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The globalization of socio-ecological systems: An agenda for scientific research

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Abstract

We argue that globalization is a central feature of coupled human–environment systems or, as we call them, socio-ecological systems (SESs). In this article, we focus on the effects of globalization on the resilience, vulnerability, and adaptability of these systems. We begin with a brief discussion of key terms, arguing that socio-economic resilience regularly substitutes for biophysical resilience in SESs with consequences that are often unforeseen. A discussion of several mega-trends (e.g. the rise of mega-cities, the demand for hydrocarbons, the revolution in information technologies) underpins our argument. We then proceed to identify key analytical dimensions of globalization, including rising connectedness, increased speed, spatial stretching, and declining diversity. We show how each of these phenomena can cut both ways in terms of impacts on the resilience and vulnerability of SESs. A particularly important insight flowing from this analysis centers on the reversal of the usual conditions in which large-scale things are slow and durable while small-scale things are fast and ephemeral. The fact that SESs are reflexive can lead either to initiatives aimed at avoiding or mitigating the dangers of globalization or to positive feedback processes that intensify the impacts of globalization. In the concluding section, we argue for sustained empirical research regarding these concerns and make suggestions about ways to enhance the incentives for individual researchers to work on these matters.

Keywords: Globalization; Resilience; Vulnerability; Adaptation; Socio-ecological system

1. Introduction

Studies of resilience, vulnerability, and adaptability have moved forward in tandem from analyses focusing either on ecological systems or on social systems toward holistic conceptualizations and models of socio-ecological systems (SESs) (Gallopín et al., 1989), social-ecological systems (Berkes and Folke, 1998), or coupled human–environment systems (Turner et al., 2003a, b). They have particularly focused on the behavior and evolution of such systems in the face of threats or hazards posed by many different forms of perturbation or stressors. Resilience studies evolved from an original focus on resilience and multi-stable states in ecological systems (Holling, 1973) to the study of nested cycles of adaptive change in SESs in which persistence and novelty are intertwined, and finally to transformations that can cascade up scales when small, fast events trigger big, slow ones (Holling et al., 2002). Likewise, new conceptualizations of vulnerability build on risk-hazard and pressure-and-release models of social and economic systems. These studies consider coupled

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systems and their capacity to respond to hazards as well as the origins of the hazards within the coupled systems themselves and in the world beyond (Turner et al., 2003a, b; O'Brien et al., 2004). Thus, both resilience and vulnerability studies now accept the interaction between endogenous and exogenous processes as central to their understanding.

These complex relationships are far easier to conceptualize than to identify in empirical—and especially quantitative—assessments of resilience and vulnerability (see O'Brien and Leichenko, 2000; Carpenter et al., 2001; Walker et al., 2002; Luers et al., 2003; Turner et al., 2003b; Adger et al., 2005). Such difficulties are amplified in studies that take a broad and dynamic approach to exogenous socio-economic conditions, one that includes cognitive, demographic, institutional, and technological factors. Including these considerations, however, seems essential in a world characterized by "globalization", in which space and time are increasingly compressed with regard to flows of information, people, goods, and services (Held et al., 1999; Hirst and Thompson, 1999). In this article, we focus on the effects of globalization on the resilience, vulnerability, and adaptability of SESs at scales ranging from the local to the global. Globalization itself is not treated as a single, measurable variable, owing to the complex set of phenomena captured by the term and the absence of standard measures or indicators of globalization. Rather, globalization refers to phenomena whose elements can be disaggregated and analyzed one at a time.

To provide a firm basis for the analysis to follow, we start with an effort to sharpen the conceptual foundation of our argument before moving on to some general comments about the nature of globalization and an account of a number of key analytical features of globalization. In the process, we develop questions and hypotheses about the impact of various aspects of globalization on resilience, vulnerability, and adaptability in SESs. Because human behavior is reflexive in the sense that people observe both natural and social occurrences and modify their behavior on the basis of knowledge and their expectations about future occurrences, we also consider social responses to globalization. In our final substantive section, we highlight the key questions outlined in the preceding sections of the article and endeavor to frame them as priorities for a research program that will interest members of the community concerned with the human dimensions of global change.

2. Getting the terminology straight—resilience, vulnerability, and adaptability

Research on resilience, vulnerability, and adaptability is expanding at a rapid pace and in a number of directions. Although this is fundamentally good news, it has also given rise to some confusion regarding terminology. To clarify our main concerns and to set this article in a broader context, we begin with a discussion of key concepts. A broader discussion of these concepts and their relations can be found in other contributions to this special issue (Adger, 2006; Folke, 2006; Gallopin, 2006; Janssen et al., 2006; Smit and Wandel, 2006).

2.1. *Resilience, vulnerability, and adaptability as features of actors and of systems*

In the literature that concerns us, the ideas of adaptation and adaptability are somewhat older than resilience and the concepts related to it, robustness and vulnerability. In the life sciences, adaptation goes back a long way, and was brought to prominence by Darwin and others in attempting to explain the genesis of diverse forms of life. In the social sciences, it dates back at least to the cultural ecology of the 1940s and 1950s (e.g. White, 1949; Steward, 1955). In these contexts, *adaptation* refers to the process of structural change in response to external circumstances. *Adaptedness* then refers to the extent to which a particular dynamic structure is effective in dealing with its environment, and *adaptability* refers to the capacity to adapt to future changes in the environment of the system concerned. Adaptation and adaptability have, moreover, a connotation of *re*-activity to changing exogenous circumstances, whereas resilience, robustness, and vulnerability are more often used in a setting in which society and its environment are deemed to be *inter*-active and so dynamic. Adaptation and adaptability are rather general concepts that do not point to the why and how of the underlying system dynamics. Resilience, robustness, and vulnerability point to structural characteristics of the systems concerned, and to whether or not adaptation is necessary.

The concepts "resilience", "robustness", and "vulnerability" can only be understood in relation to one another (van der Leeuw, 2001). All three are properties of a combined SES. *Robustness* is the most recent of these terms (Wagner, 2005). Its intrinsic meanings are still under (sometimes heated) discussion (cf. www.santafe.edu/robustness). In the present context, it seems to refer to the structural and other properties of a system that allow it to withstand the influence of disturbances without changing structure or dynamics (Anderies et al., 2004). Current levels of robustness may be based on past adaptations. If these were highly specific, the system may need to adapt upon encountering new types of disturbances (Carlson and Doyle, 2002). As defined by Holling (1973), by contrast, *resilience* refers to "the capacity of a system to absorb and utilize or even benefit from perturbations and changes that attain it, and so to persist without a qualitative change in the system's structure." Such a system may take new external conditions into account by absorbing them into its mode of functioning (Holling, 1986). The difference between the two concepts thus seems to lie in the extent to which (non-structural) changes in dynamics may be introduced into a system under the impact of perturbations. Resilience allows for temporary changes in functioning and dynamics, as long as the system remains within the same stability domain. *Vulnerability* refers to situations in which neither robustness nor resilience enables a system to survive without structural changes. In such cases, either the system does adapt structurally or it is driven to extinction. All three terms express a temporary condition of the interaction between a system and its context.

The terms resilience, vulnerability, and adaptability can be—and commonly are—used at all spatial and temporal levels in a dynamic structure, whether societal, environmental, or socio-ecological. They may refer to capacities of the system as a whole, but also to those of any one (or more) of its components, even down to the level of the individual actor.

2.2. The meaning of resilience, vulnerability, and adaptability in social and in biophysical systems: similarities and differences

In most systems, whether social or biophysical, external or internal disturbances trigger a number of reactions across spatial and temporal scales. Which of these reactions eventually overcomes the disturbance and returns the system to normal functioning and whether the episode will affect the future dynamics of the system, depends on the persistence of the disturbance as well as on the size of its impact.

A clear example of the impact of an external disturbance on an SES involves an agro-pastoral society experiencing drought. The impact of a drought is determined in part by the extent of the water shortage experienced by the crops, the animals, and the human population. One could say that the size of its impact can be quantified in terms of the "missing" amount of water at any one time and place, and the disturbance this lack of water causes in the subsistence and growth patterns of the plants, animals, and people involved.

The duration of the drought is another important variable. Ethnographic, historical, and archaeological observations confirm that in the first year, the population usually can survive even a serious drought by dipping into grain reserves and other resources. In the second year of a drought, those reserves are generally insufficient, and people will begin to slaughter some of their animals. Generally, in the third year, they slaughter so many of these that, in the fourth year, the long-term survival of the group is threatened. Unless they migrate to better lands, or disband as a group, or institute other structural changes ("borrowing" from a neighboring group, for example, which generally leads to long-term exchange relations), they face collective death. Thus, if in the first year, the group's subsistence dynamics are sufficiently *robust* to cope with the drought with only minor adjustments, in the second year, the group survives on its *resilience* or, in other words, by relinquishing part of the resources that serve as a long-term "backbone" to its way of life. In the third year, the group becomes *vulnerable* to further mishaps, and if nothing structural is done, the group ceases to exist in the fourth year. Thus, the temporal scale of a perturbation—as well as the scale of the system's own dynamics—is an important measure of the system's adaptive capacity, robustness, resilience, and vulnerability. In this respect, SESs do not differ from purely biophysical or purely social systems. In addition to temporal scale, the spatial scale of the phenomenon determines how many people (or animals, crops, etc.) are involved in the disaster, and indirectly how long it will take for natural restorative processes (demographic processes, recolonization of the vegetation, etc.) to overcome the damage done. Compared with the problems we must come to terms with today, this example is extremely simple. Yet its very simplicity helps to clarify the meaning of resilience, vulnerability, and adaptability in coupled systems.

In improving our understanding of the differences between anthropogenic and biophysical system dynamics, an important difference is that people and organizations are capable of learning, and learning how to learn (Bateson, 1972). They communicate by means of self-referentially negotiated symbols (Luhman, 1985), and act individually as well as in conjunction with others. They have the capacity to create objects, informing a wide range of substances, and substantiating a wide range of forms.

Relative to their lifespan, human societies therefore have a variety of very rapid adaptive dynamics at their disposal. These have enabled them to insert themselves into the dynamic structure of biophysical systems to the extent that the latter have, in the true sense of the word, become socio-ecological. In the process, many human societies have exchanged external (environmental) for internal (societal) complexity. They have homogenized parts of their environment in order to bring their dynamics under control, as in the cases of deforestation, cultivation, and grazing. Over the last 10,000 years, the survival of SESs has therefore become increasingly dependent *on the resilience of their social dynamics in contrast to their purely biophysical dynamics.* This is particularly clear in "old" settled areas, such as the Mediterranean Basin (Naveh and Liebermann, 1984; van der Leeuw, 1998) and the Swiss Alps (Netting, 1981).

The counterpart to this is that they have transformed the spectrum of dangerous or threatening situations in which they intervene (van der Leeuw, 2001). This is due to the fact that they have acted to dampen or remove risks that occur frequently. Such interventions are based on a reduced image of the dynamics involved, in which the short time scales predominate. In the process, a range of new (unknown) dynamics at different time scales may be introduced, including (very) long ones that are hard to detect in the short run. The net effect is that more and more frequent threats are brought under control, while new, infrequent dangers are created. Though this may for some time create an appearance of control, the accumulation of longer-term threats undermines that stability "unseen". Eventually, the longer-term dangers emerge, leading to what may be perceived as a "crisis", such as the gyrations of world oil prices in the face of perceived scarcity. Such crises are inevitable in SESs, because the substitution of complexity internal to social systems for external complexity will remain incomplete. Mismatches, discontinuities, non-linearities, and thresholds are likely to be revealed as this process of substitution unfolds.

3. What is globalization?

Although we lack simple—much less generic—indicators of globalization, there is widespread agreement that globalization is a defining feature of our times. We cannot solve the measurement problem in general terms. But some initial observations about the basic character and scope of globalization will help to set the stage for an analysis of the links between globalization and socio-ecological resilience and vulnerability. We are interested in the consequences of globalization for the structural characteristics of SESs at various scales. In this connection, we find it helpful to draw a distinction between global social change and global environmental change and then to consider the interactions between the two that generate what we can speak of as a truly new systemic phenomenon.

3.1. Global social and environmental change

Global social change involves the ''…widening, intensifying, speeding up and growing impact of world-wide connectedness'' (Held et al.). Taken individually, none of these trends is unprecedented. But the rate of increase in material, economic, and social interactions set the current era apart from previous periods, such as the ''belle epoque'' between 1880 and 1914. Taken together, these flows are producing major systemic consequences, a reshaping of the relationships between markets and governance, and new forms of geopolitical dependency and interdependency. Globalization appears to be increasing the mobility of economic and political power, both upwards (toward new global centers) and downwards (toward increasingly specialized nodes in global networks). The changes coincide with the spread of emblematic ideologies and the diffusion of mass consumer culture (and the ideas and behaviors that go with it) on a global scale (Leichenko and Solecki, 2005).

Environmental change also needs to be considered as a global phenomenon. Whether changes are systemic (e.g. climate change and variability) or cumulative (e.g. aggregate loss of biological diversity), the biophysical changes occurring today are global in scope. What is more, the large-scale environmental changes that mark the present era are increasingly anthropogenic in origin. People have succeeded during the last 30–40,000 years in restructuring many ecosystems (e.g. through the use of fire to alter assemblages of plants, by the domestication of animals, and by the harnessing of various kinds of energy). But, today, we are operating in a ''no analogue'' state in which human actions have driven major planetary support systems beyond the bounds of what is observable in the paleo-climatic record (Crutzen and Stoermer, 2000; McNeill, 2000; Steffen et al., 2004).

Global social change and global environmental change interact with each other. In many cases, these changes can be expected to amplify or dampen one another through the operation of feedback mechanisms. The impacts of climate change on social systems, for instance, may lead to far-reaching actions intended to decarbonize industrialized societies. Climate change is leading to the innovation and diffusion of technological options, however, that fail to alleviate the underlying forces leading to greenhouse gas emissions or that may cause new problems to arise from efforts to address existing problems (IPCC, 2005). When the impacts of these changes are multiplied or accelerated due to the operation of positive feedback mechanisms, the full weight of globalization can pose severe challenges not only to the resilience and adaptability of SESs but also to societal coping capacity in the face of growing vulnerability.

3.2. Globalization mega-trends

While our principal interest in this article is analytical, it is helpful to identify several concrete instances of globalization that can serve as reference points or paradigmatic examples in the theoretical discussion in the succeeding sections. Some mega-trends result from technological and social innovations that reduce the direct dependence of people on their immediate surroundings. A case in point is urbanization, a worldwide social phenomenon that is drastically altering human–environment relations in cultural as well as material terms. At current rates of urbanization, over half of the growing human population of the planet will reside in metropolitan areas as soon as 2007 (Kates and Parris, 2003). Other mega-trends feature a growing dependence on scarce, globally traded natural resources. A prominent example centers on the extraction of fossil fuels on a worldwide basis and their use to drive the powerful engines of industrialized societies in which welfare is largely measured in terms of increases in the consumption of material goods. Although the size of the fossil fuel reserves that are ultimately recoverable is a hotly contested issue, no doubt exists that pressure to discover new sources of fossil fuels and to control their production, processing, and marketing constitutes one of the fundamental drivers of economic and political behavior on a global scale (Roberts, 2004). A third category of mega-trends relates to the integration between connectivity and mobility—of socio-economic as well as biophysical systems. The ongoing revolution in information technologies, for example, is making it possible for people to collaborate on a global basis in real time and enhancing the capacity to respond to some of the dangers associated with other forms of globalization (Friedman, 2005).

As these illustrations suggest, globalization can have both positive and negative consequences. The prospect of severe conflict over strategic resources like oil imposes new risks and costs on people, business, and governments. Yet, advances in both transportation and communication systems make it possible to deliver aid to victims of natural disasters on a scale that was simply impossible in earlier times. Our concern is not to pass judgment on any aspect of globalization. Rather, we ask whether and how the forces unleashed by globalization will affect the resilience and vulnerability of SESs at various scales.

4. Analytic aspects of globalization: connectedness, speed, scale, and diversity

Human history has witnessed previous waves of globalization (Turner and McCandless, 2004; Jorgenson and Kick, 2003). Some of these waves—especially the one occurring in the era from 1880 to 1914—have been far-reaching in scope. Yet, the current wave is characterized by a combination of magnitude, spatial reach, and pace that has no counterpart in the history of the planet (Held et al., 1999; Steffen et al., 2004). The in-depth analysis of the large-scale processes unfolding along each of those dimensions constitutes a fruitful line of research. But these megatrends are not independent. As they unfold, they interact with one another, resulting in a changing pattern of mutual reinforcement, resistance, and interference.

Examining globalization in a more analytic fashion may help to illuminate some of the fundamental changes involved, particularly those of special relevance to systemic properties such as resilience, vulnerability, and adaptability. Looking to globalization as an ensemble of interacting changes in SESs, we can observe four generic features that stand out prominently—changes in connectedness, speed, scale, and diversity. From a systemic perspective, globalization emerges as a dynamic process within SESs characterized by increasing speed of interactions, intensification and multiplication of the linkages among elements of the system, a stretching of human activities to the global scale, and a homogenizing process that produces declines in both ecological and social diversity.[1] This section introduces these developments, characterizes them as features of globalization, provides examples to illustrate the consequences of changes in these factors, and develops a number of general hypotheses about the impacts of these developments on the robustness, resilience, vulnerability, and adaptability of SESs.

4.1. Changing connectedness

The connectedness of global SESs is increasing rapidly, both in the social and economic sphere (e.g. interdependencies arising from flows of trade, information, people, telecommunications, and so forth) and in the natural sphere (where there is an augmentation and intensification of the global linkages among the biotic and abiotic processes on land, in the oceans, and in the atmosphere). Furthermore, the interlocking between the human and the natural spheres is rapidly becoming more complex and pervasive. The new linkages may be obvious (e.g. between carbon dioxide emissions and climate change), but they can also be more subtle, as exemplified by Kennedy's (2001, p. 169) account of rubber:

> Rubber seedlings, brought in the 19th century from Brazil to Kew Gardens in England and then used to establish plantations in South Asia, came unaccompanied by the South American leaf blight fungus. Those plantations now supply most of the world's natural rubber and fuel several national economies. So if you arrive at Kuala Lumpur airport having visited South America on the same itinerary, you walk in on fungicide-soaked carpet and have your luggage irradiated. Meanwhile, the globalizing trade in radial auto tires, powered by natural rubber from Asia, brought the Asian tiger mosquito (*Aedes albopictus*) to the United States from Japan as a stowaway in used tire casings. It is well established as a nuisance in its new homeland, and because it is a competent vector for dengue fever, it worries public health officials as well. The global economy of rubber has thus created an unusual ecosystem that includes the Amazonian rain forest, Malaysian plantations, Japanese tire factories, and New Jersey marshes.

Globalization increases the number of connections between individual components; it leads especially to more crosscuts and reductions in the shortest path between nodes. This produces a faster exchange of information through the network. Some have called this phenomenon time–space compression (Harvey, 1989), in which actions taken in one locale may have direct and immediate consequences at other locales worldwide. Prominent examples include the movements of stock markets, the fluctuations of the world market for oil, and the spread of invasive species.

Changing connectedness has many implications for the adaptability and resilience of SESs (Csete and Doyle, 2002; Staber and Sydow, 2002; Sole et al., 2003; Krakauer, 2003). On the one hand, sufficient links are required to allow components of the system to learn from activities happening in other components. Further, the structure and capabilities of one component dealing with, for example, water resources is likely to differ from those dealing with air pollution, transportation, energy consumption, food production, soil conservation, and the many other productive activities of SESs. Within the social sciences, this pattern is known as polycentricity. Ostrom et al. (1961) identified a polycentric metropolitan area as one having many centers of decision-making that are formally

[1] We do not claim that this account of the analytic dimensions of globalization is exhaustive. Our colleague Tun Myint, for example, has suggested that hybridization is another analytic aspect of globalization. Nevertheless, the analytic dimensions we discuss in this article seem to us to lie at the core of globalization.

independent of each other (while nested in a larger system) but that facilitate learning via experimentation in the individual centers (McGinnis, 1999).

On the other hand, increasing connectedness leads to faster diffusion of information, population, viruses, and diseases. It follows that the kinds of components connected are more important than the number of connections; particularly important is the extent to which the connections are self-regulatory or self-amplifying. When components are not tightly linked, failure in one component has less impact upon other components than when the couplings are strong (Simon, 1973, 1981; Ostrom, 1997).

The increase in connectedness is one side of the growing integration and functional complexity of SESs (albeit accompanied by a structural simplification in parts of the ecological components in such forms as reductions in species diversity and homogenization of agro-ecosystems). In that sense, it may be seen as a developmental process leading to higher performance of SESs as a whole and particularly of their social components.

The existence of many interconnections may enhance the robustness or resilience of large-scale SESs by diluting and distributing the impact of strong changes in individual elements upon other elements of the system. High connectedness also has consequences for policy and management in general. In a ‘‘wired world’’, disturbances rapidly spread across markets and societies, ramifying the effects of change (Held, 2000). The oil shocks of recent decades are prominent examples. In this connection, the sources of changes in SESs may arise far away from their impacts. This makes the costs and benefits of policy options fuzzier and the world more uncertain.

But there is also a more worrisome side to increasing connectedness. Systems analysts have established (Ashby, 1959; Gardner and Ashby, 1970; May, 1973; Sinha, 2005) that in networks whose components or nodes are connected at random, an increase in the complexity of the network leads almost inevitably to the destabilization of the system as a whole. This means that increasing the number of connected elements, enhancing the density of links or connections, or intensifying the strength of interactions between elements increases the probability that the system will become unstable or lose its resilience. Furthermore, the transition from stable to unstable behavior beyond some critical level of connectedness is often a sharp one. These results seem to hold also for at least some types of regular (non-random) networks (Sinha, 2005). Other recent works show that some of the fundamental structural properties of importance in any kind of network have been used to classify vulnerabilities of networks (Albert et al., 2000; Dunne et al., 2004). For example, scale-free networks, which have a high level of centrality, are vulnerable to targeted attacks on the nodes that function as hubs. Yet, scale-free networks are robust to random removal of links, whereas random networks are more vulnerable to random removal of links.

The apparent contradiction between these results and the body of evidence linking diversity to stability in ecosystems has been attributed to the fact that in nature, ecological connectedness results from a long history of co-evolution, selection and mutual adjustments, rather than from an arbitrary assemblage of many species put together at random (Margalef, 1985; McCann, 2000). In effect, the elements of diversity causing instability have been selected against in evolutionary terms.

These observations indicate that the increase in complexity and connectedness (especially non-evolved and non-planned connectedness) may lead to a sharp increase in the costs of errors. Globalization is increasing not only the connectedness of SESs but also the strength of many of the linkages. And while the evolution of SESs is certainly not a random process, the new linkages are neither the end result of a long process of evolution nor the product of planned changes. Under these conditions, we cannot ignore the likelihood of an overall decrease in the robustness or resilience of (especially large-scale) SESs and an increase in their vulnerability. Some analysts (e.g. Giarini, 1997) arrive at similar conclusions based on research in the field of insurance and risk management.

4.2. Increased speed

As Held et al. (1999) describe it, the growing extent and intensity of global interconnectedness is linked to a speeding up of global interactions and processes. As the evolution of worldwide transport and communication systems proceeds, the velocity of the diffusion of ideas, information, goods, capital, decisions, and people increases. This is reflected, for instance, in the global economy, now more open, fluid and volatile, with international markets and investment patterns reacting rapidly to changing political and economic signals. The increasing vulnerability of agricultural systems to diseases that spread rapidly is another example.

It is this exponential acceleration of communications and transport that made possible the current wave of globalization, allowing enterprises to distribute their products and production processes to different countries and continents in search of comparative advantages and allowing financial markets to react within minutes to the occurrence of distant events, such as currency devaluations or terrorist attacks. The fast transmission rate allows for quick responses to stresses, threats, and opportunities. This increasing speed of response is typically seen as enhancing resilience and adaptive capacity and reducing vulnerability (through real-time monitoring, fast delivery of humanitarian aid, etc.). On the other hand, as the pace of change accelerates, monitoring and decision-making can be overwhelmed and lag behind, and a reduction of resilience and adaptive capacity may result. As we suggest below, moreover, this speeding up in the time scale may interact with the broadening of the spatial scale, with systemic consequences.

4.3. Spatial stretching

While globalization operates on many temporal and spatial scales (Held et al., 1999), one distinctive trait is that many important political, social, and economic processes and activities have been stretching upscale across national frontiers, regions, and continents. Today, many of those processes and activities occur on a global scale dominated by a few powerful actors. Many intermediate-scale social institutions have been eliminated—leaving many smaller units connected directly to global actors without the protection of intermediate units.

Some human-induced environmental changes with global consequences have occurred in the past (Turner and McCandless, 2004). Through most of history, however, human impacts on the environment had only local—or, at most regional—reach. Today, human activities are affecting the functioning of the biosphere, as evidenced by climate change, the planet-wide transformation and degradation of ecosystems (Millennium Ecosystem Assessment, 2005), global biodiversity loss, influence on global biochemical cycles (Schlesinger, 1991; Ayres et al., 1994), and global oceanic and atmospheric pollution (Turner and McCandless, 2004; Andreae et al., 2004; Crutzen and Ramanathan, 2004).

By affecting the planetary level of organization, globalization is transforming causal mechanisms previously operating more or less autonomously—such as ocean circulation—that are now associated with potential sudden changes in regional climate and processes that might trigger the "switch and choke" critical elements (GAIM Task Force, 2002) of the Earth system. Because different factors and dynamics prevail at different scales, increasing the scale of social activities may generate novel occurrences.

The decisions of many socio-economic actors (e.g. transnational corporations) have planetary consequences, both expected and unexpected. Shifting investments, redirecting financial flows, and seeking optimization across regions, production and distribution systems operate at the global scale; international trade and direct foreign investment have grown to unprecedented levels; and global aggregate consumption doubles every 20–25 years. The increasingly global scale of socio-economic activities is having significant consequences, including the recognition that the distinctions between "inside" and "outside", or "here" and "there" are becoming blurred, and that exporting domestic problems or, in other words, "dumping them out" is not justifiable (at least morally) any longer. This has important implications for global governance and for accountability at different levels.

The global impact of actions also has the effect of shifting the balance between expected and unexpected consequences. In earlier times, many actions were aimed at reducing uncertainties and risks at a local or regional scale. At this scale, the chances of anticipating consequences are better than at a global scale, if only because knowledge may be available about local or regional impacts and dynamics that is rarely available at the global scale.

Temporal and spatial scales are often intimately connected, a fact long established by basic research on hierarchical systems (Allen and Hoekstra, 1992; Allen and Starr, 1982; Mesarovic et al., 1970; O'Neill et al., 1986; Pattee, 1973; Simon, 1973). Clearly, SESs can be interpreted as hierarchical systems, made up of some combination of international, regional, national, subnational, and local systems. This hierarchy of levels is not arbitrary, since established institutional relations are visible at each of the levels (Young, 2002).

To put a complex issue in its simplest terms, large-scale things are slow and durable, while small-scale things are fast and ephemeral (Allen and Hoekstra, 1992, p. 41). In a hierarchical system, there thus exists an asymmetrical interdependence between processes occurring at different levels. The slower dynamics of a higher level appear as conditions or constraints on the dynamics of the lower level. When there is a strong dynamic interaction between different hierarchical levels in a system and asymmetry breaks down (at least temporarily), complex and counter-intuitive behavior may occur. In such situations, strong non-linear couplings between subsystems associated with different levels, or between slow and fast variables, may come to dominate the dynamics of the whole system. This is more likely to happen when the temporal and spatial scales of the relevant phenomena are similar.

One little known systemic implication of globalization is related to a reversal in the hierarchical structure of large-scale SESs as pointed out by Gallopín (1991). On the one hand, the aggregate spatial scale of billions of local actions (agricultural developments, deforestation, extraction of fossil fuels, industrial production, etc.) is approaching the level at which larger processes operate. On the other hand, some large-scale (regional or global) processes may be reducing their time scales, thus approaching the characteristic time scales of faster, lower-level processes. Due to the combination of the increasing speed and scale of human-induced environmental changes, the operation of global communications, and the global reach of many decision-making systems, the assumption that dynamic time scales at the global level are always slower than at the local level may no longer hold and the distinctiveness of intermediate scales may wash out. The consequences of such a fundamental reversal of the hierarchical arrangement of SESs are difficult to evaluate. But they may be profound, as it is known from fundamental hierarchy theory that the more similar the time scales of phenomena are, the greater the likelihood that they will interact (Allen and Starr, 1982; Mesarovic et al., 1970; O'Neill et al., 1986; Simon, 1973). Under these conditions, the assumption of near-decomposability no longer holds, and non-linear couplings between subsystems operating at different levels as well as between slow and fast variables may dominate the dynamics of the whole system (Clark, 1985; Gallopín, 1991; Holling, 1986).

4.4. Declining diversity

Yet another systemic process that seems associated with globalization involves declines in diversity. Globalization clearly fosters mixing or homogenization and therefore a reduction of diversity in many realms—including biodiversity, institutional diversity, ethnic diversity, cultural diversity, language diversity, technological diversity, and diversity of tastes, preferences, and values. Most of these changes entail a loss of local knowledge. Many observers argue that such losses in diversity of know-how will reduce the resilience of the overarching system (Staber and Sydow, 2002; McCann, 2000). In organizations, a range of skills and connections is important for the creation of a diverse portfolio of knowledge or shared organizational norms and understandings (Staber and Sydow, 2002; Ostrom, 2005). In systems with low diversity, there is less chance of creating new ideas, components, or connections (Hong and Page, 2004). Tinkering, mutations, and fortuitous errors are essential to derive new components and links in a system. In a modular system, such novelty can be tested without severely disturbing other components. Furthermore, if governance systems are much larger in scale than biophysical systems, tinkering does not easily produce useful information for learning.

While connectedness is increasing, diversity is decreasing. This implies a change in the nature of the complexity of SESs more than in the degree of complexity (a system with fewer nodes and more links may be as complex as a system with more nodes and fewer links). The links between functional and structural diversity and resilience, vulnerability, and adaptive capacity are complex, whether in biophysical or socio-economic systems (Low et al., 2003). A change in the balance between connectivity and diversity suggests that there will be consequences for resilience, vulnerability, and adaptability.

5. Reflexivity: institutions and social responses to change

Under many circumstances, social systems, biophysical systems, and (by implication) SESs are well-adapted to their environments. This does not imply that their environments are invariable—they may be highly variable—but rather that the resources, structures, and processes of these systems tend to be resilient to the levels of past variability of a system. Thus, under normal conditions, these systems would be able to avoid vulnerable states in which structural changes would become necessary.

The maintenance of this requisite degree of resilience (or adaptive capacity) may take the form of spontaneous or self-generating processes. As SESs become more complex, however, we can no longer assume that adaptability or resilience will emerge as a fortuitous side effect of actions taken for other reasons. At this stage, the achievement of adaptability or resilience requires effort, and vulnerability can be an outcome either of changed environmental conditions or of a failure to maintain adaptive capacity or both. Accordingly, scholars need to develop empirically supported theories that are the foundation for policy analysis rather than presumptions about the best ways of solving problems derived strictly from idealized models. However, to talk about an adapted state does not suggest an end to adaptation. Novelty and the emergence of new forms are continuous in biophysical and social systems, partly enabled by opportunities presented by the underlying variability of environments, and partly by changes that arise in the effort to maintain adaptive capacity (Adger, 2003). In this way, adapted systems operating with characteristic levels of variability remain dynamic and evolve.

What then are the consequences of, and responses to, more far-reaching perturbations to which systems are not resilient? And how should we consider the implications of these kinds of changes for social, biophysical, and SESs? Again, it is first useful to separate biophysical from social systems, and then to consider how differences in responses between these two types of systems affect what we can say about responses in SESs.

Of particular significance are the ways in which, to go back to Holling's (1973) formulation, persistence and novelty are generated in biophysical as compared to social systems. By definition, vulnerable systems are those that—unless new resources or capacities become available beyond those offered by intrinsic resilience—will undergo fundamental (and perhaps irreversible) change to aspects of their structure or behavior. The question is how such changes in structure and behavior come about. In biophysical systems, structural transformations occur *in reaction to* environmental perturbations (whether sudden and catastrophic or persistent and small-scale) that set in train processes of restabilization guided by biophysical laws and resource constraints through a process of selection. A new structure emerges through the autonomous interaction of system elements, generating novel configurations, and tending toward one (or several) stable state(s). One of the outcomes of the emergence of new structures and behaviors may be a renewal of the basis for the system's adaptability or resilience. The environmental perturbation may well have selected for those system components that offer more resilience. On the other hand, it may have degraded the resources upon which adaptability and resilience had been based.

In social systems, structural transformations frequently are also emergent in the sense that their final form is typically unintended and unknown ex ante (Hughes, 1987; Mokyr, 1990; Searle, 1995). There are also strong elements of purposive "shaping" occurring through the planned behavior of actors operating within institutions who seek power over others. Social actors typically act also *in anticipation of change.* These expectations, and the commitments that are associated with them, are played out in the structure and behavior of transformed social systems. Expectations about the future are also played out in the structure and behavior of social systems designed to manage the biophysical environment—witness the structure and dilemmas intrinsic to current debates about international climate policy. When the theories in use lead to adaptations that are ill-matched to the scale of the disturbances, things can get worse rather than better (Wilson et al., 1999).

Although foresight and reflexivity are not altogether absent from biophysical systems—animals often adjust their behavior to accommodate anticipated conditions—reflexivity is a central attribute of the adaptive capacity and the resilience of social systems. This suggests that there will be a disparity between the capacity of social systems to respond to environmental perturbations and to rebuild resilience, when compared with biophysical systems. Transformations in ''managed'' biophysical systems—where foresight and ingenuity are employed to modulate and orient the transformation of biophysical systems—will be an intermediate case. One of the effects of economic and cultural globalization may be that it increases—through increases in connectivity, speed, and scale—the capacity of social systems to be transformed, and to regenerate their adaptability and resilience, while at the same time undermining that of biophysical systems.

6. Research priorities

It seems to us that research priorities in this realm must be of two kinds, relating generally to the inherent properties of socio-ecological dynamics and more specifically to the different ways in which these dynamics are instantiated in different cases. At present, we have no more than a rough conceptual model of the overall dynamics of SESs. Comparative study of a number of different instances of such dynamics as well as considerable theory-building and testing will be necessary to refine this conceptual model to the point that we can actually use it with some confidence as the basis for a more formal approach using tools like complex systems analysis or simulation modeling to explore the impact of globalization on adaptability, resilience, and vulnerability in SESs.

By comparing concrete instances of the process of globalization in different parts of the world as well as studying the individual mega-trends that characterize coupled SES dynamics, we may hope to come to some generalizable insights. Using our current rough conceptual model, we can derive abstract, but potentially testable, hypotheses about the generic dynamics of SESs and then make use of modeling to experiment with the behavior of these systems under various circumstances. Thus, examining globalization at a higher level of abstraction may help to illuminate some of the fundamental changes involved that are of special relevance to such systemic properties as resilience, vulnerability, and adaptability.

Viewing globalization as an ensemble of interacting changes in SESs, as we have done in this article, highlights changes in connectedness, speed, and scale (see Section 4). In other words, looking at globalization from a systemic perspective draws attention to dynamic processes characterized by increasing speed of interactions and intensification and multiplication of the linkages among elements of the system resulting in a stretching of human activities to broader scales. This is compatible with Held et al.'s (1999) definition of globalization as the ''widening, deepening, and speeding up of global interconnectedness.''

This way of thinking about globalization has three advantages. It presents globalization as an integrated systemic change transcending the details of specific mega-trends, such as those identified in Section 3. Second, it allows us to draw on insights about systems in general to improve our understanding of SESs. Third, a systemic view of globalization highlights the influences of globalization on resilience, vulnerability, and adaptability, which are also systemic properties of SESs.

We can illustrate and test the insights thus gained through an analysis of mega-trends identified in comparative studies. At that level, the insights would be confronted with empirical evidence of their positive and negative effects. The positive effects arise from social responses to these unprecedented flows of information, people, trade, and investments. Knowledge of health risks and how to avert them as well as new medical treatments have spread rapidly throughout the world. The average human lifespan has increased from 46 to 66 years between 1950 and 2000 due to substantial reductions in child and infant mortality, improved nutrition, better water and sanitation, and reductions in the incidence of age-old diseases (World Bank, 2000; World Resources Institute, 2000). Knowledge production has expanded greatly, and information is available to a broader community than in any previous era—even though the differences between developed and developing countries are still dramatic as are the differences between the extremes of wealth and power within countries. The expanded knowledge and its use are more and more dependent, however, on hard and soft knowledge infrastructures and the global links that are the result of globalization, and less and less applicable to local systems and cultures. At the same time, new ''knowledge hierarchies'' are emerging that are linked to the capacity to apply knowledge in pursuit of technical and institutional innovations. This new hierarchy also has profound consequences for the governance of global biophysical systems and resources, and has introduced fundamentally new relations of power into the world system.

On the other hand, globalization processes have generated many social and ecological challenges: new epidemiological threats (HIV, dengue fever, lyme disease), invasive species, rapid financial collapses, and, most recently, networks of terrorism that are global in scope. For those who study the resilience, vulnerability, and adaptability of SESs, the speed at which changes occur and the chaotic connectivity across multiple scales offer warning signals. In his recent book, *Collapse: How Societies Choose to Fail or Succeed*, Jared Diamond (2005) asks why some societies in the past have failed to avoid extinction or radical losses of welfare and coherence. After providing a review of some of the major factors leading to collapse (including environmental change), he summarizes these factors into a sequence of failures:

> First of all, a group may fail to anticipate a problem before the problem actually arrives. Second, when the problem does arrive, the group may fail to perceive it. Then, after they perceive it, they may fail even to try to solve it. Finally, they may try to solve it but may not succeed. (Diamond, 2005, p. 421)

Generally, a lack of experience with the "problem" underlies all four of these sources of failure. Given that globalization processes are relatively recent phenomena, no society in the past has had sufficient experience to be able to anticipate the full array of possible consequences, know what the indicative signals might be, or understand what actions to take to cope effectively with the problem.

One key area for future research that exemplifies these concerns relates to urbanization (O'Brien and Leichenko, 2000). Some analysts argue that urban areas are changing more rapidly than rural areas; they point to concrete occurrences such as the loss of jobs that once kept central cities alive economically and socially (Savitch and Kantor, 2002). As noted above, a key challenge pointed out by prior research on SESs is the need to match the scale of problems and the social and governance mechanisms devised to cope with them. A substantial puzzle in regard to many urban areas is that they are both too small and too large for the disturbances affecting their vulnerability and adaptability. Kates and Parris (2003, p. 8062) report that by 2007, "…for the first time in human history, more people will live and work in the urban centers of the world than in rural areas." They predict a massive increase in the number of mega-cities that will be constructed, mostly in the developing world, between now and the middle of the 21 century.

As more and more urban residents must have their coffee first thing in the morning, this small-scale event cumulates to affect the prices received by coffee growers in Indonesia (as well as Guatemala, Honduras, and Brazil) leading to massive rates of deforestation when prices are high and tragic economic losses when prices are low (O'Brien and Kinnaird, 2003; Tucker et al., 2005). The demand of urban residents for products grown and manufactured elsewhere in the world has many impacts that remain unknown to urban residents. Air pollution spills out over vast regions and water is imported from afar, further depleting already heavily overused surface and groundwater sources (Blomquist and Ingram, 2003; Blomquist et al., 2004). How to induce mega-cities to take some responsibility for the costs they impose on others in the form of externalities is a major design issue that has not yet been tackled (for analyses of the challenges of institutional design in a globalizing era, see Young, 1999; Dietz et al., 2003; NRC, 2005).

While many aspects of urbanization lead to recommendations for creating larger scale organizations, other aspects lead to a recommendation for smaller units nested in larger structures. As migration accelerates, urban neighborhoods often find themselves the home of large numbers of strangers who have few opportunities for legitimate ways of making a living and may turn to crime and violence at a higher level than in settled neighborhoods. New immigrants may have few ways of communicating their problems to authorities with the resources to mitigate their situation. Robert Sampson's long-term research in large American cities provides impressive empirical evidence regarding organizational factors that reduce crime. Neighborhoods with effective network structures and with local NGOs that take on responsibilities that local governments still undertake in smaller urban settlements are much less crime ridden. Citizens in such neighborhoods in mega-cities are more likely to engage in effective civic activities than citizens in neighborhoods lacking effective micro-organization (Sampson et al., 1997, 2005). Students served by smaller schools also have higher achievement levels and face lower rates of violence (Solomon, 1999; Langbein and Bess, 2002; Greene and Winters, 2005).

These observations regarding urbanization help to identify research themes involving adaptability, resilience, and vulnerability as they relate to a specific type of globalization. From a theory-building perspective, however, there is also a need to identify and explore interdependencies among various mega-trends that seem critical in terms of their potential effects on the resilience, vulnerability, and adaptability of SESs. This suggests the need to examine a range of research questions regarding connectedness of the following sort:

- Is co-evolved connectedness being replaced by quasi-random connectedness?
- Is "stabilizing connectedness" being replaced increasingly by "destabilizing connectedness"?
- What important linkages are being eliminated and which ones are being created?

Similarly, the rise of cross-scale linkages generates a set of issues that are important in terms of both research and policy. We need to learn more about how the impacts of globalization cascade up and down scales affecting adaptability, resilience, and vulnerability from the local to the global level. The reversal of time scales between large systems and small systems is not well-understood either. But it may have profound implications for the adaptability, resilience, and vulnerability of SESs.

7. What is needed to implement this agenda?

High on the agenda for future work by scholars in both social and natural science disciplines is a consideration of how to organize effective research on globalization and its diverse impacts on SESs. We need to see vastly more effort asking how globalization is affecting the behavior of SESs at different temporal and spatial scales and how these impacts affect resilience, vulnerability, and adaptability with regard to particular challenges.

To develop such a research program will require a reorientation of research related to globalization. While some progress is being made by scholars from many disciplines and multiple centers working on new paradigms for analyzing SESs (Hughes et al., 2005; Anderies et al., 2004), universities and other research agencies remain conservative organizations clinging to long-established internal decision structures. The ever-greater division of knowledge into specialized disciplines (and subdisciplines) has been productive as a means for enabling scholars to define fields of study clearly, to adopt the technical terminology needed for advancement, and to establish consistent criteria for what is regarded as progress. Knowledge about many particular aspects of the components of SESs has developed rapidly. But no discipline alone can address the issues raised above related to globalization's diverse and multiple impacts on SESs.

Without large changes in the way academic research is organized, therefore, we may find that we learn ever more about focal disciplinary questions and ignore studies of complex coupled social and biophysical change. Programs that organize research, teaching, and outreach on global processes are still primarily organized within the biophysical domain *or* the social domain. A few innovative programs have made concerted efforts to cross disciplinary boundaries; they need to be joined by others. Research programs such as those sponsored by the International Human Dimensions Programme on Global Environmental Change are an important step in the right direction, as are efforts by the U.S. National Science Foundation and other funding agencies to support global environmental change programs. But young scholars who are applying to graduate school are still counseled to avoid applying to interdisciplinary socio-ecological programs. Untenured faculty members are advised to publish in strictly disciplinary journals and not to publish in high impact interdisciplinary journals or invest heavily in interdisciplinary research efforts. If this type of strong advice continues, many of the best and the brightest of our young scientists will follow the conservative advice to focus on a specific discipline. Cash et al. (2003) have stressed the importance of boundary management functions—communication, translation, and mediation—as essential for mobilizing and developing science and technology to address key threats to sustainable development. One of the major objectives for scholars and practitioners interested in resilience, vulnerability, and adaptability is to work together in conducting research that crosses temporal and spatial scales and, even more challenging, crosses disciplinary boundaries that are of long standing.

8. Conclusion

Two phenomena that have far-reaching implications for resilience, vulnerability, and adaptability are unfolding simultaneously and increasingly converging. The linkages between biophysical systems and social systems have grown to the point where we routinely speak of human-dominated ecosystems and realize the critical need to understand the dynamics of socio-ecological systems (SESs). Simultaneously, social and economic globalization has led to increased flows of goods, resources, people, and information and ideas across greater distances with interactions operating at various scales from local to global. Thus, biophysical systems need to be seen as interacting with social and economic systems, while social processes like globalization need to be seen as being coupled to the dynamics and constraints imposed by biophysical systems. In seeking to understand (and modulate) these complex and uncertain coupled systems, we need to move beyond conventional notions of risk, stability, and control, and instead shift our attention to the dynamics of resilience, vulnerability, and adaptability. We need to begin to tie our analysis of adaptability, resilience, and vulnerability in biophysical systems to an understanding of these same features in social and economic systems.

The consequences of these developments are by no means uniformly bad. We have pointed to instances in which globalization can prove helpful in bringing relief to victims of disasters occurring in remote areas and in disseminating innovative ideas arising in one location to the rest of the world. Nonetheless, the convergence of these phenomena does pose serious challenges. Human pressure in such forms as overharvesting of living resources and growing emissions of greenhouse gases can lead to abrupt changes or system flips that leave little time or room for adaptive responses. Short of this, as our examples involving rubber and coffee attest, we live in a world in which linkages between biophysical and social systems across space and time produce surprising dynamics and novel emergent properties. Recent studies of SESs constitute a step in the right direction in addressing these issues. But, as we have sought to demonstrate in this article, current and ongoing developments in the Earth system have opened up an array of new issues that will challenge the ingenuity of analysts interested in robustness, resilience, vulnerability, and adaptability.

References

Adger, W.N., 2003. Social capital, collective action and adaptation to climate change. Economic Geography 79 (4), 387–404.

Adger, W.N., 2006. Vulnerability. Journal of Global Environmental Change 16 (3), 268–281.

Adger, W.N., Hughes, T.P., Folke, C., Carpenter, S.R., Rockström, J., 2005. Socio-ecological resilience to coastal disasters. Science 209 (5737), 1036–1039.

Albert, R., Jeong, H., Barabasi, A.L., 2000. Error and attack tolerance of complex networks. Nature 406, 376–382.

Allen, T.F., Hoekstra, T., 1992. Toward a Unified Ecology. Columbia University Press, New York.

Allen, T.F., Starr, T.B., 1982. Hierarchy: Perspectives for Biological Complexity. University of Chicago Press, Chicago, IL.

Anderies, J.M., Janssen, M.A., Ostrom, E., 2004. A framework to analyze the robustness of social–ecological systems from an institutional perspective. Ecology and Society 9 (1), 18.

Andreae, M.O., Talaue-McManus, L., Matson, P.A., 2004. Anthropogenic modification of land, coastal, and atmospheric systems as threats to the functioning of the earth system. In: Clark, W.C., Crutzen, P., Schellnhuber, H.-J. (Eds.), Earth System Analysis for Sustainability. MIT Press, Cambridge, MA, pp. 245–264.

Ashby, W.R., 1959. The stability of a randomly assembled nerve-network. Electroencephalography and Clinical Neuro-Physiology 2, 471–482.

Ayres, R.U., Schlesinger, W.H., Socolow, R.H., 1994. Human impacts on the carbon and nitrogen cycles. In: Socolow, R., et al. (Eds.), Industrial Ecology and Global Change. Cambridge University Press, Cambridge, pp. 121–156.

Bateson, G., 1972. Steps to An Ecology of Mind. Balantine Books, New York.

Berkes, F., Folke, C. (Eds.), 1998. Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press, Cambridge.

Blomquist, W., Ingram, H.M., 2003. Boundaries seen and unseen: resolving transboundary groundwater problems. Water International 28 (2), 162–169.

Blomquist, W., Schlager, E., Heikkila, T., 2004. Common Waters, Diverging Streams: Linking Institutions and Water Management in Arizona, California, and Colorado. Resources for the Future, Washington, DC.

Carlson, J.M., Doyle, J., 2002. Complexity and robustness. Proceedings of the National Academy of Sciences 99, 2538–2545.

Carpenter, S.R., Walker, B.H., Anderies, J.M., Abel, N., 2001. From metaphor to measurement: resilience of what to what? Ecosystems 4 (8), 765–781.

Cash, D.W., Clark, W.C., et al., 2003. Knowledge systems for sustainable development. Proceedings National Academy of Sciences 100 (14), 8086–8091.

Clark, W.C., 1985. Scales of climate impacts. Climate Change 7, 5–27.

Crutzen, P.J., Ramanathan, V., 2004. Atmospheric chemistry and climate in the anthropocene: where are we heading? In: Clark, W.C., Crutzen, P., Schellnhuber, H.-J. (Eds.), Earth System Analysis for Sustainability. MIT Press, Cambridge, MA, pp. 265–290.

Crutzen, P.J., Stoermer, E.F., 2000. The 'Anthropocene'. IGBP Newsletter 41, 17–18.

Csete, M.E., Doyle, J.C., 2002. Reverse engineering of biological complexity. Science 295, 1664–1669.

Diamond, J., 2005. Collapse: How Societies Choose to Fail or Succeed. Viking Press, New York.

Dietz, T., Ostrom, E., Stern, P.C., 2003. The struggle to govern the commons. Science 302, 1907–1912.

Dunne, J.A., Williams, R.J., Martinez, N.D., 2004. Network structure and robustness of marine food webs. Marine Ecology-Progress Series 273, 291–302.

Folke, C., 2006. Resilience: the emergence of a perspective for social-ecological systems analyses. Journal of Global Environmental Change 16 (3), 253–267.

Friedman, T.L., 2005. The World is Flat: A Brief History of the Twenty-First Century. Farrar, Straus and Giroux, New York.

GAIM Task Force, 2002. Hilbertian questions. Research GAIM (Newsletter of the Global Analysis, Integration and Modelling Task Force of the International Geosphere-Biosphere Programme) 5(1), 1–16. Retrieved from http://gaim.unh.edu/Products/News/Summer2002/index.html.

Gallopín, G.C., 1991. Human dimensions of global change: linking the global and local processes. International Social Science Journal 130, 707–718.

Gallopin, G.C., 2006. Linkages between vulnerability, resilience, and adaptive capacity. Journal of Global Environmental Change 16 (3), 293–303.

Gallopín, G.C., Gutman, P., Maletta, H., 1989. Global impoverishment, sustainable development and the environment: a conceptual approach. International Social Science Journal 121, 375–397.

Gardner, M.R., Ashby, W.R., 1970. Connectance of large dynamical (cybernetic) systems: critical values for stability. Nature 228, 784.

Giarini, O., 1997. Notes on economics, globalisation and insurance. International Insurance Monitor 50 (3), 1–9.

Greene, J.P., Winters, M.A., 2005. Smaller School Districts Improve Graduation Rates. Manhattan Institute for Policy Research, New York.

Harvey, D., 1989. The Conditions of Postmodernity. Basil Blackwell, London.

Held, D., 2000. Regulating globalization? the reinvention of politics. International Sociology 15 (2), 394–408.

Held, D., McGrew, A., Goldblatt, D., Perraton, J., 1999. Global Transformations. Polity Press, Cambridge.

Hirst, P., Thompson, G., 1999. Globalization in Question, second ed. Polity Press, Cambridge.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4, 2–23.

Holling, C.S., 1986. The resilience of terrestrial ecosystems: local surprise and global change. In: Clark, W.C., Munn, R.E. (Eds.), Sustainable Development of the Biosphere. Cambridge University Press, Cambridge, UK.

Holling, C.S., Gunderson, L.H., Ludwig, D., 2002. In quest of a theory of adaptive change. In: Gunderson, L., Holling, C.S. (Eds.), Panarchy: Understanding Transformations in Human and Natural Systems. Island Press, Washington, DC, pp. 3–24.

Hong, L., Page, S.E., 2004. Groups of diverse problem solvers can outperform groups of high-ability problem solvers. Proceedings of the National Academy of Science 101 (46), 16385–16389.

Hughes, T.P., 1987. The evolution of large technical systems. In: Bijker, W., Hughes, T., Pinch, T. (Eds.), The Social Construction of Technological Systems. MIT Press, Cambridge, MA, pp. 51–82.

Hughes, T.P., Bellwood, D.R., Folke, C., Steneck, R., Wilson, J., 2005. New paradigms for supporting the resilience of marine ecosystems. Trends in Ecology and Evolution 20 (7), 380–386.

IPCC (InterGovernmental Panel on Climate Change), 2005. Special Report on Carbon Capture and Storage. IPCC, Geneva November.

Janssen, M.A., Schoon, M.L., Ke, W., Börner, K., 2006. Scholarly networks on vulnerability, resilience, and adaptation within the human dimensions of global environmental change. Journal of Global Environmental Change 16 (3), 240–252.

Jorgenson, A.K., Kick, E.L., 2003. Globalization and the environment. Journal of World-Systems Research 9 (2), 195–203.

Kates, R.W., Parris, T.M., 2003. Long-term trends and a sustainability transition. Proceedings National Academy of Sciences 100 (14), 8062–8067.

Kennedy, D., 2001. Black carp and sick cow. Science 292, 169.

Krakauer, D.C., 2003. Robustness in biological systems—a provisional taxonomy. Working Paper 2003-02-008, Santa Fe Institute, Santa Fe, NM.

Langbein, L.I., Bess, R., 2002. Sports in school: source of amity or antipathy. Social Science Quarterly 83 (2), 436–454.

Leichenko, R.M., Solecki, W.D., 2005. Exporting the American dream: the globalization of suburban consumption landscapes. Regional Studies 39, 241–253.

Low, B., Ostrom, E., Simon, C., Wilson, J., 2003. Redundancy and diversity: do they influence optimal management? In: Berkes, F., Colding, J., Folke, C. (Eds.), Navigating Social–Ecological Systems. Cambridge University Press, Cambridge, pp. 83–114.

Luers, A.L., Lobell, D.B., Sklar, L.S., Addams, C.L., Matson, P.A., 2003. A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley. Global Environmental Change Part A 13, 255–267.

Luhman, N., 1985. Ecological Communication. Polity Press, London.

Margalef, R., 1985. Ecosystems: diversity and connectivity as measurable components of their complication. In: The Science & Praxis of

Complexity. United Nations University (UNU), Tokyo, GLDB-2/UNUP-560.
May, R.M., 1973. Stability and Complexity in Model Ecosystems. Princeton University Press, Princeton, NJ.
McCann, K., 2000. The diversity-stability debate. Nature 405, 228–233.
McGinnis, M.D. (Ed.), 1999. Polycentricity and Local Public Economies: Readings from the Workshop in Political Theory and Policy Analysis. University of Michigan Press, Ann Arbor, MI.
McNeill, J.R., 2000. Something New Under the Sun. W.W. Norton, New York.
Mesarovic, M.D., Macko, D., Takahara, Y., 1970. Theory of Hierarchical, Multilevel Systems. Academic Press, New York.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.
Mokyr, J., 1990. The Lever to Riches: Technological Creativity and Economic Progress. Oxford University Press, Oxford.
Naveh, Z., Liebermann, A.S., 1984. Landscape Ecology: Theory and Applications. Springer, New York.
Netting, R.McC., 1981. Balancing on an Alp: Ecological Change and Continuity in a Swiss Mountain Community. Cambridge University Press, New York.
NRC (National Research Council), 2005. In: Brewer, G.D., Stern, P.C. (Eds.), Decision Making for the Environment. National Academies Press, Washington, DC.
O'Brien, K.L., Leichenko, R.M., 2000. Double exposure: assessing the impacts of climate change within the context of economic globalization. Global Environmental Change 10 (3), 221–232.
O'Brien, K., Leichenko, R., Kelkar, U., Venema, H., Aandahl, G., Tomkins, H., Javed, A., Bhadwal, S., Barg, S., Nygaard, L., West, J., 2004. Mapping vulnerability to multiple stressors: climate change and globalization in India. Global Environmental Change 14 (4), 303–313.
O'Brien, T.G., Kinnaird, M.F., 2003. Caffeine and conservation. Science 300 (April 25), 587.
O'Neill, R.V., De Angelis, D.V., Waide, J.B., Allen, T.F.H., 1986. A Hierarchical Concept of Ecosystem. Princeton University Press, Princeton, NJ.
Ostrom, E., 2005. Understanding Institutional Diversity. Princeton University Press, Princeton, NJ.
Ostrom, V., 1997. The Meaning of Democracy and the Vulnerability of Democracies. University of Michigan Press, Ann Arbor.
Ostrom, V., Tiebout, C.M., Warren, R., 1961. The organization of government in metropolitan areas: a theoretical inquiry. American Political Science Review 55, 831–842.
Pattee, H.H., 1973. The physical basis and origin of hierarchical control. In: Pattee, H.H. (Ed.), Hierarchy Theory: The Challenge of Complex Systems. Georges Braziller, New York.
Roberts, P., 2004. The End of Oil. Houghton Mifflin, New York.
Sampson, R.J., Raudenbush, S., Earls, F., 1997. Neighborhoods and violent crime: a multilevel study of collective efficacy. Science 277, 918–924.
Sampson, R.J., McAdam, D., MacIndoe, H., Weffer-Elizondo, S., 2005. Civil society reconsidered: the durable nature and community structure of collective civic action. American Journal of Sociology 111 (3), 673–714.
Savitch, H.R., Kantor, P., 2002. Cities in the International Marketplace: The Political Economy of Urban Development in North America and Western Europe. Princeton University Press, Princeton, NJ.
Schlesinger, W.H., 1991. Biogeochemistry: An Analysis of Global Change. Academic Press, New York.
Searle, J.R., 1995. The Construction of Social Reality. The Free Press, New York.
Simon, H.A., 1973. The organization of complex systems. In: Pattee, H.H. (Ed.), Hierarchy Theory: The Challenge of Complex Systems. Georges Braziller, New York.
Simon, H.A., 1981. The Science of the Artificial, second ed. MIT Press, Cambridge, MA.
Sinha, S., 2005. Complexity vs. stability in small-world networks. Physica A 346, 147–153.
Smit, B., Wandel, J., 2006. Adaptation, Adaptive Capacity, and Vulnerability. Journal of Global Environmental Change 16 (3), 282–292.
Sole, R.V., Ferrer-Cancho, R., Montoya, J.M., Valverde, S., 2003. Selection, tinkering, and emergence in complex networks. Complexity 8 (1), 20–33.
Solomon, B., 1999. For high schools, small is beautiful. National Journal May 29, 1484–1485.
Staber, U., Sydow, J., 2002. Organizational adaptive capacity: a structural perspective. Journal of Management Inquiry 11 (4), 408–424.
Steffen, W., Sanderson, A., Tyson, P.D., Jager, J., Matson, P.M., Moore III, B., Oldfield, F., Richardson, K., Schnellnhuber, H.J., Turner II, B.L., Wasson, R.J., 2004. Global Change and The Earth System: A Planet Under Pressure. Springer, New York.
Steward, J., 1955. Theory of Culture Change. University of Illinois Press, Urbana.
Tucker, C., Munroe, D.K., Nagendra, H., Southworth, J., 2005. Comparative spatial analyses of forest conservation and change in Honduras and Guatemala. Conservation and Society 3 (1), 174–200.
Turner II, B.L., McCandless, S., 2004. How humankind came to rival nature: a brief history of the human–environment condition and the lessons learned. In: Clark, W.C., Crutzen, P., Schellnhuber, H.-J. (Eds.), Earth System Analysis for Sustainability. MIT Press, Cambridge, MA, pp. 227–243.
Turner II, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A., 2003a. Science and technology for sustainable development special feature: a framework for vulnerability analysis in sustainability science. Proceedings of the US National Academy of Sciences 100 (14), 8074–8079.
Turner II, B.L., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Hovelsrud-Broda, G.K., Kasperson, J.X., Kasperson, R.E., Luers, A., Martello, M.L., Mathiesen, S., Naylor, R., Polsky, C., Pulsipher, A., Schiller, A., Selin, H., Tyler, N., 2003b. Illustrating the coupled human–environment system for vulnerability analysis: three case studies. Proceedings of the U.S. National Academy of Sciences 100 (14), 8080–8085.
Van der Leeuw, S.E., 1998. The Archaeomedes Project—Understanding the Natural and Anthropogenic Causes of Land Degradation and Desertification in the Mediterranean. Office of Official Publications of the European Union, Luxemburg.
Van der Leeuw, S.E., 2001. Vulnerability and the integrated study of socio-natural phenomena. IHDP Update 2/01, 6–7.
Wagner, A., 2005. Robustness and Evolvability in Living Systems. Princeton University Press, Princeton, NJ.
Walker, B., Carpenter, S., Anderies, J.M., Abel, N., Cumming, G., Janssen, M., Lebel, L., Norberg, J., Peterson, G.D., Pritchard, R., 2002. Resilience management in social–ecological systems: a working hypothesis for a participatory approach. Conservation Ecology 6 (1), 14 Retrieved from http://www.consecol.org/vol6/iss1/art14.
White, L.A., 1949. The Science of Culture: A Study of Man and Civilization. Farrar, Straus, and Giroux, New York.
Wilson, J.A., Low, B., Costanza, R., Ostrom, E., 1999. Scale misperceptions and the spatial dynamics of a social–ecological system. Ecological Economics 31 (2), 243–257.
World Bank, 2000. World Development Indicators. International Bank for Reconstruction and Development, Washington, DC.
World Resources Institute, 2000. World Resources 2000–2001. World Resources Institute, Washington, DC.
Young, O.R., 1999. The Effectiveness of International Environmental Regimes. MIT Press, Cambridge, MA.
Young, O.R., 2002. The Institutional Dimensions of Environmental Change: Fit, Interplay, and Scale. MIT Press, Cambridge, MA.