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Robustness Trade-offs in Social-Ecological Systems

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Abstract: The governance of common-pool resources can be meaningfully examined from the somewhat broader perspective of the governance of social-ecological systems (SESs). Governance of SESs invariably involves trade-offs; trade-offs between different stakeholder objectives, trade-offs between risk and productivity, and trade-offs between short-term and long-term goals. This is especially true in the case of robustness in social-ecological systems – i.e. the capacity to continue to meet a performance objective in the face of uncertainty and shocks. In this paper we suggest that effective governance under uncertainty must include the ongoing analysis of trade-offs between robustness and performance, and between investments in robustness to different types of perturbations. The nature of such trade-offs will depend on society's perception of risk, the dynamics of the underlying resource, and the governance regime. Specifically, we argue that it is impossible to define robustness in absolute terms. The choice for society is not only whether to invest in becoming robust to a particular disturbance, but rather, what suit of disturbances to address and what set of associated vulnerabilities is it willing to accept as a necessary consequence.

Keywords: Resilience, robustness, social-ecological system, common-pool resources, trade-offs

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1. Introduction

A structure composed of a common-pool resource (CPR), its users, and an associated governance system is an example of what we call a Social-Ecological System (SES). All SESs are subject to a wide variety of perturbations to their governance systems, the resource users themselves, and to the underlying ecological system (e.g. pasture, fishery, lake, forest, or the atmosphere) that constitutes the resource. Given such perturbations, the capacity to maintain system performance when subjected to external or internal unpredictable perturbations (Carlson and Doyle 2002), can be of critical importance in SESs. Here, we define this capacity as robustness (following the engineering literature for reasons discussed below). System performance here refers to some set of quantitatively measured, desirable characteristics of the system such as economic productivity, economic growth and environmental quality. Obviously, undesirable characteristics can be robust too, so it is important to define performance carefully. In the case of SESs, robustness depends jointly on the humanly designed governance system and the resilience of the underlying ecological system.

Given increasing pressure on ecosystem services globally, many scholars have begun to focus on how to generate resilience or robustness in social-ecological systems (Folke 2006). Folke et al. (2002, p. 10), for example, state in a policy white paper: 'Managing for resilience enhances the likelihood of sustaining development in a changing world where surprise is likely. Resilience-building increases the capacity of a social-ecological system to cope with surprise. A changing, uncertain world in transformation demands action to build the resilience of the social-ecological systems which embrace all of humanity.' However, we suggest that from a governance perspective, the question is not only how to generate robustness or resilience, but also how to manage trade-offs between robustness and performance, and between different forms of robustness to different classes of perturbations. It must be noted that the resilience community is well aware of the problem of the specifics of 'resilience of what to what' (Carpenter et al. 2001) but has not emphasized the trade-offs discussed here. Furthermore, we argue that in developing robustness to unpredictable perturbations at particular levels or scales in the system, we need to accept the potential for increased chances of failure at other levels and scales. In fact, we emphasize the notion that only due to short-term failures we can derive long-term robustness. To put it another way, when all 'low-hanging fruit' is taken to increase robustness cheaply, SESs will eventually reach a point at which it is no longer possible to generate additional robustness without a cost to performance and/or decreased robustness somewhere else in the system.

Because of challenges that CPR governance systems constantly face, we believe that a discussion of robustness trade-offs is particularly relevant to the process of crafting effective institutional arrangements for common-pool resources. We focus especially on CPRs – like irrigation systems – that are characterized by substantial investment in the design and maintenance of physical infrastructure. Some of the major problems regarding the governance of contemporary irrigation systems are related to a lack of understanding by irrigation engineers and development specialists of the investment required for the design of relevant institutions that will match the ecological- and the engineered-systems as well as the cultural-, political-, and social-systems of the users (Lam 2006). Furthermore, present-day irrigation systems are challenged by rapid cultural and economic changes as well as changing climatic circumstances (Janssen et al. 2007).

Developing a rigorous methodology to define, analyze and explore the policy implications of trade-offs between performance and robustness and for robustness to different classes of disturbances, lies beyond the scope of this paper. Doing this is important, but requires a long-term research agenda (some of the initial efforts to set up such an agenda can be found in Rodriguez et al. (submitted)). Instead, we rely on biological examples to illustrate such fundamental trade-offs. We then extend these ideas to SESs. using concepts from neoclassical economics to aid in the discussion.

We will begin the paper by discussing the inconsistent use of terminology concerning the robustness and resilience of social-ecological systems. Here, we will use the Tower of Babel as a metaphor. We will identify a general confusion about the use of terms from various disciplines in the resilience and robustness literature, and we will discuss how we will use terminology in this paper. We will continue with a discussion of a number of insights concerning robustness trade-offs that emerge from research on immune systems and ant colonies, respectively. The remainder of the paper will be devoted to outlining a general framework for understanding robustness trade-offs in social-ecological systems based on insights from biological systems. We will illustrate this framework with case study descriptions of irrigation systems.

2. The tower of Babel of resilience and robustness

The concept of resilience, as developed in the ecological literature (Holling 1973), measures the amount of change or disruption that is required to transform a system from being maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures. Resilience has become an important concept in the study of both particular SES's (Carpenter et al. 1999a 1999b; Scheffer et al. 2000; Anderies et al. 2002; Janssen et al. 2004; Carpenter and Brock 2004; Walker et al. 2004; Anderies 2005; Anderies et al. 2006; Folke 2006; Gunderson et al. 1995; Berkes and Folke 1998; Berkes et al. 2003; Gunderson and Holling 2002) as well as more general issues including understanding long-term change in human societies (Redman and Kinzig 2003; Janssen et al. 2003). There are at least two types of resilience considered: ecological resilience and engineering resilience (Holling 1996). Engineering resilience assumes that ecological systems exist close to a stable steady-state and measures the ability of a system to return to this steady state following a perturbation (Pimm 1984). Ecological resilience emphasizes conditions far from any stable steady-state, where perturbations can shift a system from one regime of behaviour to another i.e., to another stability domain (Holling 1973). An example of engineering resilience is a bridge which one would prefer to be close to its stable steady-state. A bridge that starts oscillating in the wind is not desirable. When the oscillations of the bridge lead to its destruction, another undesirable steady-state is reached. In the normal functioning of a lake, the concentrations of various chemical compounds and the populations of various organisms may fluctuate over time. These fluctuations may allow or even enable the lake to remain within a particular stability domain, as measured by some aggregate variable or collection of variables – for example, the lake may remain oligotrophic. The capacity to remain in this domain in the face of perturbations is what we call ecological resilience. Only when fluctuations lead to a structural change, for example from a clear lake to an algae-dominated lake, has the system shifted to another stability domain.

Although our thinking is conceptually consistent with ecological resilience, we prefer to use a term more commonly used within engineering: robustness (Anderies et al. 2004; Janssen et al. 2007). The reason for this choice is our focus on human constructs and institutional rules designed by humans. Crafted institutional arrangements aim to stimulate and support a particular performance of a SES, like engineers design systems to meet certain performance criteria. Read (2005) discusses robustness and resilience for social systems, but his definition of resilience is based on the concept of ecological resilience, whereas his treatment of robustness is similar to what we have referred to here as engineering resilience. We use the term robustness in a similar way as ecological resilience and define it as the capacity of a system to maintain its performance when subjected to internal and external perturbations. The key difference between robustness and ecological resilience as we use it in this paper is the focus in our analysis of humanly designed components within the SES of interest that control responses to perturbations. Unlike the ecological resilience perspective, which often considers human activities as perturbations of an ecological system, we consider social-ecological systems where humans develop institutional feedback loops to respond to perturbations. In the rest of the paper we will use the term resilience for ecological resilience of natural systems, and the term robustness for social-ecological systems with man-made control and feedback systems. In sum, several different terms are used in the literature for similar or related concepts. A rough distinction between these different terms can be drawn by differentiating systems that remain within a stability domain and systems that remain in a particular equilibrium state. Concepts related to the first broad set of systems are ecological resilience (Holling 1973), robustness (Anderies et al. 2004), and resilience (Read 2005). Concepts belonging to the latter type of systems are engineering resilience (Pimm 1984) and robustness (Read 2005).

We focus our analysis on SESs where humans engage in many actions to meet their various needs, often unrelated to the state of the ecosystem. Institutional arrangements affect the way humans interact. Humans interact directly and indirectly with ecosystems, and governance mechanisms are, among (many) other things, meant to avoid the undesirable consequences of impact from human activities on ecosystems. Since societies consist of humans with various goals, trade-offs – including trade-offs regarding the impacts of human activities on ecosystems – need to be made.

Besides the importance of designed components, our use of the term robustness has been inspired by findings from engineering. Although engineered systems, like airplanes, are designed for robustness, vulnerability cannot completely be eliminated. When these systems are exposed to external shocks and characterized by significant uncertainty, engineers use the term ‘robust-yet fragile,’ which refers to the acknowledgement that to generate robustness to one particular set of perturbations, a necessary consequence will be decreased robustness to another set of disturbances (Carlson and Doyle 2002). Hence, there is no such thing as absolute robustness. There is always a trade-off to be made, and society[1] has to choose the type of robustness in which it is most willing to invest. Before we discuss these trade-offs in SESs, we first discuss the general characteristics of robustness and resilience within two biological examples: immune systems and ant-colonies. We then extend these ideas to the social-ecological realm – particularly by means of an analysis of several important case studies of irrigation systems.

3. Resilience trade-offs in biological systems

An important framework in the literature on ecological resilience is the adaptive cycle (Holling 1986), which characterizes different phases in the dynamics of ecological systems. During the exploitation phase, pioneer species establish themselves. Nutrients and biomass consolidate during the conservation phase, which eventually leads to a climax. This climax, characterized by over-connectedness, makes the system more susceptible to environmental disturbances such as fire, insect pest outbreaks, or disease. When a disturbance eventually occurs, the accumulated energy is released in a creative destruction, or release phase. Ecologists distinguish different species dominating in the different phases. R-strategists, who dominate in the exploitation phase, reproduce quickly and in large numbers and are thus better able to cope with unpredictable or variable environments. Typi-

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[1] We use the term society to refer to an aggregation of interacting people who share a geographical region, a sense of common identity and culture.

cal examples of r-strategists are bacteria, insects, and weeds. K-strategists, who dominate during the conservation phase, are larger, live longer, produce fewer offspring invest more in their offspring than do r-strategists. They are thus able to better compete for limited resources and perform well in stable environments. Typical examples are elephants, humans, and pine trees.

Ecosystems tend to develop from a phase dominated by r-strategists, to a phase dominated by K-strategists. The adaptive cycle acknowledges that the K-phase is not the end state of an ecosystem. Perturbations can disrupt the K-phase, lead to a reorganization of the system, and initiate a new r-phase. When a K-phase configuration is highly resilient, the system may again evolve to the same type of K-phase configuration. When a K-phase configuration is not resilient, the system may evolve, after a perturbation, to a new K-phase configuration that is structurally different than the previous K-phase. For example, forests typically experience fires after which they recover. However, if fire is suppressed and fuel loads build up, a K-phase configuration with low resilience to fire results. Such forests are typically not able to recover from the intense forest fires that ensue. The ecological system that emerges after such a fire is fundamentally different from the previous forest (Holling 1986).

These different strategies identified in ecosystems help us to discuss different ways in which complex systems have coped with a variety of perturbations. The diversity of immune systems and ant species that have evolved over many millions of years are two important examples of how biological systems cope with both predictable and unpredictable disturbances (Janssen and Osnas 2005; Linksvayer and Janssen 2006). They illustrate that in the evolutionary pathway, different types of responses, including both r and K strategies, have evolved in particular responses to particular types of perturbations. These are examples of how selective pressures have emphasized different resilience ‘trade-offs’ in different contexts.

Organisms have developed different types of immune systems. The main difference between immune systems of vertebrates and invertebrates is that only vertebrates have what immunologists call an adaptive immune system. Unlike an invertebrate, a vertebrate will respond faster the second time a pathogen enters its body because of its immunological memory. The adaptive immune system of vertebrates arose 500 million years ago and is functionally integrated with their ancient innate immune system. The main advantage of adaptive immune systems is their ability to match spatial and temporally differentiated defence mechanisms with the particularities of pathogen evolution. There are disadvantages of being a large, long-lived vertebrate host compared to small and short-lived pathogens. Viruses and bacteria multiply rapidly, with generational intervals in the order of minutes or hours, which provide them with a great opportunity for mutation and evolutionary change. Long-lived vertebrates can never match the pace of pathogen evolution, but the adaptive immune system provides an evolutionary adaptation to this mismatch in temporal scales.

Being a large organism requires significant resource investment in an adaptive immune system. The basic function of the adaptive immune system is to detect self from non-self cells. It uses a large number of diverse white blood cells, lymphocytes, which bind with undesirable intruders. There is a large diversity of these lymphocytes, but the diversity can never be large enough to match the full repertoire of potential invaders. Therefore the immune system is constantly generating new variations of lymphocytes (mutations) and replicating lymphocytes which were successful in binding to invaders (the immune response). The immune system is not equipped at birth with an appropriate variety of lymphocytes. Therefore, the immune system is trained immediately after birth by the mother through lactation. Furthermore, the number of lymphocytes is highest just after birth, dropping slowly during development to the adult level. A consequence of these mechanisms is that adaptive immune systems become tailored through training to a particular disturbance regime. Changes in disease ecologies later in life (for example, through travel) can expose immune systems to unknown pathogens for which they have no adequate response. Another problem faced by the adaptive immune system is achieving the right balance between tolerance (immune response is too late) and rigidity (attacking self-cells, auto immune response).

We see a similar dilemma with the trade-off between small and flexible, and large and costly defence mechanisms of colonies of ant species. There is an enormous diversity of ant species (Hölldobler and Wilson 1990). Colony sizes range from a few individuals to over a million in some leaf-cutting and army ant species to hundreds of millions in some species with supercolonies. Some colonies have monomorphic workers with little division of labor, and others have an age-, size-, or morphology-based division of labor, with specialized worker subcastes, such as soldiers (Hölldobler and Wilson 1990). Some ant species practice individual-based foraging, while others have more complex foraging strategies based on maintained trunk trails.

Andersen (1992) defines ant functional groups based on trade-offs in adaptation according to three types of perturbations: extreme temperatures, habitat disturbance, and competition with other ants. This functional group scheme focuses on the responses of taxonomic groups to important predictable and unpredictable disturbances on a biogeographic scale (Andersen 1992). Although the scheme was developed in Australia, it has also been applied to North American and Neotropical ants (Andersen 1992; 2000). The basic idea is that certain ant-species are opportunists (r-strategy), some specialists (stress adaptation), and others generalists (K-strategy). The opportunists are tolerant of high levels of habitat disturbance and some stress (e.g. narrow range of nest or food resources), but are at the same time unspecialized in terms of competitive ability with other organisms and ant colonies, and tolerance of extreme temperature stress (Andersen 1992). Specialists are adapted to climates that are stressful in terms of extreme temperatures but do not tolerate high levels of habitat perturbation and cannot compete with generalists in less stressful environments (Andersen 1992). The generalists prefer less stressful environments with less variability. Colonies of generalists are competitive in such environments and develop large colonies with (physical) specialization of workers. Such ant species, like leaf-cutting ants, can dominate their habitat environment and aggressively defend their territory.

Both of these biological systems illustrate that there is not one solution providing general resilience. They illustrate a basic trade-off between being small, short-lived and flexible, and large, long-lived with heavy investment in response mechanisms. Nevertheless, there is a large diversity of ways to be small or large and hence a diversity of mechanisms to deal with different types of perturbations. We will now extend these ideas to explore robustness trade-offs in social-ecological systems which are often characterized by the fundamental tension between devoting resources to live (present consumption) and investing in response mechanisms to secure their existence against perturbations and instability.

4. Robustness trade-offs in social-ecological systems

The examples above illustrate fundamental trade-offs faced by biological systems in coping with particular types of disturbances. Selective pressures then tune these systems to their particular environmental circumstances. Although humans can use more comprehensive cognitive processes to make decisions than can lymphocytes and ants, we argue that the different components of social-ecological systems experience similar trade-offs and selective pressures. However, the relationship between robustness to different types of disturbances or between robustness and performance is not straightforward. Not as straightforward as between, for example, number and size of offspring (r versus K trade-offs) and a trade-off that is conditioned by obvious biophysical constraints. In some cases, the tension between trade-offs is obvious: simplification of ecological systems enhances production but reduces robustness to plant pathogens and pests. On the other hand, one can imagine examples where a choice of a particular (re)production technology brings with it ‘natural’ robustness characteristics. For example, irrigation technology not only can increase agricultural production but also can increase the robustness of food production to annual fluctuations in precipitation. However, if we consider that irrigation infrastructure is sensitive to large floods, we realize that there is a trade-off between enhanced robustness of food output to high frequency weather fluctuations (1/yr) and reduced robustness to low frequency weather fluctuations (0.01/yr) and thus an indirect trade-off between performance and robustness.

Are SESs always susceptible to trade-offs? If this were the case, Pareto frontiers could be constructed for production (performance) and robustness and policy choices might be meaningfully informed by these relationships. Such trade-offs often emerge from constraints involving some conserved quantity (labor, capital, mass, energy) conditioned by stoichiometric or technological relationships. In fact, it can be shown that for certain types of dynamic systems (linear time invariant) a quantity like ‘fragility’ is conserved (Bode 1945). Specifically, Bode (1945) derived an expression for the sum of the logarithm of the sensitivities for a linear, time-invariant dynamical system over all disturbance frequencies and showed that it was identical to zero. This Bode integral formula – as it is commonly referred to today – describes a robustness trade-off present in all feedback systems: reducing the sensitivity to disturbances at one range of frequencies by feedback control will increase sensitivity to disturbances at other frequencies. This insight motivates our use of production possibility frontiers and our emphasis on trade-offs, in this paper. Different instances of such trade-offs are explored in more detail below.

In their design of components of social-ecological systems, people are not necessarily focused on robustness. However, in situations where humans do make decisions with regard to robustness, they may have to make a trade-off between robustness and performance (Figure 1(A)). For example, households in irrigation systems may generate more income by earning wages in nearby urban areas, but then have less time available to maintain irrigation infrastructure. If performance is measured as household income, the irrigators may be willing to increase performance – i.e. income – with the risk of reducing the stability of the irrigation infrastructure. On the other hand, they may accept lower performance – i.e. less income – but with the irrigation system functioning at the same level. Another example is life-insurance, which makes an income of a household more robust to the death of a household member, but leads to a lower performance – i.e. resources to spend on consumption – in the short run.

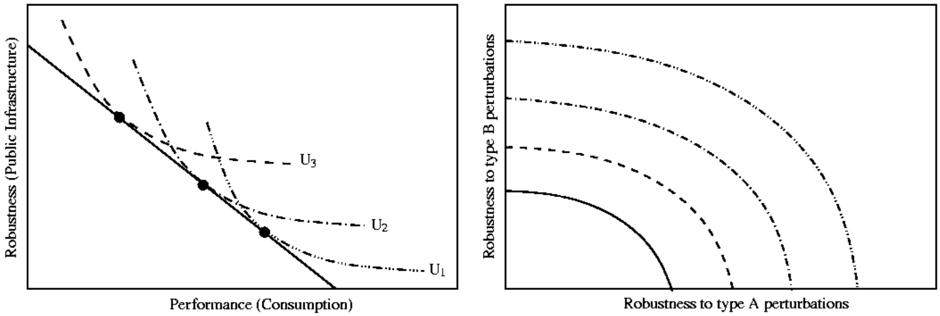
A challenge regarding decisions to invest in enhancing robustness is the lack of feedback from previous investments made. Once a society is successful in increasing robustness, a necessary consequence is that fewer undesired impacts are experienced. This leaves citizens wondering about the value or necessity of investment in enhancing robustness. When Hurricane Katrina destroyed New Orleans, it became clear to the general public that public governance had failed to maintain or enhance the robustness of the city to severe storms. The persistent underinvestment in levees and wetland restoration was known to have reduced the robustness of the city, but it was hard to generate the required resources to address these issues (Pinter 2005). After the disaster, the importance of new investments became clear and more generally accepted. But time erodes the vividness of experiences (Dooley et al 1992). For example, one hundred years after the 1906 earthquake that destroyed San Francisco, much of the city is not well prepared for a new one, which inevitably will occur in the coming decades (Johnson 2006). Disasters lead people to weigh long-term robustness more heavily in decision-making, but over time short term performance becomes more important.

Here we see the importance of failures (Dörner 1996; Ormerod 2006; Wilkonson and Mellahi 2006; Petroski 2006). When people experience small failures regularly, they might be reminded and motivated enough to invest in maintaining the robustness of the system. When no failures are experienced, there is the danger that reduced investments will increase the possibility of severe failures.

Within civil engineering it is observed that there is a regularity of major failures in the design of bridges (Petroski 2006). Every generation of engineers experiences a major failure. With each new generation, lessons from previous failures get ignored or forgotten, and less emphasis is put on the double-checking and testing of designs.

As discussed above, robustness of social-ecological systems is a somewhat misleading terminology since a system might be robust to particular perturbations but not to others. In fact, when there is the desire to improve robustness to perturbations of type A, one might have to give up robustness to perturbations of type B. This is similar to what we have seen in immune systems and ant colonies. Were different strategies in biological systems are a consequence of evolutionary processes, human societies can make deliberate choices on strategies concerning how to trade-off robustness to different perturbation types. Obviously, these trade-offs do not necessarily occur between each set of perturbations, but we argue that for each perturbation of type A it is likely that there is a perturbation of type B for which these trade-offs will occur.

The use of concepts from neoclassical economic theory helps to explain what we think are important trade-offs societies must address. It is not a description of how people actually make decisions. We often see a focus on increasing the robustness to one type of perturbation without realizing that it may decrease the robustness to another type of perturbation. Rodriguez et al. (in review) apply robust control theory to the classical logistic renewable resource problem: $\dot{x} = rx\,(1 - x/K)$ with x the resource size, r the growth rate and K the carrying capacity (Clark 1990). Even for a resource that is forgiving, like the logistic renewable resource, they found that there is always a reduction of performance when trying to increase robustness. They were also able to develop specific relationships regarding how improvement in robustness to particular types of shocks leads to reduced robustness to other types.



(A) (B)

Figure 1(A): Trade-offs between robustness and performance. The straight line is the budget constraint of society. The curves are iso-utility curves for different societies with different risk preferences (risk aversion increases from U1 to U3). The best trade-off between robustness and performance depends on the (risk) preferences of the participants involved. Figure 1(B): Trade-off between investments in system robustness to perturbation type A and perturbation type B. Each curve is a production possibility frontier for increasing levels of overall investment in robustness.

In Figure 1(B) we illustrate the dilemma of trade-offs between different types of robustness. One cannot become robust to two different potential outcomes of climatic change – predicted to lead in one case to a warmer and in another to a colder climate – and maintain the same level performance (for example, economic productivity). Western Europe faces such a situation where cooling might be caused by a change of the ocean currents. Economically, one needs to address a trade-off between preparing for one of the potential scenarios and preparing to adapt (slower than the first option, but more risk neutral) when a change in climate is observed. Such trade-offs cannot be hedged, since compromises might be even less desirable. Another option would be to accept lower performance and invest in adaptation to both possible situations.

Figure 1(B) shows a number of production possibility frontiers associated with increasing investment in robustness (moving to curves further from the origin). As long as the marginal cost of increasing robustness is less than the marginal benefits of increasing performance, increasing robustness leads to increasing performance. Hence, to a certain extent general robustness can be increased. Adding control systems to airplanes increases performance as well as robustness until further investments in control systems become so costly that within a constrained budget tradeoffs need to be made. The production possibility frontiers in Figure 1(B) suggest that with increasing performance, trade-offs between different types of robustness remain the same (the shapes of the curves are the same regardless of their distance from the origin). In the empirical irrigation examples discussed below, however, we will illustrate that in increasing performance by increasing robustness to A-type perturbations (i.e. moving from one production possibility frontier to one further out rather than moving along a particular frontier), the trade-off relationship between different types of perturbations is not necessarily preserved (Figure 2). Because ecological and social systems exhibit non-linear (more importantly, non-convex) relationships between variables and hysteretic effects, investments to increase robustness to perturbations of type A, may fundamentally alter the dynamics of the system and reduce opportunities to remain robust or increase robustness to perturbations of type B.

5. Challenges for robustness of social-ecological systems

During the last few thousand years, many societies have found, often through trial and error, ingenious arrangements to sustain their societies and the resource base upon which they depend. We discuss examples of the kind of robustness trade-offs made for a number of irrigation systems. In general, irrigation systems buffer temporal and spatial variability in water availability. Typically, mountainous areas store water during the winter in the form of snow and ice and provide a constant stream of water in the spring/summer. Some irrigation systems include human-made reservoirs to store water. As a result of buffering variation in water availability, irrigators are then faced with trade-offs concerning water-storage

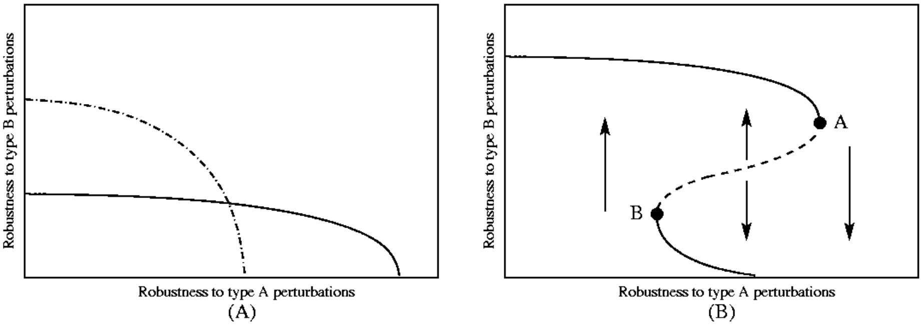


Figure 2(A): Non-linearities can generate shifts in the structure of production possibility frontiers. Figure 2(B): If productive activities depend on values of dynamic state variables (as is often the case in natural resource systems) hysteretic effects can occur. For example, once the robustness of the system to type A perturbations is increased beyond point A, the state variables that contribute to type-B robustness may become unstable and decline to zero. In this event, to regain the capacity to cope with type-B perturbations, type-A robustness must be reduced below point B to allow type-B robustness to recover (which could take a long time). Further, if point B is to the left of the y-axis (as it often is), the capacity to cope with type-B perturbations may be permanently lost.

water use. In order to use the water, complex irrigation canal systems have been built along with comprehensive institutions that have been developed to coordinate irrigators' water use. A typical dilemma is the one between upstream and downstream irrigators. Upstream irrigators might be willing to provide water to downstream irrigators for various reasons, including the help they will receive in maintaining the canal system (Ostrom 1990; 1992; Shivakoti et al. 2005) or the control of pests (Lansing and Miller 2005).

Although institutions for irrigation systems differ widely around the world, long-lived irrigation systems typically have arrangements to address the dilemmas associated with both providing and maintaining physical infrastructure and institutional arrangements. But as we will discuss below, although long-lived systems have become robust to familiar disturbances, they may have become vulnerable to new challenges as a result.

5.1. Robustness trade-offs in Bali: Balancing pests, water and rituals

The Indonesian island of Bali has a complex system of tunnels, canals, and aqueducts to guide water from high in the volcano Crater Lake to the hills densely covered with rice fields, below. The Balinese have practiced agriculture in small farming communities for about 3,000 years. Originally, they had their agricultural sites in coastal swamps, where crops such as taro, bananas, and perhaps swamp rice were grown to supplement food from the sea (Lansing 2006). At a certain point, pioneering colonists started to grow crops inland in places where natural springs had created swamps. Lansing (2006) suggests that the first location of natural-spring irrigation is located near the Sebatu water temple. This small valley has two natural springs and would therefore have been an ideal place to grow crops in ancient times. Farmers probably started to experiment with irrigation and paddy rice, and started developing tunnels, canals, and aqueducts to use the excess water in down-slope locations. The archaeological record contains inscriptions related to irrigation governance between subaks, a group of farmers owning land watered by a common source, dated from about 1,000 years ago (Lansing 2006).

Initially, kingdoms stimulated the creation of irrigation systems and provided allowances to create new canals. Expansion of rice farming led to increased use of the ‘water mountains’ which required cooperation among farmers and between communities which share the same water sources. In the archaeological record, we see a reduced influence of the powers of the kings. This did not lead to an increase in the power of the villages, as shown in ancient documents, since rice terraces were considered private property, rather, the spread of irrigation diminished the role of village councils, and increased the role of subak temples, which transcended the boundaries of individual villages (Lansing 2006). Over time Bali became a densely irrigated system that needed explicit coordination institutions to make the trade-off between the allocation of water and the spread of pests, as will be discussed below.

In time, more and more canals were dug, leading to a complex web of waterways utilizing and recycling the water from the Crater Lake. Coordination of such a complex system was only possible when the subaks were coordinating their water use activities both within and across subaks. Although their origin is not known, it is now well understood that the complex rituals and the spiritual life of the Balinese contributed to the seemingly smooth functioning of the irrigation system (Lansing 1991).

Subaks experience regular challenges to maintain the internal coherence that is necessary for cooperation in maintaining the canal infrastructure, the practice of rituals, and the coordination of water use. Interestingly, the governance within subaks differs substantially among the subaks of Bali. Some subaks have a strong hierarchical structure whereas others are more democratic and egalitarian. Despite the diversity, subaks will monitor each other and put pressure on those among them that are not able to get their act together. The non-functioning of subaks may be caused, for example, by the corruption of its leaders. Subaks can put pressure on other, non-functioning subaks by threatening to cut off water supply. Subaks are motivated to keep other subaks on track since their cooperation as well as their internal operation is needed for the successful coordination of water allocation and pest control.

As stated above, besides guaranteeing the availability of water, irrigation systems in Bali also need to coordinate in order to control pests (Lansing 1991). On the one hand, controlling of pests is most effective when all rice fields in a watershed have the same schedule of planting. On the other hand, the fact that terraces are hydrologically interdependent, and are comprised of long and fragile systems of tunnels, canals, and aqueducts, means that large areas of rice cannot be planted at the same time. To balance the need for coordinated fallow periods and the use of water, a complex calendar system has been developed that details what actions should be taken on each specific date by each organized group of farmers, i.e. the subak. These actions are related to offerings to temples, which range from small temples at the rice terrace level to temples at the regional level and, all the way up to the temple of the high priest Jero Gde, the human representative of the Goddess of the Temple of Crater Lake. Crater Lake feeds the groundwater system, which is the main source of water for irrigating in the entire watershed. These offerings are collected as a counter gift for the use of water that belongs to the gods.

During the history of more than 1,000 years of irrigation, Bali irrigators developed a complex physical irrigation infrastructure and associated institutional arrangements to coordinate water use and pest control. Lansing (2006) suggests that the strong interdependencies among the subaks may have triggered the development of religious practices that create shared norms and world views that stimulate irrigators to be cooperative. The Bali irrigation system temporarily experienced a change in the robustness trade-offs when during the Green Revolution in 1960s, farmers were forced to shift to different rice varieties with different characteristics for the timing of planting and harvesting. The function and power of the water temples were invisible to the planners and engineers from abroad as they regarded agriculture as a purely technical process. Farmers were also stimulated by governmental programs that subsidized the use of fertilizers and pesticides. After the governmental incentive program started, most of the farmers continued performing their rituals, but they no longer coincided with the timing of rice-farming activities. Soon after the introduction of the miracle rice, a plague of plant-hoppers caused huge damage to the rice crop. A new variety was introduced, then a new pest plague hit the farmers. Furthermore, there were problems of water shortage.

During the 1980s, an increasing number of farmers wanted to switch back to the old system, but the engineers interpreted this as religious conservatism and resistance to change. It was Lansing (1991) who unraveled the function of the water temples, and was able to convince the financers of the Green Revolution project on Bali and the World Bank that the irrigation was best coordinated at the level of the subaks with their water temples. Most of the subaks have returned to the previous ritual tables. However, the irrigation system now experiences other challenges. For example, alternative sources of income have become more widely available, leading to a shortage of labor in the subaks. This reduces the ability of the subaks to maintain the community structure and ritual practices that facilitate the maintenance of the irrigation infrastructure. For years, Bali irrigators were successful in balancing water availability and pest occurrences and thus became robust to two types of perturbations. The cost for achieving a high performance was a long time investment in coordination and ritual practices. In a globalizing economy, new opportunities have emerged for the younger generation to generate income (like the tourist industry). As the younger generation benefits from these new opportunities, the robustness of the Bali irrigation system is challenged since less time is invested to maintain the ritual practices. Lansing anticipates that the long-term high performance of the Bali irrigation may come to an end due to these new challenges (personal communication).

5.2. Robustness trade-offs in the Goulburn Broken: balancing salt, water and agricultural productivity

The Goulburn Broken Valley in southeastern Australia is a typical example of a modern, large-scale irrigation system that has completely transformed the landscape. The catchment's location within Australia and the present land cover are shown in Figure 3. The elevation drops moving from the southeast to the northwest. Prior to European settlement, which began in the mid 19th century, most of the catchment area was covered in native vegetation. At present only about 10 percent of the area is under native vegetation (green/darker shades area in Figure 3). Now, the catchment consists of three primary land-use types. First is the Shepparton Irrigation Region (SIR) – 500,000 hectares on riverine plains in the lower catchment. Approximately 60 percent of this land area is irrigated, with native vegetation types having been reduced to less than 2 percent of their pre-European extent. Roughly 88 percent of the irrigated land is pasture for dairy production. The riverine plains and low foothills between the forested highlands and the SIR constitute the mid catchment. Less than 15 percent native vegetation cover remains in this area and land use is dominated by broad-acre cropping. Finally, the upper catchment, Eildon Resevoir, is a large area of predominantly public land above the major water storage in the catchment. Total forest cover in this region is relatively unchanged since European settlement.

This transformation was made possible by enhancing the robustness of agricultural production to short-term fluctuations in rainfall. Most notably, Lake Eildon (see figure 3) using irrigation infrastructure developed over the last 100 years including several dams and an extensive canal system has drastically reduced variations in water supply. This increase in robustness to short-term fluctuations in rainfall has tremendously increased performance (measured as agricultural output).

However, the discussion above suggests that such increases in robustness to short-term fluctuations will be accompanied by a decrease in robustness to other types of perturbations. In the case of the Goulburn Broken, this decreased robustness is caused by high water tables and highly saline groundwater. Specifically, by clearing the Mid Catchment and SIR for grazing and irrigation activities, native vegetation with a relatively high evapotranspirative capacity was replaced

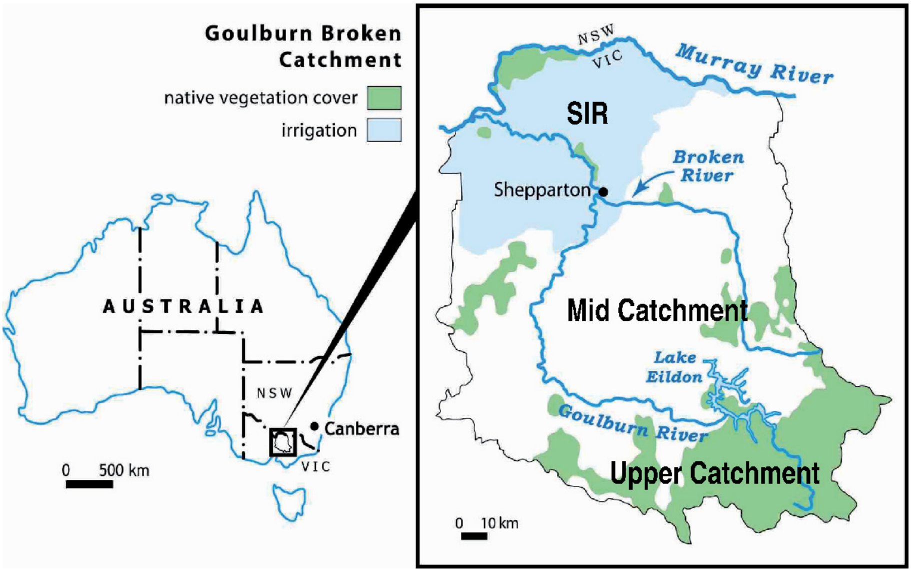


Figure 3: Location of the Goulburn Broken Catchment (GBC) with the major rivers and land use types.

with grass and crops with a relatively low evapotranspirative capacity. Thus, more water flows past the root zone of the vegetation and reaches the groundwater system. This has caused water tables to rise – reaching the surface in some cases – bringing with them salt mobilized from paleo salt deposits. The result has been waterlogging, increased soil salinity, and increased salinity in rivers. Ironically, in becoming more robust to dry periods, the system has become less robust to wet periods.

In 1973, very heavy rain generated a crisis in the Goulburn Broken Catchment when water tables rose to the surface in many places. This event was labeled as a crisis because of the scale of the economic loss and the fact that even though some actors were well aware of rising water tables and their consequences, it came as a real surprise to many. According to estimates, if nothing were done, high water tables could destroy the economic base of the entire region. Under pre-European conditions similar wet periods would not have generated a crisis. That is, during that time the system was robust to wet periods, as the ground water system could absorb all the water, but it was not robust to dry periods and primary production would suffer during droughts. The investment in irrigation infrastructure has now reversed these robustness characteristics.

It would seem that a natural response to such a crisis – i.e. the wet spell that occurred in 1973 – would be to focus on enhancing the capacity of the system to cope with wet periods. In terms of Figure 1(B) this would mean either shifting investment and moving along a production possibility frontier or increasing investment overall and moving to a curve further away from the origin. However, in the case of the Goulburn Broken Catchment, the increase in robustness to drought has fundamentally altered the biophysical system so that the situation is more like that in Figure 2(A) or (B). Specifically, increased soil salinities and waterlogging make re-vegetation difficult so the production possibility frontier shifts from the dash-dot curve to the solid curve. If soil salinities become too high – as is the case in some areas, currently – recovery and revegetation is impossible and the only way to reduce water tables is through pumping. In this case, the situation is as depicted in Figure 2(B) (Anderies et al. 2006, Anderies 2005).

In addition to these biophysical limitations, institutional and economic constraints have further limited the ability of the Goulburn Broken Catchment to increase robustness to wet periods and salinity problems. In fact, Anderies et al. (2006) contend that the actual responses of resource management agencies reduced intervention options and further decreased, rather than increased, the system's robustness to shocks. This is the result of an irrigation ideology – the perceived need to control water and put it to valuable use. Australia has a long history of heavy investment in irrigation infrastructure – arguably a part if its national identity – including the Snowy Mountains Scheme. Begun in 1949 and completed in 1974, the immense project diverts water from the Snowy River to the Murray Darling Basin in which the Goulburn Broken Catchment is located. Such heavy national investment in irrigation infrastructure has encouraged low value, high water use activities (dairy) and left little incentive for efficient water use (Langford et al. 1999). The regional economy became 'tuned' to irrigated agriculture with the production and processing of dairy and horticultural goods generating roughly half the regional economic output. The crisis of 1973-74 and the idea that such a large portion of the regional economy was under threat had a major impact on communities and government.

The state government responded by introducing new institutions and devolving responsibility for management to regional communities. Concurrent reforms in the state water management agencies and the appointment of an interstate commission to manage the Murray Darling Basin created the larger scale institutional framework in which the Goulburn Broken Catchment now operates (Langford et al. 1999). The formation of the Murray Darling Basin Commission (MDBC) established a mechanism for community groups to access federal resources for large-scale infrastructure development (see http://www.mdbc.gov.au/). The region now operates within a four-way partnership between the community, local government agencies and state and national agencies. The key point here is that the response by communities and government did not emphasize revegetation (moving along a curve in Figure 1(B)). Rather, it focused on investment in the generation of more complex, large-scale institutional structures to manage an increasingly sensitive system based on enhanced technical efficiency and engineering solutions (move out to a curve further from the origin in Figure 1(B)). This response likely changed the shape of the curve as in Figure 2(A), or moved beyond the point of no return as in Figure 2(B). In sum, the past focus on irrigated agriculture has led to a trajectory for economic and institutional development that leaves very few options for the real, large-scale changes needed to make the Goulburn Broken Catchment capable of dealing with minor change. Through this process, the Goulburn Broken Catchment may have become highly optimized in its ability to continue to generate high output from irrigated dairy activities while tolerating high water tables and soil salinity. However, the system has become much more vulnerable to wetter climate phases and shifts in larger scale social and political processes (e.g., salt quotas). It seems that this process of foreclosure of options in pursuit of efficiency dictated by past investment toward a highly optimized, but extremely fragile system is, if not inevitable, unfortunately, very likely for many social-ecological systems.

The examples presented here are particular examples of the robustness trade-offs depicted in Figures 1 and 2. Each case exhibits typical characteristics common to many SESs: human populations exploiting a complex set of natural resources that interact on multiple spatial and temporal scales, investment in physical infrastructure aimed at reducing environmental variation to enhance production, investment in the creation and maintenance of institutional arrangements aimed at fairly distributing the resources generated by physical infrastructure, and maintaining the physical infrastructure itself. In these cases, robustness to particular spatial and temporal variability can be maintained as long as a system can continue to produce sufficient social and physical infrastructure. However, increasing investment is often required to maintain system performance as social and physical infrastructure becomes more complex (Tainter 1988). In the case of Bali, the investment was made to fine-tune the rituals in order to coordinate an increasingly complex system of irrigation canals. In the case of the Goulburn Broken Catchment, investments were made in physical infrastructure to maintain a desired groundwater level and to control salinity levels in soils and waterways. In both cases, the systems lost their ability to adapt to new challenges, such as alternative sources of income (Bali), wetter climate phases and shifts in larger scale institutions such as salt quotas (Goulburn Broken Catchment).

6. Discussion

Although there have been many failures of local-scale social-ecological systems (Tainter 1988), at a broader scale, human societies have persisted and continue to thrive and evolve. However, the recent globalization of social, economic, political, and ecological processes generates important opportunities and challenges for the robustness of social-ecological systems (Young et al. 2006). As a result of globalization, experience and technology can be shared, which may increase robustness in some domains. But we also see important challenges. Institutional solutions which are successful in one location are imitated and implemented in other locations which are not appropriate. This leads to a decrease of institutional diversity which, in turn, causes the loss of local knowledge and expertise that is required to solve collective action problems in many diverse situations such as in the case of the Green Revolution and its consequences for the Bali irrigation system discussed above.

The concepts of resilience and robustness coupled with the idea of the adaptive cycle (Gunderson and Holling 2002), implies that small cycles of failure and recovery need to be accepted to avoid the occurrence of large scale failures. Therefore, we may tolerate modest failures at the system level and intelligently experiment with different institutional designs. This may mean that we have to accept the failure of local and regional social-ecological systems, at least temporarily, in order to learn how to improve the robustness properties of social-ecological systems at larger scales. To maintain robustness of social-ecological systems in the longer term, we may need to avoid the temptation of specializing our responses to increase robustness to specific perturbations. In order to maintain the ability to make robustness trade-offs as conditions change, one has to accept being somewhat less robust to particular classes of disturbances in order to remain flexible to adjust system robustness characteristics when changes occur.

This approach runs counter to the policy recommendations in much of the resource management literature that focuses on developing very specific responses based on specific models of the relevant social, economic, and ecological processes which are often assumed to be perfectly understood. When uncertainty about these underlying processes is admitted, it is typically assumed that the distributions for the unknown variables are perfectly known. Policy based on such characterizations of uncertainty is fundamentally about making the best bet when the odds are known. In fact, the odds are never really known: developing policy to cope with high levels of uncertainty is not akin to playing a game of chance repeatedly. The approach discussed above, which recognizes and seeks to manage fundamental robustness trade-offs, on the other hand, takes as its starting point that irreducible uncertainty is at the core of policy issues (rather than some form of optimality condition), that it is impossible to hedge away all such uncertainty (society cannot become robust to all disturbances), and that understanding the robustness trade-offs associated with policy decisions is core to sound policy development. This approach shares many attributes with resilience-based management as discussed above. Our observation that there is no free lunch for robustness might sound obvious for some readers. Therefore, it is important to remind readers that most of the discussion within the resilience/robustness community focuses on enhancing resilience/robustness in general, without addressing the crucial question of the fundamental trade-offs involved (Folke et al. 2002). We do not claim that all SESs are at the point where trade-offs must be made, but we suggest they will eventually reach such a point. This frontier might be reached either as a consequence of increasing intensity of resource use, or due to changes in the SESs (e.g. climatic change) that will constrain existing activities. There is more to robustness trade-offs than not having a 'free lunch'. Not only can these robustness considerations be costly in terms of implementation, they can also lead to a collapse of the SESs when society tunes the system to be robust to very specific disturbances, and makes it vulnerable to unanticipated challenges.

The study of robustness trade-offs offers the possibility of developing more specific policy based on a rough characterization of a particular SES. It thus takes many important ideas from the resilience literature and moves them toward more practical application. However, more research needs to be done to understand these trade-offs in SESs, and this paper provides a modest contribution to that venue.

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