.[1] Loss of the ability of a system to reorganize and recover after a disturbance may lead to a collapse of the SES.

Irrigation systems are always linked to water sources that are upstream or downstream of each other. Multiple channels and distribution devices are used for irrigation, and are potentially linked with urban or commercial users. Because marine resources are mobile, the productivity of one inshore fishery may be affected by activities in neighboring fisheries and by wastes from nearby industrial and agricultural sites. These are examples where the recognition of the multiscale nature of these systems is essential. A multilevel system, on the other hand, is one in which resource users and the providers of infrastructure are linked either formally or informally with other governance regimes. Without considering the multilevel nature of such systems, key insights concerning the robustness of the system will be missed. Efforts at reform may eliminate a level of organization that is not recognized as playing a key role in dealing with ecological and social disturbances.

Changes in Variability

Due to changes in the ecological, economic, and political variability, various well-adapted SESs have been transformed, have experienced serious challenges to their persistence, or have adapted and continue their activities. What makes SESs respond differently? The changes in variability are largely caused—it appears from reading many case studies—by an increasing connection of SESs with higher level phenomena such as national governmental policies, technological change, or international economic developments. Thus, connectivity to previously unexperienced disturbances from outside the SES may challenge the capacity of the system to adapt.

Connections with other scales may also provide new opportunities as well as new challenges for the actors within the SESs. From our reading of many case studies, we distinguish two types of challenges. The first type of challenge is a slow, persistent change in socioeconomic conditions or technology. This may affect the users' dependency on the resource and may lead to a transformation of the SES. Such a transformation may have both winners and losers, and the transformed SES may become adapted to the new spatial and temporal variability shaped by the socioeconomic changes. The second type of challenge is a top-down imposed change of institutional arrangements. For example, from the perspective of higher level authorities, a local SES might not be recognized as being well adapted to the challenges it faces. The ambitions of higher level authorities may lead to changes in local institutions in the expectation of meeting their goals. Lack of understanding of the SES leads to an inability to meet participants' goals and a reduction of the performance of local and sometimes larger scale SESs.

In the remainder of the article, we discuss the two types of adaptations (SESs adapted to mobile resources and SESs adapted to stationary resources) and the two types of challenges (long-term slow challenges and top-down interventions) that they face in more detail. For each category, we discuss one relevant case study in more detail and refer to a number of additional case studies for additional context. Finally, we discuss the general insights derived from this analysis and their consequences for future research and policy.

Categories of Robustness and Regional Variability: The Case Studies

To illustrate how institutional arrangements that are adapted to specific types of ecological variation may become vulnerable in different ways to changing conditions, we discuss four cases in some detail. These four cases can be placed within a matrix generated by two types of adaptations and two types of external change (see Table 1). The two types of institutional adaptations are (1) institutions that enable resource users to utilize the spatial and temporal distribution of resources and avoid excessive pressure on particular locations within the ecological system (top-left cell of Table 1) and (2) institutions that enable the coordination of resource management and use to regular, but not predictable, events like drought and cyclones (bottom-left cell of Table 1). Two types of external changes are (1) slow, persistent structural change, and (2) relatively abrupt change imposed from the top down. The case study descriptions are organized to move across row one and then row two of Table 1.

SESs Adapted to Utilize Spatial and Temporal Variability that have Experienced Slow, Persistent Changes

This category of SESs includes, for example, systems that combine different types of resource uses on communal and private land during the year as a consequence of seasonal changes. Institutional adaptations in such systems relate to the mechanisms of access to communal land. Examples include the movements of cattle in Törbel, Switzerland (Netting 1981, 1982), and the open-field system in medieval Europe (Smith 2000). Technological (transportation systems) and economic changes (European agricultural subsidies) affect the relative benefits for maintaining such institutional adaptations. Gradually, these types of SESs may disappear by the reallocation of agricultural activities that makes better use of current opportunities. The original SESs were adapted to a particular local variability regime. The slow, persistent change led to an adaptation of the SES and may have shifted the vulnerability of the system to different types of larger scale variability. For example, a SES can be adapted to local variability, but due to lower transportation costs and regional specialization, the SES becomes vulnerable to variability within a larger system. Hence, adaptation to a slow, persistent change can make the system vulnerable to a different type of variability.

Let us examine the example of the medieval open-field system in Europe, especially England, in more detail. In the open-field system, peasants had private

Table 1. Main characteristics of the case studies discussed in the section "Different Categories of Robustness to Regional Variability": Adaptations to ecological processes, institutional solutions, and the challenges they face

Types of adaptations	Long-term challenges	Top-down intervention
Reliance on mobile resources	*Peasants in medieval Europe*: Spatial allocation of grazing and grain production. Solving property-rights conflicts and strategic behavior due to scattering of strips in landscape. Reduction of transportation costs led to specialization of regions.	*Gaddi shepherds*: Seasonal migration patterns. Property rights for grazing: trading grazing rights for manure. Indian government block-migration patterns.
Reliance on fixed resources subject to regular, periodic disturbances	*Farmers in Polynesia*: Diversity of crops. Food storage, diversity in agricultural production, maintaining memory. Trade opportunities led to monoculture of cash crops.	*Irrigation associations in Taiwan*: Water allocation via irrigation system. Irrigation associations for maintenance and coordination. Fee payments by government and other top-down regulations leading to reduced levels of local collective action.

property rights to the grain they grew on their individual strips of under one acre each. These strips were scattered around a central village. However, during particular seasons, peasants were obligated to throw the land open to all the landowners in a particular village so that they could all graze their sheep on the stubble under a common herdsman. The decision to convert the strips of privately used land to common land for a period during each year was made by a village council. This enabled people to take advantage of economies-of-scale in grazing (as well as providing manure for their land) and private incentives in grain growing (that lack important scale economies and suffer from free-riding when communal groups try to share labor inputs).

The patterns of scattering small strips of land have been a mystery to many, as the benefits of the two scales could be achieved with or without the scattering of the agricultural land. And the scattering appears to be an inefficient system, given that a single farmer had to divide his time between multiple, small agricultural strips rather than being able to economize on his own time and focus on one piece of land. Some authors have focused on the need to share risk due to different soil and precipitation patterns and this may have been a contributing factor (McCloskey 1975). Carl Dahlman (1980), however, offers a more convincing explanation of the scattering aspect of the system. By not allowing any one farmer to gain a large amount of contiguous land, the village avoided creating a situation of asymmetric bargaining power. No farmer owned enough land to be able to "hold out" that farmer's agricultural land from the commons and graze his own animals on his own land. Nor did an individual have a right to exclude others once the village decided the land should convert from agriculture to pasture. If all of the farmers had owned sizable chunks of agricultural land in fee simple, rather than the village being responsible for land-allocation decisions, transaction costs would be very high.

If this was the reason for the existence of this mixed system for multiple centuries, why did this system disappear? And why did it take a long time for it to disappear across most of northern Europe? If private property alone was a very efficient solution to the production of food—once a particular location discovered this efficient solution—one would expect to see a change occur rapidly throughout Europe. The so-called "enclosure movement" occurred over multiple centuries. with spurts of activity noted in particular places.

Due to high transportation costs, local communities needed to produce both meat and grain in a small local area, which was feasible if they could convert agricultural land to a common pasture when the crops had been harvested. The communities also needed to deal with the potential incentive of farmers acquiring sufficient land to pasture their own animals on their own land—which would have greatly reduced the available pasture land for other farmers dependent upon the common grazing land. A suitable adaptation was to reduce the incentives of free-riding by scattering individual properties.

When the transportation networks improved and communities had access to markets in grain and meat, no need existed to continue this complicated adaptation. Communities could specialize in meat or grain. The areas of England, for example, that appear never to have used the open-field system were able to specialize in grain production very early and get their grain to a large market, earn a good return, and purchase their meat rather than growing it at home.[2] Dahlman also reports that specialization in production tended to occur quite soon after enclosure occurred, but that enclosure itself took a long time to spread throughout Europe and involved high levels of conflict in some locations where specialization was not easy to achieve.

An example of the changed vulnerability of the contemporary European agricultural system is the list of livestock diseases that have spread throughout Europe during the last decade, including foot-and-mouth disease, pig plague, and chicken plague. Keeling et al. (2001), in a detailed study of the spread of foot-and-mouth in the 2001 outbreak in the United Kingdom, showed that the high connectivity among farmers and the movement of livestock was an important factor in the long-lasting spread of foot and mouth disease.

SESs Adapted to Utilize Spatial and Temporal Variability that have Experienced Changes Imposed from the Top Down

This type of SES includes pastoralist systems that have adapted to seasonal and regional rainfall variability. This adaptation is reflected in pastoralists moving around a large spatial landscape in order to be at the right place at the right moment. Institutional adaptations include mechanisms to gain access to the land of various landowners. An increasing number of such SESs are experiencing the challenge of changes of access by physical or institutional barriers often imposed from the top down (Chakravarty-Kaul 1998; Mwangi 2003).

We now discuss, in more detail, a case study by Chakravarty-Kaul (1998) on the complex dynamics of Gaddi shepherds with their landscape in Himachal Pradesh, India. No particular place in this landscape is ideal for the maintenance of goats and sheep throughout the entire year. The only way that these animals can be cared for is to move them across a substantial terrain. These pastoralists originally adapted their institutions to the harsh ecological conditions in order to survive. They moved their animals, goats, and sheep across a vast mountainous landscape within Himachal Pradesh. During winter, they descended from the mountains and grazed in the valleys and the lower elevation forests. The shepherds have made arrangements with agriculturalists (who own private plots of land) to graze on the stubble left after a harvest from private fields in return for the highly valued manure of the goats and sheep.

In the summertime, it is too hot at lower elevations, so the pastoralists move into the mountains around the tree line. Lyall (1872, 46; cited in Chakravarty-Kaul 1998) writes:

> Snow and frost, in the high ranges, and heavy rain and heat in the low, make it impossible to carry sheep-farming on a tolerably large scale with success in any part of the country. The only way is to change ground with the seasons, spending the winter in the forests in the low hills, retreating in the spring before the heat, up the sides of the snowy range, and crossing and going behind it to avoid the heavy rains in the summer.

These seasonal movements are based on reciprocal relationships. The Gaddis shepherds invest a lot of time in social networking among themselves and with outsiders to provide access to grazing areas in return for manure and other goods and services.

The informally evolved rights of the Gaddis shepherds have never been formally recognized by the national government. In 1947, the Indian government adopted policies that reduced the possibility of providing access of shepherds to the usual grazing grounds by building dams and by providing strictly private property rights to farming communities. This has resulted in more concentrated areas where livestock can graze, and may have contributed to erosion in the forests' hills. The government has accused the Gaddis of free-riding in a commons dilemma.[3] The government has not recognized an efficient solution that took years to work out; in fact, the shepherds and agriculturalists had come to an efficient bargaining solution by trading manure for grazing rights. Agrawal (1999) described a similar system among the Raika shepherds in the semi-arid zones of Rajasthan, India.

The shepherds adapted to the temporal and spatial variability by moving within the landscape in a certain order. Activities that hinder this movement pattern on the landscape hit the vulnerable point of the transhumance system. When these movement patterns are affected, the shepherds are forced to use a smaller area that may in turn lead to overgrazing. Thus, the transhumance system is highly tolerant to seasonal variation by very specific institutional arrangements, but is extremely vulnerable to changes in access by social or physical barriers.

SESs Adapted to Regular Disturbances that have Experienced Slow, Persistent Change

SESs can experience regular disturbances such as floods, droughts, cyclones, and other season-related events. Although the timing and magnitude of the disturbance are unknown, regular exposure to such disturbances leads to adaptations that prepare the SES for disturbance events, such as the creation of buffering capital, which might be food and water resources to be used in periods of scarcity. These SESs can experience a slow, persistent change that enables them to respond differently to regular disturbances. A common challenge is the change of technology and economics that make the SESs able to derive scarce resources from abroad when a disturbance affects the SES. The adaptations to the technological and economic changes make the SES more dependent on external resources.

We illustrate this with an interesting example from the Polynesia islands (Colding et al. 2003). When Polynesia islands are hit by cyclones, the institutions change temporarily to stimulate the recovery of traditional agriculture. These cyclones are unpredictable, severe disturbances. In Samoa, cyclonic storms are relatively frequent (40 cyclones in the last 160 years, with severe cyclones at intervals of 20–30 years). The agricultural system is embedded in a sophisticated institutional structure that organizes community response to periodic environmental disasters. Adaptations are crop diversity, cooperation in planting and restoration after cyclones, and emergency food storage. In other areas of Polynesia where the cyclones are lower in frequency, the agricultural system has been transformed into monocultures of cash crops. In the event of a severe cyclone, these islands are not able to recover without outside help, and must rely on outside subsidies for survival. The island system temporarily seeks to exploit capital stocks from another system. Access to global markets has led some islands to transform, but they have lost their local adaptive capacity as a result. The vulnerability of the system has changed from being able to buffer disturbances locally, to being able to have regions abroad buffer the disturbances. For islands with high intensity of (frequency of) cyclones, the benefits of transformation do not (yet) outweigh the costs of losing adaptive capacity.

SESs Adapted to Regular Disturbances that have Experienced Top-Down Imposed Changes

Like the previous category, SESs in this category are originally adapted to regular disturbances by creating a buffering infrastructure. In this category, we mainly look at irrigation systems that have developed comprehensive coordination strategies to allocate water and to solve collective-action problems for the maintenance of the irrigation infrastructure. There is a significant number of examples where the coordination mechanisms are exposed to a top-down intervention that affects the functioning of the SES (Lansing 1991; Lam 2001; Baker 2005). Such an intervention disrupts the coordination processes, leading to a reduction of the buffering capacity and an increased vulnerability to the regular disturbances.

An interesting example of such a top-down intervention is the nested irrigation system in Taiwan (Levine 1977; Moore 1989; Lam 2001). 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. These irrigation associations are formal corporations, organized by the farmers, that also possess considerable public power. Membership in an irrigation association is mandatory for farmers who own irrigated lands in the service area of an irrigation association. Farmers have been required to pay fees to their local association. The associations, in turn, have taken 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 associations were linked to a higher level public governance system. 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 1998). In some cases of multilevel SESs, relatively robust, local SESs have been seriously challenged by a lack of understanding of how they operated and why an effective linkage between the resource users and governance structures is so important.

Taiwan, like India and 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 2005, 353). 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 consequence.[4]

The cancellation of the fees has had substantial adverse consequences since farmers no longer experienced having a meaningful stake in the continued maintenance of their irrigation system. Farmers are much less likely than before 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 (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 2005, 357). 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 been given a major setback by an effort "to help" the resource users by changing the link between resource users and governance structures. The problem of misunderstanding what actually makes a local SES robust can lead to public policies at higher levels that undermine the more successful SESs.

Discussion

Although SESs can develop institutional configurations over time that fit spatial and temporal variability, survive, and even flourish for long periods, all long-lived SESs continue to be vulnerable to some internal or external disturbances. As we have seen, tailored adaptation to a particular type of variability can make a SES especially vulnerable to a change in that variability. Such changes can be caused either by larger scale environmental changes or by changes in institutional context (e.g. national policies or globalization). When SESs with mobile resources and natural variability adapt themselves to specific movement patterns in the landscape, accompanied with time- and place-specific reciprocal arrangements, they become vulnerable to changes in accessibility. A slow, persistent change of technology and economic opportunities may lead to a relatively smooth transition of the SESs. A top-down intervention of institutional or physical barriers may affect access more abruptly and the SES may not be able to adapt rapidly enough.

When SESs with fixed resources adapt via institutions designed to buffer disturbances, changes in commodity prices or alternative sources of income may compromise the maintenance of physical infrastructure, the associated institutional infrastructure, and the practical operation of the system. In the case studies, we see that slow, persistent change can transform the original SES to one that is more adapted to buffering resources to shocks from outside the SES. SESs that are more dependent on global commodity prices or external employment opportunities are also more vulnerable to fluctuations of larger scale SESs. Top-down interventions that affect local coordination mechanisms have a more severe effect since they may lead to maladaptations (such as heavy overharvesting in a single location). Such maladaptations may be caused by higher level actors having a limited understanding of the local ecological dynamics, making the system more vulnerable to regular disturbances.

We have tried to extract some regularities from in-depth case studies of long-term SESs. These observed regularities should be seen as hypotheses to be tested in future research. Many SESs can successfully adapt to long-term variability and regular disturbances. These adaptations lead to arrangements to coordinate the pressure on the system in time and space. Our analysis suggests that such adaptations make SESs vulnerable in specific ways to particular changes in the types of variability and disturbances. The originally adapted SESs experience different types of challenges. One type of challenge is the slow, persistent change that may transform the original SES through a relatively smooth adaptive process. Nevertheless, this adaptation makes the system more vulnerable to global technological and economic fluctuations. The other type of challenge is top-down intervention that does not recognize the original adaptive mechanisms inherent in local SESs. Such interventions directly affect the functioning of the original SES. With this challenge, the SES might become maladapted, which may lead relatively rapidly to severe consequences for the relevant actors.

SESs become adapted to spatial and temporal variability over time. Each type of adaptation is intended to address some form of real or perceived vulnerability, and each challenge and readaptation may leave the system vulnerable to new changes in the system. We have initially identified two types of adaptations and two types of challenges and the diverse consequences that changes can have on SESs. A further in-depth study will identify, we think, still other important patterns. As the process of globalization proceeds, such analyses may help identify which vulnerabilities are more likely to become most challenging for particular local SESs. If, at the global scale, a collection of many small-scale SESs may better address environmental problems than could a smaller number of larger scale nation-states, then it is critical to understand the robustness–vulnerability trade-offs inherent in small-scale SESs. The analysis presented in this article is a first step in this direction.

Notes

1. In cases of high water levels, dikes get saturated with water, weakening the strength of the dike and thus leading to collapse. Collapses due to droughts are rare, but in the extremely dry European summer of 2003, a dike collapsed in Wilnis, the Netherlands, as a consequence of the drought. The recent tragedy in New Orleans was largely caused by the collapse of water-logged dikes after the height of the storm had passed over the region.
2. Kent, England, is used as one example of an early specialist in grain. Kent is located near London and became the granary for the capital city.
3. Mwangi (2003) documents a similar problem of governments accusing pastoralists of free-riding when ecologists have documented that the Masaai pastoralist system was well-adapted to the dry, spotty ecology in which it evolved.
4. Douglass Vermillion (2001, 188) recounts a similar event that occurred in the Philippines in the early 1990s, where candidates running for the Philippine senate announced that they would abolish the national irrigation service fee since they felt that the "farmers were too poor and shouldn't have to pay the fee." In the Philippines, farmers actually protested this possibility as they argued that the "payment of the fee was their only basis for demanding an acceptable irrigation service from the government." That was not the end of the story, however, and fees were substantially reduced at a later juncture.

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