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structures enable non-place-based access and temporary working arrangements, and cognitive capability built into network tools can facilitate economic integration of the disabled. This enhances not just the economic performance of society, but the quality of life of individuals involved; virtually all marginalized groups are highly interested in participating in the economy if they can and if the work can be structured to suit their requirements, which is precisely the flexibility the network-centric structure can provide. Thus, for example, seniors in the United States report a high interest in continuing to work flexibly (fewer hours, no required office, and no lengthy commutes) (24, 25). On the demand side, the need for adequate knowledge workers will grow substantially as the baby boom generation retires (25), and management of pension shortfalls and old-age support policies might well be facilitated by the operational and social flexibility enabled by network-centric economic organization.

The range of ancillary effects discussed in this brief example illustrates the complexities and challenges of adopting the principle of resiliency as a policy and planning touchstone, as well as the potential value of dual-use tools and technologies. Understanding the interplay of these systems and how various investments and policy choices integrated into a resiliency

portfolio can simultaneously enhance both security and economic and social stability and growth is not a trivial challenge, but the potential benefits argue strongly for such a course.

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VIEWPOINT

Social-Ecological Resilience to Coastal Disasters

W. Neil Adger,^{1*} Terry P. Hughes,² Carl Folke,³ Stephen R. Carpenter,⁴ Johan Rockström⁵

Social and ecological vulnerability to disasters and outcomes of any particular extreme event are influenced by buildup or erosion of resilience both before and after disasters occur. Resilient social-ecological systems incorporate diverse mechanisms for living with, and learning from, change and unexpected shocks. Disaster management requires multilevel governance systems that can enhance the capacity to cope with uncertainty and surprise by mobilizing diverse sources of resilience.

Human populations are concentrated along coasts, and consequently coastal ecosystems are some of the most impacted and altered worldwide. These areas are also sensitive to many hazards and risks, from floods to disease epidemics. Here, we explore how a better understanding of the linkages between ecosystems and human societies can help to reduce

vulnerability and enhance resilience of these linked systems in coastal areas. By resilience, we mean the capacity of linked social-ecological systems to absorb recurrent disturbances such as hurricanes or floods so as to retain essential structures, processes, and feedbacks (1, 2). Resilience reflects the degree to which a complex adaptive system is capable of self-organization (versus lack of organization or organization forced by external factors) and the degree to which the system can build capacity for learning and adaptation (3, 4).

Part of this capacity lies in the regenerative ability of ecosystems and their capability in the face of change to continue to deliver resources and ecosystem services that are essential for human livelihoods and societal development. The concept of resilience is a profound shift in traditional perspectives, which attempt to control changes in systems that are assumed to be

stable, to a more realistic viewpoint aimed at sustaining and enhancing the capacity of social-ecological systems to adapt to uncertainty and surprise.

Coastal Hazards and Resilience

Natural hazards are an ongoing part of human history, and coping with them is a critical element of how resource use and human settlement have evolved (5, 6). Globally, 1.2 billion people (23% of the world's population) live within 100 km of the coast (7), and 50% are likely to do so by 2030. These populations are exposed to specific hazards such as coastal flooding, tsunamis, hurricanes, and transmission of marine-related infectious diseases. For example, today an estimated 10 million people experience coastal flooding each year due to storm surges and landfall typhoons, and 50 million could be at risk by 2080 because of climate change and increasing population densities (8). More and more, adaptive responses will be required in coastal zones to cope with a plethora of similar hazards arising as a result of global environmental change (9).

Hazards in coastal areas often become disasters through the erosion of resilience, driven

¹Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK. ²Centre for Coral Reef Biodiversity, School of Marine Biology and Aquaculture, James Cook University, Townsville QLD 4811, Australia. ³Centre for Transdisciplinary Environmental Research and Department of Systems Ecology, Stockholm University, SE-10691 Stockholm, Sweden. ⁴Center for Limnology, University of Wisconsin, Madison, WI 53706-1492, USA. ⁵Stockholm Environment Institute, Box 2142, SE 103 14 Stockholm, Sweden.

*To whom correspondence should be addressed. E-mail: n.adger@uea.ac.uk

by environmental change and by human action (10–12). For example, when Hurricane Andrew, a powerful category 5 storm, struck Florida in 1992, it caused devastation valued at \$26.5 billion and 23 people lost their lives. An equivalent tropical typhoon that ravaged Bangladesh in 1991 resulted in over 100,000 deaths and the displacement of millions of individuals (13) from widespread flooding. In Florida, social resilience from strong institutions, early warning systems, and a high capacity to deal with the crisis confined the impact to manageable proportions, whereas social vulnerability in affected areas of Bangladesh caused a human disaster of a far greater scale. Yet adaptive capacity can be increased through purposeful action. Consequently, Bangladesh has reduced mortality associated with typhoons and flooding in the past decade through careful planning focused on the most vulnerable sectors of society (14, 15).

The resilience (or conversely, the vulnerability) of coastal societies is more tightly linked to larger-scale processes today than in the past. For example, economic linkages and the globalization of trade in commodities and ecological goods and services tie regions much more closely together than before (16–18). In coastal regions, this is often evident in the vulnerabilities created by global tourism (an ecosystem service), where the growing demands of visitors impact previously undeveloped coastal areas (19). Similarly, increased mobility of people has spread infectious diseases such as human immunodeficiency virus–acquired immune deficiency syndrome [which have high prevalence in some coastal fishing communities (20)], whereas global-scale environmental change is certain to exacerbate vulnerability to vector-borne diseases [e.g., malaria and cholera (21, 22)]. Conversely, greater mobility, improved communications and awareness, and the growth of national and international NGOs that link societies can all strengthen resilience to crises and improve responses when they occur.

During periods of gradual or incremental change, many important sources of resilience may be unrecognized or dismissed as inefficient or irrelevant. Typically, therefore, components of resilience are allowed to decline or are deliberately eliminated because their importance is not appreciated until a crisis occurs. For example, chronic overfishing and declining water quality around coral reefs have made them more vulnerable to cyclones and global warming (23). Instead of absorbing recurrent disturbances as they have done for millennia, many overfished and polluted reefs have recently undergone radical regime shifts,

where coral populations fail to rebuild after external shocks and have instead been replaced by fleshy seaweeds (24, 25). Rebuilding resilience, by improving water quality and maintaining adequate stocks of herbivores, can promote the regenerative capacity of corals after recurrent disturbances. Thus, loss of ecological and social resilience is often cryptic, and resilience can be eroded or bolstered accidentally or deliberately through human action (26).

Resilient social-ecological systems incorporate diverse mechanisms for coping with change and crisis (27, 28). In ecosystems, biodiversity, functional redundancy, and spatial pattern can all influence resilience. Biodiversity



Fig. 1. Mosque and crop field in Banda Aceh, Indonesia, before (top) and after (bottom) the 2004 Southeast Asia tsunami, illustrating the impact of natural disasters on the delivery of ecological goods (agriculture) and the social cohesion of resilient societies.

enhances resilience if species or functional groups respond differently to environmental fluctuations, so that declines in one group are compensated by increases in another (24, 29). Spatial heterogeneity can also confer resilience, as when refuge areas provide sources of colonists to repopulate disturbed regions (30). Similarly, in social systems, governance and management frameworks can spread risk by diversifying patterns of resource use and by encouraging alternate activities and lifestyles. Such practices sustain ecosystem services, analogous to the way that management of a diverse portfolio sustains the growth of investments in financial markets (31).

After catastrophic change, remnants (“memory”) of the former system become growth points for renewal and reorganization of the social-ecological system (28). Ecological memory is conferred by biological legacies that persist after disturbance, including mobile species and propagules that colonize and reorganize disturbed sites and refuges that support such legacies and mobile links (30, 32). Social memory comes from the diversity of individuals and institutions that draw on reservoirs of practices, knowledge, values, and worldviews and is crucial for preparing the system for change, building resilience, and for coping with surprises (33).

Responding to Change in Coastal Areas

How can coastal zones be transformed into systems that are more resilient and adaptive to a rising incidence of large disturbances? We review two case studies as examples. The first is the 2004 Asian tsunami, which shows that social-ecological resilience is an important determinant of both the impacts of the tsunami and of the reorganization by communities after the event. The second is from research on planning for and adapting to severe storms and climate change in coastal zones and on small islands. In both cases, individuals and communities undertake adaptive strategies that involve the mobilization of assets, networks, and social capital both to anticipate and to react to potential disasters. Crucially, the causes of vulnerability are embedded in the political economy of resource use and the resilience of the ecosystems on which livelihoods depend.

The 2004 Asian tsunami. On 26 December 2004, countries in South and Southeast Asia experienced an enormous tsunami associated with the second-largest earthquake in the instrumental record. Coastal areas in parts of Indonesia, Thailand, and Malaysia closest to the epicenter received little or no warning (Fig. 1). A key lesson is that resilient social-ecological systems reduced vulnerability to the impacts of the tsunami and encouraged a rapid, positive response. This response needs to be sustained in the longer term, long after the tsunami fades from global news reports.

Chronic degradation of local environments has influenced the short- to medium-term impact of the tsunami and will continue to shape the longer-term options for rebuilding. In Banda Aceh, Indonesia, the presence or absence of sand dunes, mangrove forests, and coral reefs made no dif-

ference in the impact of giant waves that penetrated kilometers inland. Further from the epicenter, however, in Sri Lanka, the energy of smaller waves was reduced by natural barriers (34, 35). Moreover, wherever ecosystems have been undermined, the ability to adapt and regenerate has been severely eroded. For example, throughout coastal Asia, deforestation of mangrove for intensive shrimp farming, a lucrative export industry, has reduced the livelihood options available to local farming and fishing communities (36). In many locations, environmental degradation such as land clearing, coastal erosion, overfishing, and coral mining has reduced the potential for economic recovery from the tsunami because of the loss of traditional income sources related to coastal ecosystems rich in biodiversity and ecological functions.

Social resilience, including institutions for collective action, robust governance systems, and a diversity of livelihood choices are important assets for buffering the effects of extreme natural hazards and promoting social reorganization (Table 1). Coastal communities harboring knowledgeable, prepared, and responsive institutions are more likely to be able to prevent the tsunami from making the transition from extreme natural hazard to longer-term social disaster (37). For instance, fishing communities on Simeulue Island, west of Sumatra and close to the epicenter of the earthquake causing the tsunami, and on Surin Island, Thailand, survived the tsunami thanks to inherited local knowledge of tsunamis and to institutional preparedness for disasters.

There has been a well-meaning rush by organizations and international aid agencies to apply engineering approaches to rebuilding coral reefs damaged by the tsunami by transplanting corals and constructing miniature artificial reefs. However, none of these engineering interventions actually work at mean-

ingful scales or provide realistic solutions to the increased global threats to coral reefs. Fundamentally, the upsurge in investment in artificial rehabilitation of reefs is misguided because it fails to reverse the root causes of regional-scale degradation. Before the tsunami, runoff from land, overfishing, destructive fishing practices (bombing and poisoning), and climate change had already seriously degraded many reefs. Throughout the region, chronic pollution and overfishing of herbivorous fishes have promoted blooms of turfing and fleshy seaweed that overgrow and smother juvenile corals. Regeneration of damaged reefs continues to be impaired by these and other ongoing human impacts. Now the tsunami has added to the destruction in many locations, smashing corals and smothering reefs with choking sediments. Realistically, regeneration processes in the wider seascape are the only means by which coral reefs can reestablish after large-scale damage (25). Consequently, restoration efforts should focus on improving water quality and restoring depleted fish stocks to bolster the innate resilience of coral reefs (24). Scarce reconstruction aid should not be squandered on simplistic and ineffective reef rehabilitation projects. Rather, support should be directed to provide ecologically sustainable, long-term employment for coastal communities, to eliminate poverty, and to improve local and regional governance systems for managing the natural resilience of coral reefs.

The 2004 Asian tsunami tragedy demonstrates that formal and informal institutions with the capacity to respond to rapid change in environmental and social conditions are a key to mitigating the social effects of extreme natural hazards. Rather than attempting to reduce or eliminate inherent change and variability (the conventional engineering approach to “control” nature), governance systems, from governments through to local

marine and land tenure systems, need to focus on sustaining and enhancing the sources of resilience of societies and their life-supporting ecosystems. The hidden success story of the tsunami was the prevention of widespread secondary mortality of injured and traumatized victims from infection and disease, due in large part to the unprecedented scale of national and international responses.

Coping and adapting to hurricanes. Hurricanes, typhoons, and their related impacts affect societies throughout the world. They do so both directly through acute damage on human settlement, often with major loss of life, and indirectly through their impact on coastal ecosystems such as coral reefs, seagrass beds, and mangroves (38, 39) that support local societies and economies. There is growing consensus than human-influenced climate changes are now evident in hurricane regions and are likely to affect hurricane intensity and rainfall (which cause much of the damage), although the effect of climate change on hurricane frequency in the future remains uncertain (40). Although the costs of weather and climate events in terms of economic damage and lives at risk are rising through time, the observed increases are caused by changing social vulnerabilities as much as by changing physical hazards (39).

In the Caribbean, responses to hurricanes and their effectiveness depend on social and ecological resilience. The Cayman Islands, for example, has implemented adaptation actions at national and community levels, building both preparedness and community resilience. The implementation of these activities followed economic and ecological impacts of three major hurricanes in 1988 (Gilbert), 1998 (Mitch), and 2000 (Michelle). The resilience of the islands was subsequently put to the test by Hurricane Ivan (2004) and was demonstrably improved. Adaptations included changes in the rules and governance of hurricane risk, change in organizations, establishment of early warning systems, and promotion of self-mobilization in civil society and private corporations. Social learning, the diversity of adaptations, and the promotion of strong local social cohesion and mechanisms for collective action have all enhanced resilience and continue to guide planning for future climate change (41). After Hurricane Ivan in 2004, private sector interests in tourism and banking accelerated recovery by rebuilding public infrastructure such as roads and electricity supply. In Trinidad and Tobago, networks associated with present-day coral reef management also play a key role in disaster preparedness and in building resilience (42, 43). Hence, social resilience to disasters in the Caribbean has been promoted through a wide diversity of institutional forms.

However, large sections of society in the Caribbean region remain vulnerable, and cur-

Table 1. Examples of local- and regional-scale actions to enhance resilience in social-ecological systems exposed to abrupt change.

Elements of vulnerability	Local action	National and international action
Exposure and sensitivity to hazard	Maintenance and enhancement of ecosystem functions through sustainable use Maintenance of local memory of resource use, learning processes for responding to environmental feedback and social cohesion	Mitigation of human-induced causes of hazard Avoidance of perverse incentives for ecosystem degradation that increase sensitivity to hazards Promotion of early warning networks and structures Enhancement of disaster recovery through appropriate donor response
Adaptive capacity	Diversity in ecological systems Diversity in economic livelihood portfolio Legitimate and inclusive governance structures and social capital	Bridging organizations for integrative responses Horizontal networks in civil society for social learning

rent adaptation processes are not always appropriate or effective. The impacts of Hurricane Mitch on Honduras, Nicaragua, and El Salvador in 1998 were exacerbated by unsound economic policies, such as export-driven agriculture. Farmers who had adopted modern management practices suffered greater losses than those who had more traditional agro-ecological practices (44). Industrialized agricultural practices also generated unexpected impacts and risks, such as the release of 70 tons of toxic pesticides into the environment in Honduras after the destruction of several warehouses, exposing rural populations to long-term harm (45). Even today, the lessons of implementing postdisaster planning to increase adaptive capacity do not appear to have been learned by many of the states that were impacted by Hurricane Mitch.

In summary, the social-ecological resilience of tsunami- or hurricane- and typhoon-affected regions involves many elements and actions (Table 1), and each of these involves human agency. Exposure to hazards can often be modified through government interventions or informal norms that regulate the use of coastal ecosystems. Reducing the perverse incentives that destroy natural capital and thus exacerbate vulnerability in the first place should, in many cases, be the priority. Networks and institutions that promote resilience to present-day hazards also buffer against future risks, such as those associated with climate change. Effective multilevel governance systems are critical for building capacity to cope with changes in climate, disease outbreaks, hurricanes, global market demands, subsidies, governmental policies, and other large-scale changes. The challenge for social-ecological systems is to enhance the adaptive capacity to deal with disturbance and to build preparedness for living with change and uncertainty (28).

Conclusions

The case for building resilience in coastal regions is urgent, given trends in human settlement, resource use, and global environmental change. Two-thirds of the coastal disasters recorded each year are associated with extreme weather events, such as storms and flooding, that are likely to become more pervasive threats because of anthropogenically driven shifts in Earth's climate and sea level rise. These risks in particular are exacerbated by human action, raising the possibility that greenhouse gas emitters may one day become

legally liable for impacts (46). Clearly, the reduction of greenhouse gas emissions is necessary in this context but not sufficient in the management of hazards in coastal regions. Already, the resilience of many social-ecological systems has been eroded, particularly in vulnerable, marginalized societies.

The capacity of coastal ecosystems to regenerate after disasters and to continue to produce resources and services for human livelihoods can no longer be taken for granted. Rather, socio-ecological resilience must be understood at broader scales and actively managed and nurtured. Incentives for generating ecological knowledge and translating it into information that can be used in governance are essential. Multilevel social networks are crucial for developing social capital and for supporting the legal, political, and financial frameworks that enhance sources of social and ecological resilience (33, 47). The sharing of management authority requires cross-level interactions and cooperation, not merely centralization or decentralization. In many cases, improved, strong leadership and changes of social norms within management organizations are required to implement adaptive governance of coastal social-ecological systems. There is no time to waste.

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