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Insight, part of a Special Feature on Exploring Resilience in Social-Ecological Systems

Scale Mismatches in Social-Ecological Systems: Causes, Consequences, and Solutions

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ABSTRACT. Scale is a concept that transcends disciplinary boundaries. In ecology and geography, scale is usually defined in terms of spatial and temporal dimensions. Sociological scale also incorporates space and time, but adds ideas about representation and organization. Although spatial and temporal location determine the context for social and ecological dynamics, social-ecological interactions can create dynamic feedback loops in which humans both influence and are influenced by ecosystem processes. We hypothesize that many of the problems encountered by societies in managing natural resources arise because of a mismatch between the scale of management and the scale(s) of the ecological processes being managed. We use examples from southern Africa and the southern United States to address four main questions: (1) What is a "scale mismatch?" (2) How are scale mismatches generated? (3) What are the consequences of scale mismatches? (4) How can scale mismatches be resolved? Scale mismatches occur when the scale of environmental variation and the scale of social organization in which the responsibility for management resides are aligned in such a way that one or more functions of the social-ecological system are disrupted, inefficiencies occur, and/or important components of the system are lost. They are generated by a wide range of social, ecological, and linked social-ecological processes. Mismatches between the scales of ecological processes and the institutions that are responsible for managing them can contribute to a decrease in social-ecological resilience, including the mismanagement of natural resources and a decrease in human well-being. Solutions to scale mismatches usually require institutional changes at more than one hierarchical level. Long-term solutions to scale mismatch problems will depend on social learning and the development of flexible institutions that can adjust and reorganize in response to changes in ecosystems. Further research is needed to improve our ability to diagnose, understand, and resolve scale mismatches in linked social-ecological systems.

Key Words: *scale; scale mismatch; conservation; management; ecosystem function; sociological scale; southern Africa*

INTRODUCTION

The topic of scale is one of the themes that unifies different disciplinary perspectives. Phenomena of interest such as processes, patterns, individuals, and networks exist within a context that may vary in its dimensions, e.g., size, speed, complexity, or other attributes. Studies of particular phenomena usually focus on events that occur within a particular combination of dimensions that defines a single scale at which empirical observations are made. Two considerations affect the choice of scale. On the one hand, there is the empirical reality of the phenomenon of interest, which may range across many scales. On the other, there is the subjectivity of our observations, which are by necessity tied to the scale or range of scales at which we can collect information. The objectives of scaling studies are to consider how our perceptions of phenomena of interest change as the scale of analysis changes and to try to assess objectively the multiscale nature of the phenomenon. When we consider the interactions of two systems, particularly those in which a cause-and-effect relationship exists, we are faced with the problem of understanding how scale influences the number and nature of those interactions.

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Social and ecological systems interact in many ways. In this paper, we consider the relevance of scale in the management of natural resources. We hypothesize that many of the problems encountered by societies in managing natural resources arise as a consequence of a mismatch between the scale of management and the scale of the ecological processes or natural resources being managed. Interactions occur because of the effects of humans on ecosystems and vice versa. Here we address four main questions: (1) What is a “scale mismatch?” (2) How are scale mismatches generated? (3) What are the consequences of scale mismatches? (4) How can scale mismatches be resolved?

SCALE CONCEPTS AND SCALE MISMATCHES

Sociological and ecological scales

Societies and ecosystems interact over many spatial and temporal scales. This paper is not an attempt to review or redefine the concept of scale, which has received thorough treatment elsewhere (e.g., Wiens 1989, Levin 1992, Gibson et al. 2000, Turner et al. 2001), so we provide here only a brief summary of relevant ideas. The concept of scale is used in subtly different ways in sociology and in ecology (Gibson et al. 2000). In ecology, scale usually refers to the spatial and temporal dimensions of a pattern or process. Ecological scale, also called “geographic scale,” has two main attributes: grain and extent (Turner et al. 2001). Extent describes the total area or time period under consideration; grain describes the resolution of observations (Turner et al. 2001, Rietkirk et al. 2002). Changes in the number and nature of the interacting units in a system, for example, from individuals through populations to an entire species, are usually considered to be changes in the level of organization (e.g., Simon 1962). In contrast, sociological scale includes the representative nature of social structures from individuals to organizations as well as the social institutions, i.e., rules, laws, policies, and formal and informal cultural norms, that govern the spatial and temporal extent of resource access rights and management responsibilities (e.g., Barbier 1997, Chidumayo 2002, Ziker 2003, Bodin and Norberg 2005).

Social and ecological scales are often, but not always, aligned. Humans may interact with ecosystems as individuals or as representatives of organizations. Human actions are influenced by institutions, by perceptions of how ecosystems function, and by perceptions of future change. Ecosystems in turn are structured by processes and feedbacks, including human influences, that arise from the interactions of organisms with their environment. The goods and services that humans obtain from ecosystems may be localized, e.g., fruit from a single tree, or derived from a relatively large area, e.g., flood control by wetlands (see Daily et al. 1997). Although spatial and temporal location determine the underlying context for both social and ecological dynamics, the interactions between societies and ecosystems can create dynamic feedback loops in which humans both influence and are influenced by ecosystem processes (Levin 1999).

An important difference between societies and ecosystems is that some individual humans, especially those in organizational roles, are able to influence ecosystem patterns and processes at scales well beyond what might be expected, and far exceeding those at which the influence of any individual organism of another species might be felt. Human influence can be a direct result of the number of people represented or led, or can occur via informal rules, transitory regulations, or more permanent laws. The connection between representation and power contributes to a sociological concept of scale in which different levels of an organizational hierarchy respond and act at particular spatial and temporal scales that may range from small to very large. Recognition of the importance of social scale has been an underlying motive for the development of political ecology, which focuses first on local land users and their social relations and then traces those relations to higher scales of decision-making power (Blaikie 1985, Schmink and Wood 1992, Peterson 2000).

Scale mismatches

Although there are frequent references in the literature to scale mismatches between ecological and social systems, most investigations are circumstantial rather than direct (e.g., Wolf and Allen 1995, Gunderson and Holling 2002, Perry and Ommer 2003). The specific impacts of scale mismatches on natural resources and sustainability are seldom described, and no explicit framework has been proposed for examining scale mismatches within linked social-ecological systems. Folke et al. (1998) have considered the problem of social-ecological mismatches, but without offering either a definition or a mechanism by which scale mismatches arise. In this paper we are particularly interested in the relationship between human management and biophysical systems. We propose as a working definition that scale mismatches occur when the scale of environmental variation and the scale of the social organization responsible for management are aligned in such a way that one or more functions of the social-ecological system are disrupted, inefficiencies occur, and/or important components of the system are lost.

Several aspects of this definition require further clarification. Building on the suggestions of Lee (1993), we envisage that scale mismatches between social and ecological systems may be spatial, temporal, or functional. Spatial mismatches will occur when the spatial scales of management and the spatial scales of ecosystem processes do not align appropriately (Fig. 1). Temporal mismatches will occur when the temporal scales of management and the temporal scales of ecosystem processes do not align appropriately (Fig. 2). Functional mismatches will occur when the functional scales of management do not align appropriately with the functional scales of ecosystem processes (Fig. 3). By functional scale, we mean the magnitude or rate of a process of interest such as production, consumption, or a management manipulation. Appropriate alignment indicates a relationship in which the functioning of the social-ecological system is affected by scale-related issues. Another way of illustrating the same principles is to consider the ways in which social and ecological hierarchies (Fig. 4) are aligned relative to one another.

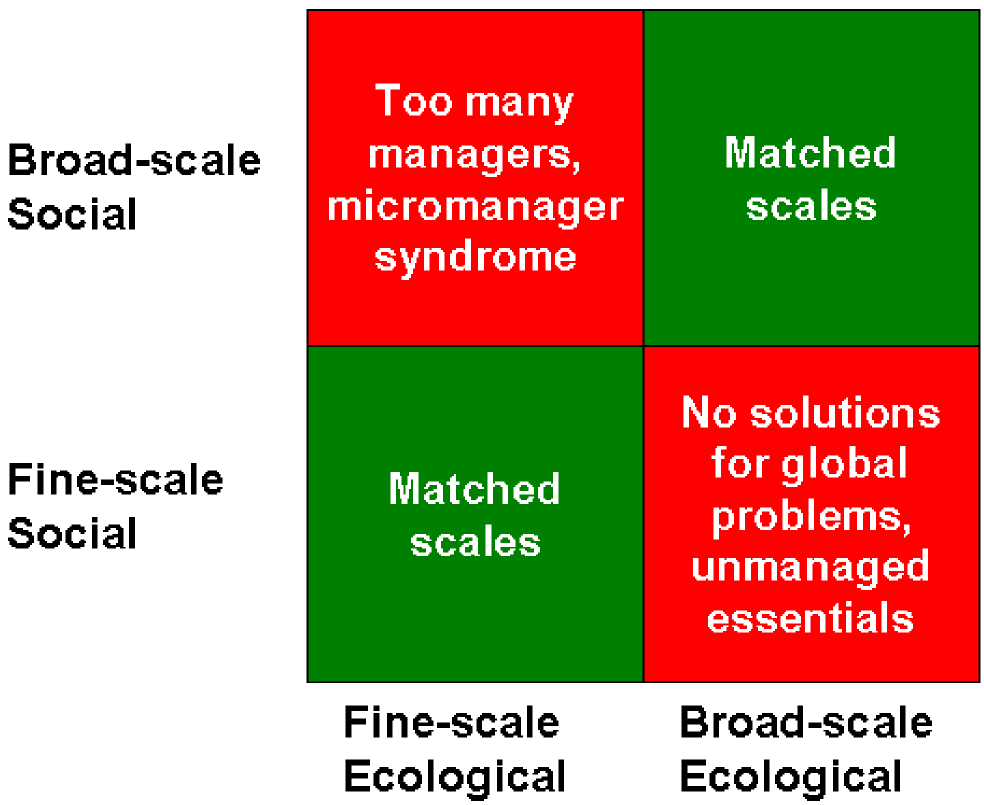
Scale mismatches arise through changes in the relationships between the spatial, temporal, or functional scales at which the environment varies, the scales at which human social organization occurs, and the demands of people and other organisms for resources. When there is a suitable match between the scales of social organization and environmental variation in such areas as production, disturbances, and recycling, management can cope adequately with environmental variation, demand and production can be balanced, and the system as a whole functions effectively (e.g., Wolf and Allen 1995). When the scales of social organization and environmental variation are mismatched, problems inevitably arise in either the social institutions that are responsible for management or the ecological systems that are being managed. In these cases, the system may stop working, experience a disruption of function, work inefficiently, and/or start to simplify through the loss of important components. The functions that are disrupted might include such things as the provision of ecosystem goods and services, self-maintenance or self-organization, and key processes like information exchange or nutrient cycles (Daily et al. 1997, Levin 1999). For example, many countries currently lack the broad-scale institutions that are necessary to manage regional deforestation; the resulting haphazard loss of forests can disrupt a wide range of ecological functions, including climate regulation, fruit provision, game species populations, and fire regimes (e.g., Nepstad et al. 1999).

Scale mismatches are not always easy to diagnose. In natural resource management systems, we suggest that scale mismatches will be evidenced by a loss of adaptive capacity in resource managers and the social system in which they are embedded, together with a loss of species, functions, and other system components, processes, or relationships that contribute to ecological resilience. The loss of adaptive capacity in the system can be caused by a failure in feedback signals or an inability to respond appropriately. An individual or organizational inability to respond in an appropriate manner, i.e., adapt, may be caused by externally imposed constraints such as policy instruments or by depleted resources, e.g. loss of reserves or capital, within the hierarchical level in question. Effective ecosystem management will respond to ecological processes at the scales at which they occur and will often simulate or recreate formerly broad-scale processes that have been disrupted. We next explore the causes and consequences of scale mismatches in more depth.

CAUSES AND CONSEQUENCES OF SCALE MISMATCHES

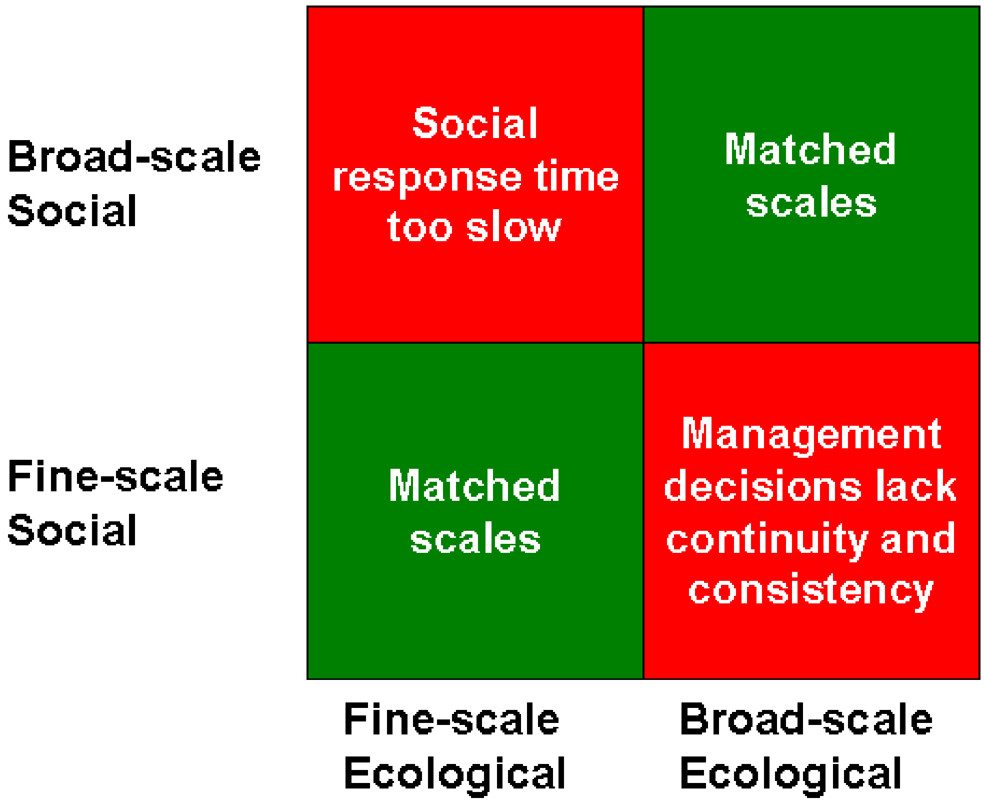
Scale mismatches result from changes in either the scale of environmental variation, the scale of the social organization responsible for management, or both. In other words, they can arise from the internal dynamics of social and ecological systems respectively, or from the dynamics of the social-ecological interaction. The processes that lead to scale mismatches can thus be summarized as primarily social, primarily ecological, or coupled

Fig. 1. Consequences of mismatched spatial scales (indicated in red) between social and ecological systems. For example, the scale of social organization at which control resides is too small for many global environmental problems, such as regulating carbon emissions and managing oceanic fisheries. In contrast, global conventions or national regulations that make sense for the average location over a broad scale can have unfortunate consequences at finer scales at which local conditions may differ substantially from the mean. A typical example would be the introduction of standard regulations governing the trade, production, or use of an ecosystem service that is overabundant in some places and rare in others; harvesting regulations typically need to be determined at relatively fine scales.



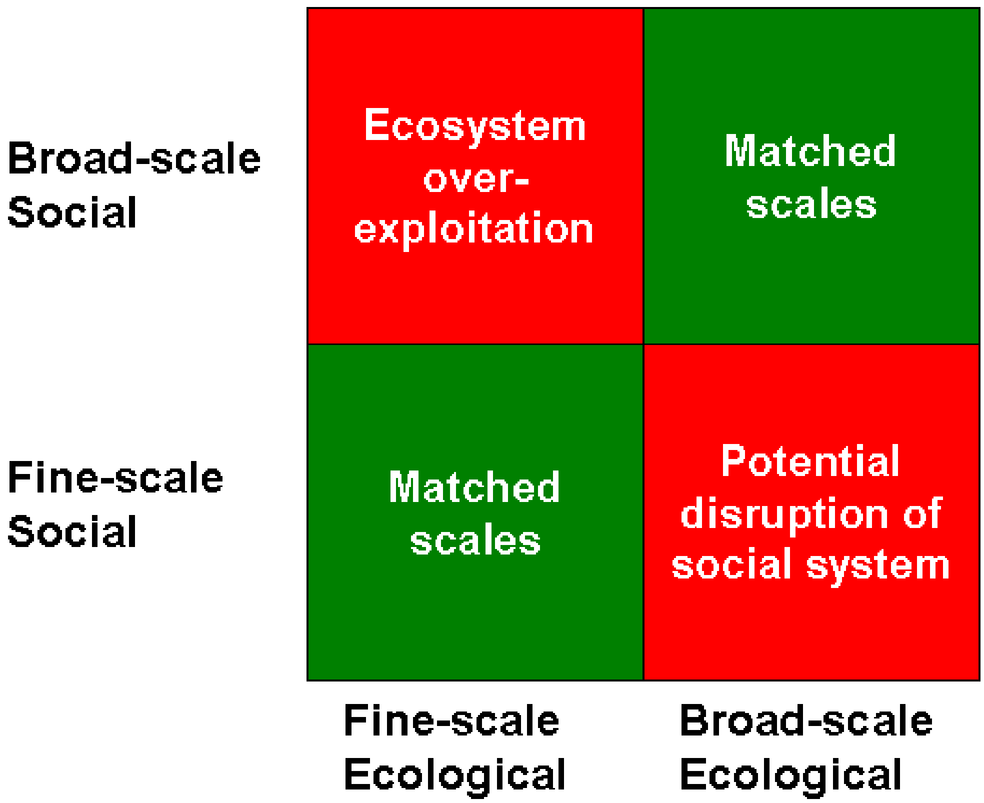
social-ecological. The social processes that lead to scale mismatches revolve primarily around land tenure, which constitutes the social institutions that control the allocation, use, and management of land and its associated resources; these institutions include rules, rights and restrictions and the organizations that enforce them. Land tenure is further influenced by changes in human populations, governance, technology, infrastructure, and values. The ecological processes that lead to scale mismatches primarily involve changes in the resource base through such things as trophic cascades, disease, reductions in productivity, and changes in the abiotic environment. Coupled social-

Fig. 2. Consequences of mismatched temporal scales (indicated in red) between social and ecological systems. For example, some ecological problems, such as the management of long-lived and slowly reproducing species like redwood trees, baobabs, whales, and elephants, require consistent, long-term policies that may be difficult to achieve over time horizons of 50 yr in western democracies. In contrast, it may take time for large bureaucracies and cumbersome organizations to face up to and deal with rapid ecological changes that demand immediate management action, such as the sudden introduction of an invasive species.



ecological processes that lead to scale mismatches include changes in the nature, i.e., magnitude, rate, frequency, or qualitative aspects, of social-ecological interactions. These changes are often set in motion by changes in societies or ecosystems and so overlap considerably with the previous two categories, but they are typically dominated by a feedback dynamic between social and ecological systems rather than by processes that are intrinsic to either. Social-ecological processes may result in system behaviors that differ from those of either social or ecological systems (Westley et al. 2002).

Fig. 3.Consequences of mismatched functional scales (indicated in red) between social and ecological systems. For example, problems arise when a city grows beyond the ability of the ecosystem to provide it with fresh water, whereas large-scale environmental changes, such as rising sea levels or relatively sudden reductions in primary production, can create crises for local communities.



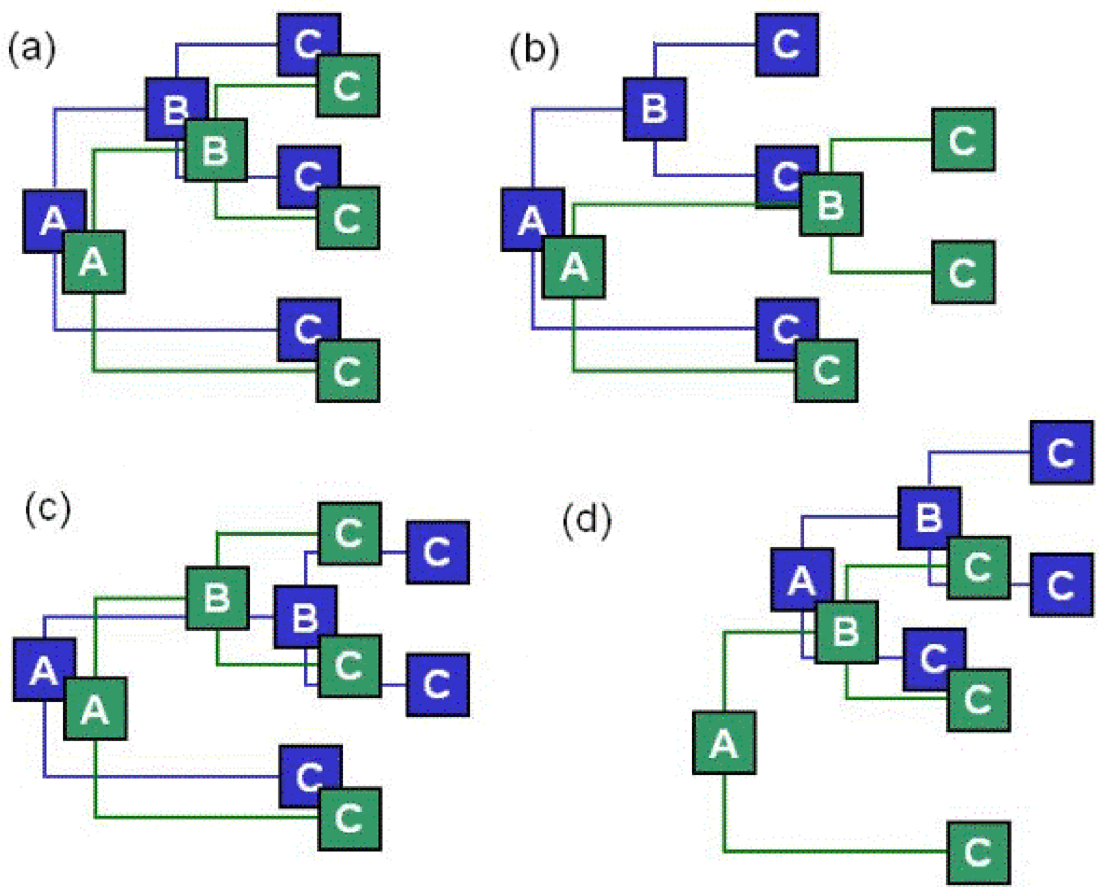
Social processes leading to scale mismatches

A diverse array of social processes has progressively altered the scales of social-ecological relationships:

1. At different times, different regions have seen a shift from dependence on hunted and gathered food resources to a reliance on agricultural production (Bender 1975, Messerli et al. 2000). These and more recent changes in food production have altered the geographic scale, i.e., grain and extent, of land use and land tenure (Boserup 1965, 1981, Alados 2004).

2. The global population has grown well beyond any historical precedent (Whitmore et al. 1993, UNEP 2002). Population growth has been accompanied by the sedentarization of people into villages, towns, and cities.

Fig. 4. Examples of how hierarchies may be aligned or misaligned in a natural resource management situation. Ecological processes (green boxes) are managed by people (blue boxes). Overlapping boxes indicate interactions between units, and the labels A, B, and C denote matching levels between hierarchies. (a) In an ideal situation, ecological processes will be managed by people who have the mandate and the power to act at the same scale as the process. (b) Scale mismatches may result in upper-level managers who have nothing to do but micromanage their juniors, while lower-level managers are confronted with ecological problems that they lack the resources to deal with (C-B mismatch). (c) Another kind of mismatch results in a lack of management at some key scales (unmanaged B) and the involvement of higher-level managers in lower-level resource management (B-C mismatch), leaving junior managers with little power to effect change (dangling C). (d) In a global or international context, a common scale mismatch occurs when no institution exists to deal with the broad-scale environmental problem (unmanaged A). Note that in many examples, scale mismatches are not necessarily system-wide.



3. There has been a global shift in the style of governance toward the nation-state, with increased levels of bureaucracy, changes in the distribution of power among individuals, and increasing creation of boundaries, together with a fragmentation of responsibility.

4. New technologies, such as chainsaws and tractors, have allowed people to greatly alter the scale at which they use land.

5. There has been a huge increase in the amount of infrastructure in many places in the world, making ecosystems more accessible than ever and providing opportunities for many areas to become involved in national and global economies (e.g., Forman 2000).

6. Human values and the ways in which societies view nature have changed, leading to fundamentally different kinds of social-ecological interactions (Messerli et al. 2000, Lambin et al. 2003). Together, these processes, each of which is discussed in more detail below, have resulted in both matches and mismatches between key scales of ecological and social systems.

Changes in land tenure and food production

Shifts in human production systems, and particularly in agriculture, have occurred over very long time periods. In Zimbabwe, for instance, a shift from hunter-gatherer life-styles to agro-pastoralism began between AD 200 and 700 and was further modified by the introduction of capitalist systems of production during colonization (Drinkwater 1991). Government acts in 1911 and 1923 and their subsequent amendments resulted in an agricultural system that was divided between traditional forms of land tenure and freehold commercial farmlands. The country's population grew from approximately 500,000 people in 1900 to more than 12 x 10^6 in 2000. However, communal areas, which cover 45% of the country, are still dominated by subsistence agriculture despite the fact that the populations in these areas have reached levels well beyond those that can be sustained by low-input agriculture alone (e.g. Murphree and Cumming 1995, Campbell et al. 2002). Similar conditions apply to much of sub-Saharan Africa, where continuing loss of nutrients is resulting in declining yields and increasing food insecurity (Drechsel et al. 2001). However, past events and traditional practices may take long periods to work their way out of social-ecological systems, and societal responses are often slow (Scheffer et al. 2003).

Changes in the human population

The global human population has led to increasing pressure on natural resources and more competition between individuals and organizations at many levels of society. Competition has occurred both for the resources themselves and for markets for products. In some instances, increases in the human population have also resulted in greater cooperation. In both cases, although change is frequent, the social, political, and economic framework in which land management occurs has a great deal of inertia (Scheffer et al. 2003). Relevant institutions and novel practices arise to solve newly perceived problems. Problem solution is often tied to existing conditions and to the scales involved; small enterprises and families can be adaptable, but entire cultures are often highly resistant to change. Institutions are rarely as flexible as the world that they emerged to deal with. Key aspects of natural resource policy and law were formulated at an earlier time, when encouraging exploration was the main goal. Hence, mining law and subsidies, water law, and public lands leasing were developed under socioeconomic conditions that no longer prevail. Resistance to institutional change may be active or passive, stemming from such causes as the naïveté of managers to the immediate relevance of system change, institutional inertia, or the fact that most institutions offer disproportionate benefits to some individuals over others. Inequalities that were justified in the original context of the institution's emergence may have diminished or disappeared completely as the context changed. Additionally, individuals often develop strong vested interests in maintaining institutions that are inadequate or inappropriate to new conditions once they derive social or economic benefits from them. For example, many countries still have laws governing mining and forestry rights that hark back to an earlier era of exploration.

Shifts in governance toward nation-states

As societies have shifted toward the model of a nation-state with rigid boundaries and a central government, natural resource rights have been increasingly sequestered in the hands of centralized agencies such as government departments. Centralized institutions frequently lack the necessary multiscale outlook and associated flexibility to solve unusual problems or those that occur at scales that they are not used to considering. The higher levels of centralized government are typically based in the capital city, and the decision makers with the most power are often unaware of the true situation "on the ground" in each of the localities under their administration. Consequently, finer-scale environmental heterogeneity may be overlooked or ignored, and policies emanating from centralized bureaucracies will often adopt a "one-size-fits-all" outlook that meshes poorly with a diverse social and ecological reality. Similarly, the structure of government departments may parcel out a range of different administrative functions in an illogical way or lump too many functions together in a single unit. Both cases have their associated weaknesses: "policy silos" lack cohesion and the exchange of essential information, whereas "multitasking" structures often ignore certain sectors and fail to clearly allocate responsibility for achieving solutions to particular problems. Not all management problems stem from mismatched central governance; in many cases, the evolution of tenure systems is driven by social and economic pressures to further misalign ecological and social scales. For example, many traditional societies require that land holdings be distributed among all sons or children, with the result that farms eventually become too small to be sustainable.

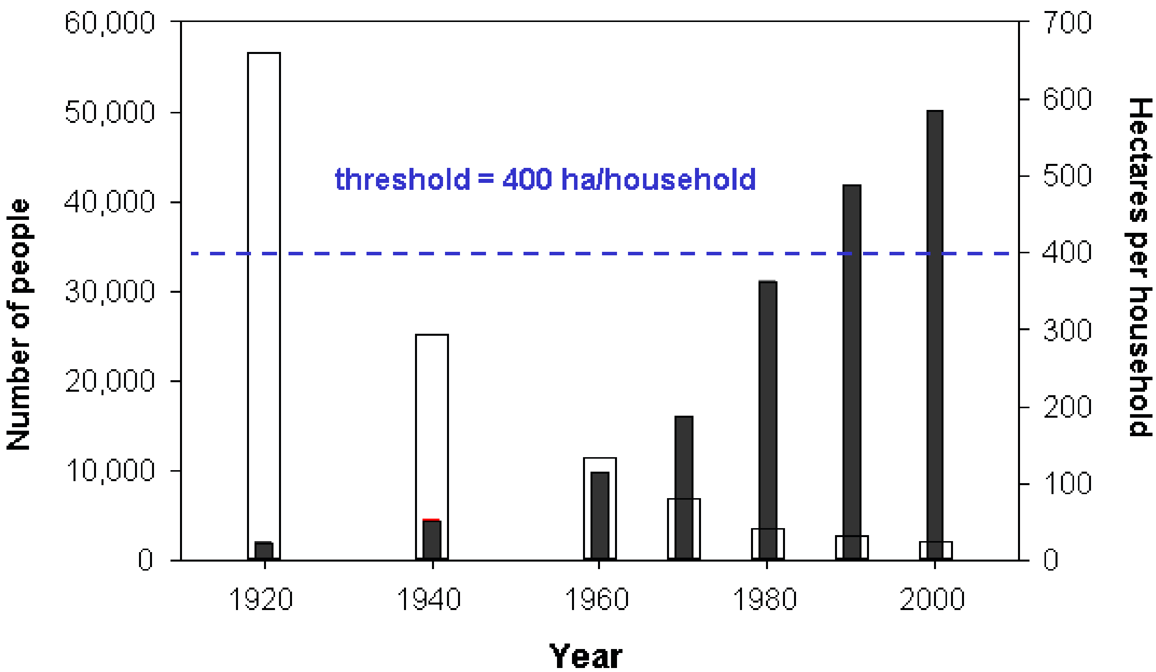
The actions of organizations that regulate resource use are closely related to the process of boundary creation. It is often suggested that humans homogenize habitats, reducing the diversity of landscapes and regions. This is true of many contemporary landscapes, such as the famous cornfields of Iowa in which a single crop has replaced naturally occurring plant diversity, or in Bangkok, where monotonous urban sprawl has encroached on a formerly diverse landscape. Of equal interest are those cases in which human action has resulted in greater than expected patchiness or excessive landscape heterogeneity. For a variety of reasons, humans often act to create additional boundaries in their environments, resulting in smaller patches than would exist without their presence. Through boundary formation, humans define their individual and group identities, create or enhance economic values, construct asymmetric power relations, secure resources against competitors, and increase control over the way in which resources are used. Boundary formation is strongly related to increases in human population density, particularly in cultures in which land tenure occurs at the household scale. The inefficiencies created by having to deal with units of a different scale may introduce potential vulnerabilities into the system, but they also create opportunities that can be exploited for economic, social, or political gain. Both boundary formation and boundary bridging occur with different degrees of success in different locations and cultures, and both processes can create social-ecological scale mismatches. The process of boundary formation is antagonistic to some other socioeconomic processes, such as the need for trade or companionship, that necessitate the development of approaches to bridging or permeating boundaries. The ways in which human and biophysical drivers lead to boundary formation have been widely discussed in the social scientific literature (e.g., Barth 1962, 1967, Adams 1974, Boone et al. 1990), but not usually in reference to their ecological impacts. Others have argued that human groups not only take advantage of extant biogeophysical distinctions but also create boundary conditions through distinct ethnic identities, religions, or adaptive strategies (Astuti 1995, O'Connor 1995, Guston 1996).

Changes in technology

Changes in the scales of management have also been driven by technology. With the development of faster, more efficient ways of planting and harvesting crops, individual land owners could occupy larger areas, and improvements in hunting, fishing, and forestry technologies have fundamentally changed the ways in which humans interact with natural resources. In many cases, technologies with huge impacts have been developed well in advance of the appropriate management institutions. The many recent collapses of global fisheries provide a case in point. Effective harvesting technologies have allowed societies to overexploit fisheries and many other natural resources in the absence of regional and global institutions with the power to regulate harvests at spatial and temporal scales that are appropriate for the ecological processes of reproduction and dispersal (Larkin 1977, Hillborn 1992, Pauly et al. 1998, Jackson et al. 2001).

Another consequence of technological advances has been the increasing ease with which societies can subsidize one another. Subsidies arise when institutions are created for the flow of expertise and other resources from one area to another. Just as landscapes typically contain areas that are net

Fig. 5. Changes in the human population and the area available per household in the Matibi II Communal Land in South Eastern Zimbabwe. With minimal external inputs, a household requires 20 ha of arable land, i.e., 4 ha with a minimum 5-yr rotation, and about 400 ha of grazing land to support a herd of 25 head of cattle and 35 goats. The threshold of 400 ha per household was reached during the 1940s. Filled bars indicate the number of people in the area (left-hand y-axis); empty bars indicate available area for farming (right-hand y-axis). Figure after Cumming (2003).



exporters or net importers of individuals of particular species, termed “source” and “sink” areas respectively in the population ecology literature, different societies or parts of societies may be sources or sinks for resources. Source-sink dynamics can maintain maladaptive institutions and scale mismatches. As Fig. 5 shows, the amount of land needed by a household in the semi-arid South East Lowveld (SEL) of Zimbabwe is about 20 ha of arable land, i.e., 4 ha with a minimum 5-yr rotation, and about 400 ha of grazing land. The threshold of 400 ha/household was passed 60 yr ago, and, by 2000, the land available per household in the Matibi II Communal land, for example, was about 35 ha (Cumming 2005). The increase in population density in the area has been possible primarily through subsidies, mostly in the form of money remitted from town to country and government and international food aid during drought years.

Changes in infrastructure

Social subsidies are intricately connected to transport and the associated infrastructure. Relatively recent improvements in the speed and capacity of transport have linked systems that were formerly independent of one another. This increase in connectivity has allowed societies to develop alternative solutions to ecological problems, in particular through institutions that provide spatial subsidies, without necessarily addressing the primary causes of the problem (e.g., Berlik and Kittredge 2002). This kind of perverse subsidy is particularly clear in the SEL, in which the current high density of farmers would be impossible without continuing international subsidies in the form of humanitarian assistance (Abel et al. 2006). Social organization facilitated by infrastructure and improved communications has allowed an unfavorable social-ecological situation to persist and has enabled the authorities to avoid addressing the underlying issues of ecosystem productivity and the sustainability of human livelihoods.

Scale mismatches can also arise through the influence of infrastructure. The development of road networks allows regional and national sociological processes to have a far greater effect on the ecosystems in a particular area than they ever did before. Champions of infrastructural development have emphasized the positive impacts of infrastructure, such as increased competitive ability for farmers through access to markets (Vance 1986, Owen 1987). Detractors point out the many negative impacts of roads, including forest fragmentation in areas near to roads (Nepstad et al. 1999), increases in fire frequency and carbon emissions, and species introductions and extinctions (Forman and Alexander 1998, Trombulak and Frissell 2000). Infrastructural development can have negative consequences for indigenous peoples (Davis 1977, Treece 1987) and lead to increased conflict, violence, inequality, and poverty in tropical regions (Hall 1989, Schmink and Wood 1992).

Changes in values

Finally, many of the institutions that are responsible for the management of natural resources operate according to a particular set of values, including both intrinsic preferences and the economic values associated with certain ecosystem goods or services (Raskin et al. 2002). The two may be closely linked; for example, tourism is driven largely by aesthetic values, but these may in turn alter the economic values related to developing land vs. keeping it in a more aesthetically pleasing state. Because values are subjective and may vary, particularly in an economic context, the aesthetic and market values of resources can undergo dramatic swings. As formerly valuable resources become less so, or vice versa, the economic returns from a particular tenure unit may change in such a way as to make the current relationship between ecological and sociological scales untenable. When changes in societal values produce large changes in anthropogenic activities, institutions frequently fail to adjust accordingly. Changes in economic values can produce changes in the kind and intensity of resource use. Similarly, as particular kinds of land use are tested, economically unviable options will be discarded unless they are supported by state or international subsidies, e.g., European subsidies to beef production in developing countries (Pearce 1993). The search for new solutions can lead to the formation of novel and scale-matched institutions, as happened in the SEL of Zimbabwe when failing commercial cattle ranches successfully made the transition to wildlife-based tourism by removing boundary fences and jointly managing wildlife resources over very much larger areas (Cumming 1999, Abel et al. 2006).

Ecological processes leading to scale mismatches

The development of scale mismatches does not depend solely on societal change. Mismatches can also arise through ecological change or unexpected ecological responses to management, such as in rapid regime shifts (Scheffer and Carpenter 2003). Resources are seldom static; they change through time, with production increasing or decreasing as the environment changes. Changes in the structure of ecological communities through both intrinsic and extrinsic mechanisms can alter the production of particular resources or ecosystem services that humans need. Disease outbreaks and predator-prey interactions can create spatial and temporal fluctuations in the population sizes of species that humans depend on (Bakun and Broad 2003); changes in herbivore communities can influence seed dispersal and, hence, plant diversity (Wright and Duber 2001, Bruun 2002); and populations of keystone species such as elephants, sea otters, or kangaroo mice can have impacts that ramify through food webs to influence the spatiotemporal scales at which different kinds of resources are available (e.g., Power et al. 1996, Simberloff 1998, Krogh 2002).

For example, in both protected areas and ranching systems, degradation of grazing areas as herbivore numbers increase or water supplies change can result in a gradual decrease in ecosystem productivity (e.g., Pamo 1998, Walker and Janssen 2002, Thiam 2003) or rapid transitions to alternative stable states (Westoby et al. 1989). The obvious solution to this problem is to increase the scale of management to take better advantage of broad-scale environmental variation. If both grazing and water are available over larger areas, degraded areas are given longer to recover and a more sustainable system, based on a mosaic of patches in different successional stages, can be initiated. In this example, tenure and management institutions at scales that initially seemed well matched to the scales of key ecological processes gradually become less and less appropriate as the resource base changes; failure on the part of existing institutions to recognize these changes and adapt to them or, alternatively, awareness of a problem followed by management actions that accentuate it can result in an ever-worsening scale mismatch.

Social-ecological processes leading to scale mismatches

Social-ecological interactions can lead to scale mismatches when the nature of the interaction is substantially changed. Interactions that have been stable for a long period of time may suddenly be transformed by changes in the broader context in which they occur or by a set of destabilizing feedbacks between social and ecological systems (Muradian 2001). Levin (1999) considers that tightening the feedbacks between social and ecological systems is an important component of sustainability. For example, when a fisherman harvests fish of a single species at the same spatial and temporal scales as fish production, changes in the fish population are immediate and obvious, and there is a tight feedback from fish population to fisherman. This creates a strong incentive to manage the population sustainably, for example, by periodically reducing offtake to allow stocks to recover. In contrast, if the fisherman can harvest over multiple populations and species, he has a less clear idea of the current state of each individual fish stock and is less directly dependent on it; feedbacks from fish to fisherman become weaker, even though the feedback from fisherman to fish may remain strong, and there is an increasing likelihood of overexploitation of one or more populations.

Anthropogenic activities often amplify resource changes or modify the resource base directly. They may have a direct influence, for instance, by reducing the productive potential of the land or removing species such as large predators that play important ecological roles, or they may follow indirectly from such changes as the introduction of a new crop, new technologies, or swings in world market prices. In each of these cases, societies can trigger changes in the ecosystem processes that underlie resource production. Changes in ecosystems in turn lead to alterations in the scales at which management and policy solutions are needed. Anthropogenic activities often modify not only the immediate biophysical environment but also the action of broad-scale natural processes. Some of the classical examples of human impacts include changes in flooding, fire regimes, and the migratory movements of large herbivores (e.g., Pamo 1998, Cochrane and Laurance 2002, Laurance et al. 2002). In each of these instances, humans dampen natural variation through command-and-control management approaches (Holling and Meffe 1996). By changing the scale of natural variation in the landscape, ecosystem processes may be disrupted or modified in such a way that scale mismatches occur. Reductions or increases in the range of natural variation can be both a cause and a consequence of scale mismatches.

A fascinating example of a social-ecological scale mismatch comes from the early harvesting and later conservation of populations of marine mammals. These efforts have largely been undertaken at scales smaller than entire oceans and have focused on populations and individual species rather than on communities. Recent evidence (Springer et al. 2003) suggests that reductions in the populations of great whales, a consequence of excessive whaling by maritime nations, may have left some killer whale populations with insufficient food resources. As a result, several killer whale pods have turned to seals and sea otters for food. Sea otters are keystone species (Power et al. 1996) that can regulate populations of sea urchins, influencing algal production and the near-shore food web. The outcome of declining whale populations has been a series of sequential crashes in conserved populations of smaller marine mammals and a lot of finger-pointing and accusations in the social system. The mismatch between the scale of whale offtake by humans, which is a social phenomenon, and the scale of whale reproduction, which is an ecological phenomenon, has had ecosystem-wide consequences that influence other kinds of social-ecological interactions in complex ways and may take decades to resolve. Hopefully, management actions at broad spatial and temporal scales will eventually lead to the recovery of the whale population and the restoration of the food chain that supports killer whales, while maintaining smaller-scale institutions that mitigate smaller-scale threats, such as by-catch, hunting, and disease, to marine mammal populations.

General consequences of scale mismatches

As the preceding discussion has illustrated, mismatches between the scales of ecological processes and the institutions that are responsible for managing them can contribute to a decrease in social-ecological resilience. Resilience is reduced when the integrity or long-term sustainability of desirable components of either ecological or social systems, or both, are compromised. Degraded ecological systems become less able to provide the goods and services that humans rely on. Degraded social systems result in a net decrease in human well-being, including negative impacts on such things as health, freedom, and rights.

One of the most pervasive problems resulting from scale mismatches is the mismanagement of ecosystems. Mismatched organizations are frequently confronted with ecological situations in which they do not understand the nature of the problem, are incapable of managing effectively, or lack the necessary power to achieve the scale of management that is required. Territorial institutions in these circumstances are often reluctant to give up power, and fine-scale decisions seldom add up to the kind of cohesive action that is required for broad-scale ecological management. Institutional confusion over the nature of the problem translates into a lack of clear responsibility for finding solutions. At the same time, key decisions may be made by individuals acting on their own, rather than in a coordinated manner across the organization.

Mismatched organizations may also lack appropriate monitoring frameworks. Consequently, the kind and amount of information that they acquire about the problem may be inadequate for the formulation of a true solution. When the available information is incomplete or incorrect, it becomes harder to realize the significance of the problem. In other instances, too much information of the wrong kind is collected; data gathering and analysis can then become traps that distract members of the organization from truly coming to grips with the key issues.

As members of mismatched institutions gradually become aware of the problems with their approach, several responses are possible; they range from making a measured attempt to reach a new solution to ignoring problems for as long as possible. A common outcome is that organizations become more inward-looking or get caught up with in-fighting. In the meantime, the ecological problem may either fix itself or get worse. In either instance, there tends to be a further decoupling of social and ecological processes. The consequences of scale mismatches for the environment may be severe: inappropriate management often results in a loss of natural landscape heterogeneity and further impacts on broad-scale ecological processes such as the movement of fire or species through landscapes.

As property sizes in a particular area decrease, social networks grow larger and economies of scale are reduced. Economies of scale occur when the profit per item as a function of the number of items produced increases more rapidly than the per item cost. Higher production rates lead to greater economies of scale, although this trend may also be accompanied by a reduction in the market value of each item in a competitive situation unless returns are optimized by controlling production, as in the OPEC strategy. In many natural-resource-based production systems such as forestry or agriculture, economies of scale occur with expansions in the area of production. This tendency works against the socioeconomic drivers of boundary development and property splitting. One approach to reconciling the two has been intensification to obtain higher returns per unit area. Boserup (1965) proposed that population growth will lead to more intensive forms of production through what is essentially the same mechanism. One of the consequences of mismatches in scale between the ecological production system and the embedded socioeconomic system is that increasingly greater pressure is exerted on natural resources (Campbell et al. 2002). Negative economies of scale also occur in the community; as social networks expand, the transaction costs of maintaining them increase and social capital may be lost.

Unexpected economic thresholds and constraints may emerge as property sizes are reduced. If income relates to production according to a nonlinear function, it may be relatively easy for stochastic environmental fluctuations to push the returns from a smaller property across a threshold at which management costs are greater than returns. As the sizes of holdings are reduced, it becomes less likely that a single area will contain all the necessary resources, thus compounding the problem. For example, as the sizes of farms are reduced, it may no longer be possible for all holdings to connect directly to streams or impoundments. Many kinds of activity require complementarity of resources (Fahrig 2001). Where complementarity is not present, some form of subsidy is often necessary, e.g., water may be pumped from boreholes or moved down pipelines or ditches. Reductions in property size may thus entail an increasing reliance on subsidies and a vulnerability to their continued provision.

Finally, we note that the impacts of scale mismatches are not necessarily all negative, depending on how the ensuing challenges are approached. Crowding may encourage innovations such as the development of irrigation systems and more effective systems of rules and institutions, although such changes also provide an opportunity for the imposition of asymmetries in wealth and power on the system. Shared recognition of a single obvious problem can foster social capital as people work together to overcome it, and increases in social capital can have benefits beyond the solution of the problem that produced them.

RESOLVING SCALE MISMATCHES

Given that scale mismatches are the products of a range of complex social and ecological factors, they are unlikely to be simple to resolve. Scale mismatches are difficult to find solutions to because (1) the problems that they engender are easily blamed on other, apparently more obvious factors and (2) even though a problem has been clearly identified as scale-related, it can not usually be solved at any single level or scale in the social or economic hierarchy, because a scale realignment almost always requires a restructuring of multiple aspects of the hierarchy. Because changes in hierarchical structures are difficult to achieve, successful solutions will generally have to involve either reaching a critical mass of stakeholder opinion and involvement, i.e., bottom-up forcing, or top-down forcing in the form of an appropriate grant or other intervention from outside the local system. In exceptional circumstances, we can also envisage that transformative adjustment by a single group at a single ecological and social scale might solve the problem.

The first step in resolving scale mismatches is the awareness that one of the causes of the problem is a mismatch between ecological and institutional scales. The identification of diagnostic properties of mismatched systems is challenging; similar changes will accompany many different kinds of natural resource management problems, making it difficult to separate out the explicit consequences of scale mismatches. Superficially, in systems in which scale mismatches are prevalent we would expect to see evidence of resource-related social conflict and/or feelings of powerlessness in the social system and, in the ecosystem, evidence of changes in ecosystem function and/or biodiversity. Recognition of the underlying scale dependency of the problem may require significant social learning.

The second step in resolving problems related to scale mismatches is to formulate an active approach, or a range of alternative approaches, to solving both the immediate and underlying causes of the mismatch. Given the problems of institutional inertia and continual change in both institutions and resources, the most effective solutions are likely to involve the creation of enabling conditions for adaptive co-management regimes to emerge in which experimentation, learning, and adaptation at the appropriate scales are supported and communities of resource managers are given the scope to experiment with alternative solutions (Ruitenbeek and Cartier 2001). In the short term, it is often possible to dismantle, modify, or create institutions, including tenure, that can operate at the appropriate scale. One of the best solutions to many kinds of mismatch problems may be to modify boundary locations or to alter their properties, for example, by removing fences to create permeable boundaries. Decreasing pressure on resources, an alternative solution, will generally be difficult to achieve. In any institutional rearrangement, it is likely that a number of social and political barriers will have to be overcome; in reality, successful reorganizations may have to wait for the appropriate alignment of different institutional levels at stages in which key individuals are receptive to new ideas (Westley 2002).

There are a number of examples of successful solutions to scale mismatches. The history of water use in the Salt River Valley in Arizona provides an informative case study. Mismatches have been created in many places by alternate systems of ownership for both agricultural land and the surface water flow that is used to irrigate river valleys in arid lands. During the settlement of the Salt River Valley of central Arizona during the late 19th century by immigrants of European origin, land was first allocated in discrete parcels of 160 acres, and then 640 acres, to which all normal rights of private property applied. Rights to the use of surface water flow were assigned according to temporal priority of claim and continuity of use. This principle of prior appropriation worked well in the early stages of agricultural settlement when farm densities were low and demands on the surface flow were well below capacity. Although farmland was divisible into finite units that could be individually owned, the water that gave the land its value was not as easily divisible. For instance, a downstream farmer with prior rights on water would have to be continually vigilant during a dry year to keep an upstream farmer from taking most of the water. The resulting conflicts eventually led to collective agreements on water distribution. Other examples of ecological processes that encourage collective action include the spread of pests overland and of algae through canals, and the salinization of fields because of rising groundwater (Fiege 1999). In each of these situations, individual farmers would be unable to adequately redress the problem without regional cooperation. Cooperative action was an early hallmark of irrigation farming and led to the creation of social, economic, and political institutions that reflected this pressure.

Collective action and the realignment of management institutions have also been responses to climatic variability when it exceeds the absorptive capability of small-scale farmers. In the Salt River Valley, catastrophic floods in 1890 and 1891 were followed by a severe drought during 1897–1903. These serious, but not extraordinary, environmental events threatened the existence of this still young farming center, leading the local citizenry to respond on two levels (Smith 1986). Locally, many people bound themselves together into the Salt River Water Users Association in 1903; this was later renamed the Salt River Project, and it still manages most of the water distributed in the valley. At the same time, some of the more influential citizens lobbied in Washington for a National Reclamation Act that eventually transformed many regions in the western United States, among them the Salt River Valley. These two responses were efforts to overcome the same set of threats and worked together at different scales to put in place lasting changes in the surface water regime of the Salt River Valley and the political and economic organizations that managed it. The first response, collective local action, moved the scale of water management in the valley up from individual farmers and small canal companies to a single supplier of water administered by all the users as a semi-public entity in which one acre equaled one vote. The second response was a classic cross-scale interaction in which local pressure led to national-level changes that in turn affected a much larger region and population than the group from which the political pressure had originated. Sometimes the realignment of resource management is not simply an aggregation of similar participants into a larger administrative unit, but requires the cooperation of natural resource extractors from various sectors that all depend on a common-pool resource.

Following the history in the Salt River valley of central Arizona into recent decades, the emergence of rapidly growing urban centers drawing on the same surface water flows as the existing agrarian community has led to an increasing extraction of groundwater well beyond the natural recharge rate. Although surface water flows were highly regulated, groundwater extraction was based on virtually unlimited “beneficial use” to the land owner. Growing demand from the agricultural, municipal, and industrial sectors throughout the 1950s, 1960s, and 1970s led to a rapidly dropping aquifer level with accompanying threats of ground subsidence and eventual water shortages. However, the only administrative unit with authority over all of these sectors was the state government, and it did not have the political will to force a compromise on any one of these constituencies. It was the national government that used its leverage as the financial backer of a new water project, the Central Arizona Project canal that would carry supplemental water needed by all sectors, and threatened to cut off federal funds if serious groundwater reforms were not instituted. This led to forced negotiations between competing sectors and the passage of state legislation, the Groundwater Management Act of 1980, which created four Active Management Areas paralleling groundwater basins to monitor and control groundwater pumping in the vicinity of growing urban areas, plus a new state Agency of Water Resources to ensure compliance (Kupel 2003).

As the Salt River example implies, institutional change will typically have to occur through a process of social learning that includes education, information sharing, and the formation of a common vision among stakeholders (Argyris and Schoen 1978). It may be difficult and frustrating to achieve as well as critically dependent on small windows of opportunity during which different institutional and ecological components are appropriately aligned with one another to produce the necessary social, political, and economic capitals.

Institutional reorganization is not necessarily the only solution to scale mismatch problems, although it seems to be the easiest alternative to achieve. Although it is difficult to modify the scales at which ecological processes occur, it may be possible to find a socioeconomic win-win solution by working with existing institutions to take advantage of higher-value land uses that rely on processes that occur at a scale that is more appropriate for existing institutions to manage.

The question of how best to resolve scale mismatches remains a frontier for research on social-ecological management and policy. Although we would like to be able to offer a much more detailed outline of how the resolution of scale mismatches can be achieved, there is very little literature that is explicitly about this topic and relatively few published case studies that have documented successful solutions to scale mismatch problems. Consequently, rather than trying to speculate, it seems best that we highlight this important area as a question that remains open.

CONCLUSIONS

Scale mismatches between social and ecological components are widespread in social-ecological systems. Although they often arise as an unintended consequence of human social and economic development patterns, they may also be facilitated by poorly designed policy and management initatives. Some of the main causes of scale mismatches are changes in food production, human demography, governance, technology, infrastructure and transport, and human values and perceptions of the natural world. Scale mismatches may have a variety of consequences, including the mismanagement of ecosystems and the resulting decline or degradation of both social and ecological systems. Recognizing and resolving scale mismatches is thus an important aspect of building resilience in social-ecological systems. At present, our understanding of the topic of scale mismatches is limited and would benefit from more synthetic, interdisciplinary research. In particular, we are currently lacking information in several essential areas: we need to develop the tools to accurately diagnose scale mismatches, we need to understand the dynamics that maintain maladaptive institutional arrangements, and we need to determine what kinds of remedial action are most likely to be effective. The long-term resolution of scale mismatches is part of a broader problem of developing flexible learning institutions that can change and adapt to a changing environment. Although widespread institutional reform may be too difficult an agenda to achieve, it is also clear that taking advantage of windows of opportunity to resolve scale mismatches can have profound and long-term benefits for both societies and ecosystems.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol11/iss1/art14/responses/

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