PERSPECTIVE

Broader perspective on ecosystem sustainability: Consequences for decision making

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Although the concept of ecosystem sustainability has a long-term focus, it is often viewed from a static system perspective. Because most ecosystems are dynamic, we explore sustainability assessments from three additional perspectives: resilient systems; systems where tipping points occur; and systems subject to episodic resetting. Whereas foundations of ecosystem resilience originated in ecology, recent discussions have focused on geophysical attributes, and it is recognized that dynamic system components may not return to their former state following perturbations. Tipping points emerge when chronic changes (typically anthropogenic, but sometimes natural) push ecosystems to thresholds that cause collapse of process and function and may become permanent. Ecosystem resetting occurs when episodic natural disasters breach thresholds with little or no warning, resulting in long-term changes to environmental attributes or ecosystem function. An example of sustainability assessment of ecosystem goods and services along the Gulf Coast (USA) demonstrates the need to include both the resilient and dynamic nature of biogeomorphic components. Mountain road development in northwest Yunnan, China, makes rivers and related habitat vulnerable to tipping points. Ecosystems reset by natural disasters are also presented, emphasizing the need to understand the magnitude frequency and interrelationships among major disturbances, as shown by (*i*) the 2011 Great East Japan Earthquake and resulting tsunami, including how unsustainable urban development exacerbates geodisaster propagation, and (*ii*) repeated major earthquakes and associated geomorphic and vegetation disturbances in Papua New Guinea. Although all of these ecosystem perturbations and shifts are individually recognized, they are not embraced in contemporary sustainable decision making.

ecosystem stressors | complex system behavior | sustainability analysis | cascading effects | coastal zone management

The concept of sustainability increasingly permeates government, academic, and private-sector organizational mantras. Sustainability is defined in many ways, but a common thread lies in its goal of harmonizing environmental, economic, and social opportunities for the benefit of present and future generations (1–4). In ecosystem research and management, the underlying foundations of environmental sustainability are system attributes—biosphere, hydrosphere, geosphere, and atmosphere, and the linkages among them. Superimposed on these natural ecosystem attributes is the human component, consisting of humans themselves, their economies, institutions, infrastructures, cultures, and related land use (5–7).

Belief in the balance of nature gave rise to early ecological concepts such as carrying capacity and maximum sustained yield, which view ecosystems as permanent in form and structure that strive to recover to an "equilibrium" state following disturbances (8–10); thus, much thought and research have been invested in incorporating the concept of resilience into sustainability assessments (11–13). Resilience addresses the ability of ecosystems to absorb change and disturbance and adapt to small-scale perturbations, both in the length of time it takes to recover from external stress and in the magnitude of stress from which a system can recover without rapidly moving to a new stable condition (7, 14). While many resilience concepts evolved from ecology (15), resilience has relevance to other ecosystem characteristics, such as the sustainability of surface water (16–18) and groundwater (19). Although perturbed ecosystems and components do not always return to the exact state before a disturbance, there is a recognized bound on the breadth of resilience (20): if a system is viewed as resilient, it is generally perceived as remaining within specified "bounds." While this notion of an essentially finite system is accepted even by critics of sustainable development (21), the concepts of permanent ecosystem change are typically absent from sustainability discussions.

Tipping points are encountered one step beyond ecosystem resilience and represent thresholds that, when crossed, result in catastrophic collapse of processes or functions that are extremely difficult to restore. These tipping points are closely associated with complex system behavior where small and cumulative anthropogenic and/or natural stressors push ecosystems toward critical transitions, causing an abrupt shift from one state to another (16, 22, 23). Negative tipping points are applied to projected collapses in ecosystems related to climate change (24), climate anomalies (25), and land-use change (26). In most scenarios, protracted disturbance or stress causes the system to lose resilience, followed by an abrupt alteration in state once the tipping point is exceeded (27). Positive tipping points may occur when interventions in degraded ecosystems allow processes and populations to recover with the help of human innovation (28).

A different kind of threshold is crossed when episodic natural disasters affect ecosystems. These are reached suddenly with little or no warning, and the resulting impacts on ecosystems can be dramatic and far-reaching (16). Examples include the devastating 2011 earthquake-tsunami disaster in eastern Japan (29); lahars emanating from the 1985 volcanic activity at Nevado del Ruiz, Colombia (30); climate

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change-induced glacial dam collapse and jökulhlaups in the Karakoram Himalaya (31); isostatic rebound in the Copper River Delta, Alaska, following the Great Alaska Earthquake of 1964 that caused a seaward shift in the salt marsh (32); and massive landslides in central China during a major earthquake in 1920 (33). These were all extreme events, but more frequent disasters of smaller magnitude can also inflict long-term ecosystem resetting, albeit at smaller scales. Although it is difficult to predict the timing and areal extent of sudden, episodic disasters, probabilistic hazard maps, assessments, and predictive models can help guide sustainability analysis and thus reduce risk in vulnerable regions (34–36). Furthermore, knowledge gained from episodic disasters can help break down barriers based on past experiences and ideas and reframe future decisions by noticing and bracketing new evidence, working cognitively to elucidate interconnected processes, and retaining this knowledge (37).

Because ecosystems are intrinsically linked to dynamic earth system properties, confusion persists about what sustainable ecosystems and management practices are. Vulnerability analysis links sustainability and the stressors and perturbations that interact within resilient ecosystems and their socioeconomic counterparts (6, 38), but challenges to connecting sustainability with episodic threshold changes remain (10, 16). Given that an inherent tenet of sustainability is long-term viability of ecosystem function, better focus needs to be placed on the natural resources that form the backbone of these systems—their spatial and temporal attributes and resilience—and how anthropogenic and natural stressors compromise system resilience, breach tipping points, and cause episodic change.

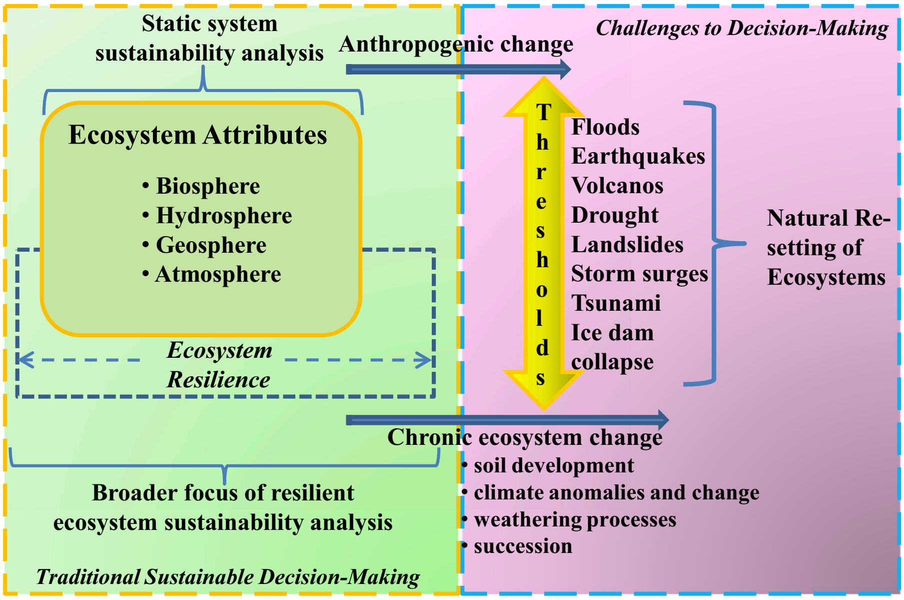

Fig. 1. Ecosystem attributes of sustainability. How assessments and decision making may change with chronic perturbations and episodic resetting.

Implementing a Broader Sustainability Perspective

Including sustainability in ecosystem research and assessment requires fundamental knowledge of earth system dynamics at appropriate scales to assess future trajectories of rural and community development, food security, disaster mitigation, reclamation, infrastructure, site productivity, hazardous waste disposal, water use, and contaminant transport. Once spatial and temporal scales of sustainability are defined, ecosystem attributes must be carefully articulated. Because sustainability has a long-term focus, ecosystem resilience should be incorporated into these attributes (6, 14, 18, 20, 27, 38) (Fig. 1). Chronic agents of ecosystem change, such as soil development, disease, and ecological succession, are accommodated by resiliency, as are minor episodic events (e.g., small earthquakes, floods, wildfires).

In cases where long-term anthropogenic pressures such as forest conversion, wetland destruction, overhunting/overfishing, poor irrigation practices, and overgrazing have impacted ecosystems, tipping points in systems may be reached. Chronic disturbances or changes may exhaust ecosystem resilience, leading to a rapid change of state (7, 27, 39). Anthropogenic perturbations can also lower the initiation threshold for certain natural disasters (40–42), complicating exceedance thresholds for ecosystem change. Furthermore, when major episodic processes exceed thresholds of resilience, they may reset ecosystem attributes (16) (Fig. 1). For example, sustainable development in cities such as San Francisco and Tokyo must consider how major earthquakes may alter topography, coastal conditions, and vegetation, and how ecosystem resilience accommodates chronic changes such as sea-level rise and vegetation change induced by global climate change. This decision making can be improved by adapting and learning from past experiences such as natural disasters or more subtle signs of resilience loss (14, 37).

Dynamic ecosystem attributes also affect how we assess sustainable management of rural lands. Widespread conversion of tropical forests to cultivated agriculture, plantations, pasture, residential developments, and recreational use has led to increased erosion, water stress, nutrient depletion, and loss of biodiversity (43–45). Although chronic ecosystem shifts are often the focus of sustainability assessments, we need to understand how land uses exacerbate episodic processes such as landslides, floods, wildfires, and droughts that can reshape systems. Several examples are presented in the next section illustrating how management decisions could benefit from broader sustainability assessments.

Understanding the potential for natural change in ecosystems is essential not only to the environmental “pillar” of sustainability but also to economic and social components. The natural system, along with economic and social counterparts, shapes and influences the well-being of individuals, societies, and ecosystems, both now and in the future (2, 10, 14, 46). For individuals, meeting basic needs such as food, shelter, and health maintenance is a prerequisite to economic and social well-being. These are met through adequate access to health care, employment, and education. Well-being for ecological systems can be defined using concepts similar to those for humans. The quality and quantity of habitat, including all facets required for survival, maintenance, and proliferation of populations and ecological functions, are analogous to human “wealth.” Although nonhuman species and their ecological systems are unlikely to be as aware of their own well-being as humans, drawing the parallel between well-being of humans and nonhumans recognizes interconnections among the natural, economic, and social components of sustainability (46). If, for example, a major power plant or toxic waste repository is sited in an area that has potential for episodic system change (e.g., major earthquake, flooding), there are strong implications for both economics and society. More gradual changes that fall within the resilience capacity of ecosystems may test the limits of societal adaptability and may incur significant economic costs to cope. A prominent example of gradual environmental change is the effect of sea-level rise on coastal ecosystems and communities (47). A socioeconomic dilemma is that huge investments continue to be made in increasingly vulnerable coastal areas when a philosophy of adaptation should be encouraged instead (48). In such cases, although the ecosystems themselves may be resilient, socioeconomic issues are driving the sustainability agenda.

Examples of Improving Sustainability Analysis in Different Ecosystems

As noted, most ecosystem sustainability assessments are conducted within static or, at best, resilient settings. Few assessments consider the potential for tipping points, such as induced by climate change or land degradation. Even greater challenges to sustainability arise when system thresholds are exceeded because of natural disasters or episodic environmental change (16). Examples exist where sustainability assessments for land, coastal, energy, and industrial development are satisfactory for static or resilient ecosystems but become highly problematic when subtle anthropogenic or natural pressures push systems to tipping points or when thresholds are exceeded due to episodic change. Here we present four cases where resilience, tipping points, or ecosystem resetting should be considered in sustainability assessments. Key environmental issues and attributes of each system, along with natural and anthropogenic stressors, are detailed in Table S1 with suggested corrective measures that support sustainability.

Cases That Would Benefit from Considering Ecosystem Resilience and Tipping Points. ***Coastal zone management, Gulf of Mexico.*** Gulf of Mexico ecosystems are essential to regional socioeconomics, and provide a foundation for rare, unique, and valued fish and wildlife species. Gulf Coast estuaries and wetlands are feeding, spawning, and nursery habitats for a rich assemblage of fish and wildlife, including shorebirds, colonial nesting birds, and migratory waterfowl. However, increasing population pressures in the Gulf of Mexico create increased use of and demands on Gulf resources (Table S1).

Given the variety of ecosystem services provided on the Gulf Coast, including commercial and sport fisheries, biodiversity, and recreation, we must understand how they interact with dynamic coastal features. For example, barrier islands, wetlands, sloughs, and the coastline itself collectively form a natural defense against landfall hurricanes as well as buffer the coast from floodwaters emanating from rivers (49). These features also provide diverse habitats for an array of fish and other marine resources. An important aspect of this complex system that is often overlooked in development, management, and restoration efforts is the transient nature of the biogeomorphic attributes. Although delta building is a progressive process (50), once these sites are developed, we tend to view the systems as static and attempt to force them to prior conditions following extreme natural events. Similarly, barrier islands, beaches, reefs, and mainland shorelines are naturally dynamic, responding to major storms and sea-level rise (51, 52). Anthropogenic activities exacerbate coastal system dynamics, including coastal development; dredging sediments from rivers; enhanced riverine flood flows from development; increased nutrient fluxes and oxygen depletion; sea-level rise due to subsidence and climate change; coastal erosion control structures; and alteration of vegetation (50, 53–56).

Turning a blind eye toward biogeomorphic processes within coastal systems poses difficulties in separating anthropogenic effects from natural phenomena, and can misguide restoration efforts. As such, there are strong implications for the lucrative commercial and recreational fishing industry along the Gulf Coast. A recent report from a federal advisory group (57) emphasizes balancing ecosystem sustainability and resilience with other priorities (e.g., navigation and structural flood control) in restoration efforts. Nevertheless, these proposed tradeoffs would benefit in the long term by recognizing natural dynamics of barrier islands and coastal features in this complex ecosystem, as well as how such changes and resilience can affect fisheries and other ecological services.

Significant restoration efforts along the Gulf Coast have focused on coastal regions of the Mississippi Deltaic and Chenier Plains, where wetlands are being lost to the sea. In Louisiana, 4,877 km^2 have been lost since the 1930s, comprising 80% of US coastal wetland losses (58, 59). Land loss in Louisiana has been called a "national emergency," with up to 4,533 km^2 threatened under status quo management (59). Louisiana wetlands are significant to the welfare of the United States—~80% of Louisiana fisheries species use wetlands for nurseries and 75% of fisheries landings in the Gulf of Mexico are adjacent to Louisiana (60). Moreover, inland flooding from storm surges, exacerbated by loss of wetlands, swamps, and barrier islands, threatens property, people, infrastructure, and unique cultural heritages (59). On average, Gulf Coast communities lose $14 billion annually from storms, which could be compounded to $350 billion by increased development and land loss (61).

Both natural and human factors have led to wetland loss in Louisiana (62). Processes identified in wetland losses range from eustatic sea-level rise and delta construction or destruction to modifications such as failed reclamation projects, canal construction, and impoundments (63). Subsidence from natural compaction and restricted sediment input caused by levees frequently leads to wetland loss (62), but debates about the strength of the effects of natural and anthropogenic factors on land-loss rates are ongoing. Locations and time periods with exceedances of natural geological subsidence rates might identify where some anthropogenic stressors have accelerated wetlands loss (64). A recent study found that decadal changes in subsidence rates trended with hydrocarbon extraction, indicating a historical influence of the latter on accelerated loss of wetlands in some areas (65).

Wetland restoration and risk reduction measures are being implemented to prevent future, as well as redress past, losses to human and wildlife habitat. Management options being developed and applied in wetlands renewal and land building initiatives include large-scale river diversions, marsh terracing, sediment-slurry additions, plantings, dam modifications, shoreline protection, sediment fences, and placement of dredged materials (59, 66–68). Major river diversions are critical to supplying sediment and nutrients, precipitating sulfides, and preventing saltwater intrusion in coastal wetlands, but require understanding of diverse considerations during implementation (59, 66). For example, positive and negative ancillary impacts on a range of attributes including eutrophication, hazardous algal blooms, and salinity changes in estuaries could occur from diversion discharges (60, 66, 68). Restoration decisions require understanding dynamic surficial and subsidence processes (63). Salt marsh areas can reach such a low vertical elevation threshold that management must focus on complete rebuilding (69). The effectiveness and uncertainties of land building and sustaining projects for keeping pace with sea-level rise, subsidence, and other factors are being both investigated and questioned. For example, predictive modeling has shown that sea-level rise and subsidence could outpace many of the benefits from sediment delivery, especially if river sediment loads are not restored to levels before damming (70). However, immediate initiation of projects to optimally decrease land loss and/or move communities away from danger is needed because of the increased future costs of delaying these efforts due to uncertainties (70).

The importance of improving decision making and learning capabilities in the Gulf region has spurred recent activities by private, federal, state, tribal, local, and nongovernmental entities. The Gulf Coast Restoration Task Force, established by executive order to address long-term Gulf-wide restoration beyond the 2010 oil spill, has identified tipping points as one critical learning need (58). Efforts of a Science Coordination Team expanded ideas in this report (58) to include additional actions for increasing resiliency in habitat types and coastal communities (71). Focused work on coastal sustainability and safety issues has culminated in the most recent Louisiana Coastal Master Plan (59), which assesses scientific and value-based needs for land-loss prevention decisions, including resiliency-related issues (Fig. 2). For decisions addressing land losses, considerations

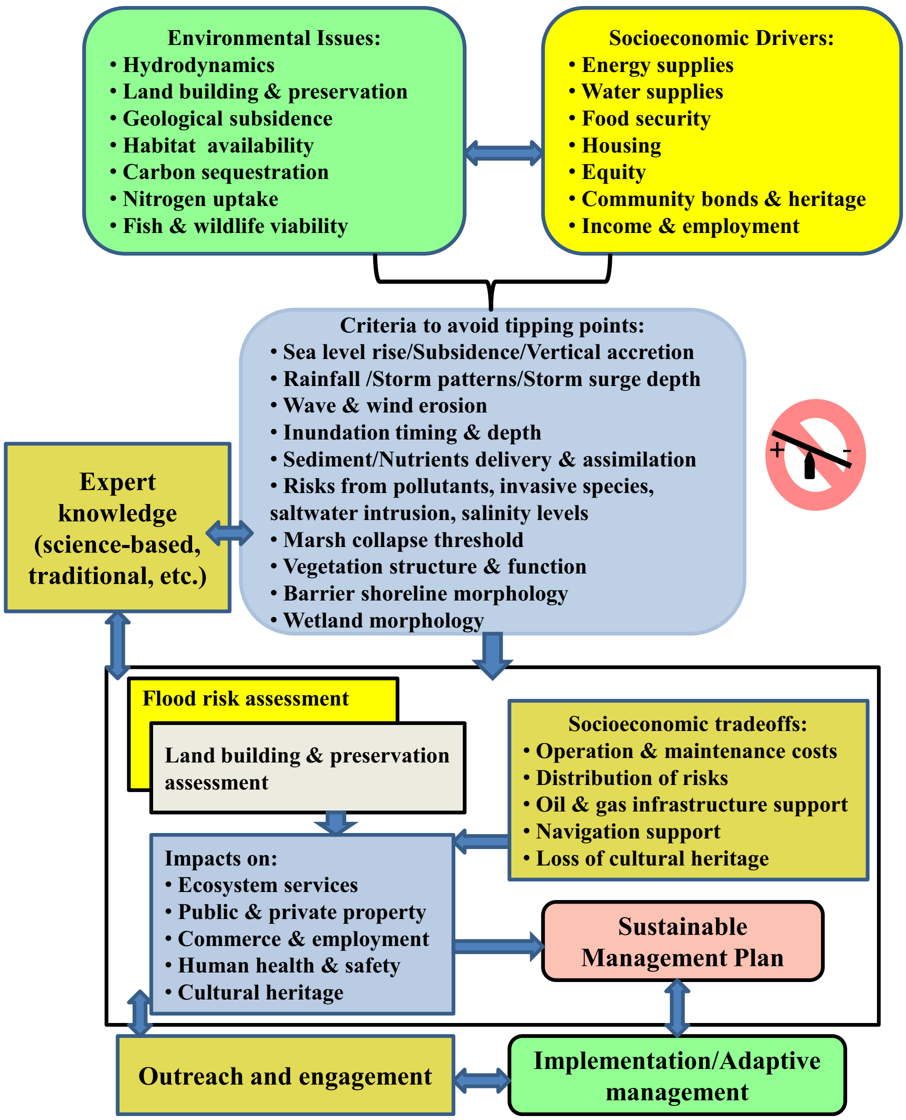

Fig. 2. Sustainability assessment example for land-loss issues in coastal Louisiana (59).

include ecosystems services (e.g., fisheries and nature-based tourism), socioeconomic issues (e.g., protecting strategic assets and significant cultural sites), and threats to resiliency (e.g., sea-level rise and invasive species) (59). Defining variables and criteria that impact stakeholders and ecological viability, along with other important factors such as causal relations and uncertainties, will support management efforts to achieve desired and avoid undesired outcomes.

Due to the magnitude of the land-loss crisis, improved governance capabilities for deriving, using, and exchanging process knowledge across scales of decision making is being implemented. The Coastal Protection and Restoration Authority (CPRA) was established to coordinate planning, implementation, and enforcement for restoring and protecting coastal Louisiana (59). Development of CPRA management plans involves community stakeholders, industry representatives, government officials, and experts. The CPRA organizes teams to implement selected projects, including evaluating and addressing design considerations, implementation barriers, and regional consequences, and develops an adaptive management framework to foster participatory benefits from collaboration, coordination, and communication (59).

Ensuring resilience in complex environments with multiple stressors requires management that is flexible and responsive to new information. Elements of structured decision making can be adapted for highly dynamic environments including frequently reexamining objectives, adapting management actions to changes, and incorporating model uncertainty into predictions (72). Although private and public decision makers work to prevent shifts from desirable to undesirable ecosystem states, consideration of the dynamic and varied nature of Gulf Coast ecosystems could improve management in all phases of decisions. Improving the decision-making process also requires a critical appraisal of the collection, interpretation, use, and communication of knowledge on ecological and social dynamics at all scales of governance. In addition to understanding the dynamic nature of Gulf ecosystems, addressing concerns of community members is essential to make informed tradeoffs in large-scale restoration projects.

Episodic erosion related to expansion of roads, Yunnan, China. Significant increases in both surface and landslide erosion caused by road construction in the mountains of northwest Yunnan, China, affect not only site productivity but also exacerbate sediment delivery to rivers (73). Unimproved roads are proliferating in this developing region due primarily to economic and tourism pressures (74, 75). This region is home of the Three Parallel Rivers of Yunnan Protected Areas, designated by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) as a World Heritage site. In this unique geologic and ecological area, the Jinsha, Salween, and Mekong Rivers run approximately parallel in deep gorges within less than a 100-km wide corridor. Sediments routed into the Salween and Mekong Rivers and their tributaries eventually flow through poorer nations (Myanmar, Thailand, Laos, and Cambodia) that depend on these waters for fishing, aquaculture, irrigation, and other livelihoods. In addition to degrading site productivity and water quality, sediments impact aquatic habitat, damage hydropower facilities, and transfer pollutants. Excessive sediment deposition in steeper headwaters may also increase the potential for flooding and catastrophic debris flows (76). The largest sediment inputs from mountain roads to rivers do not emanate from surface erosion but from landslides (Fig. 3*A*). Landslide erosion along recently constructed roads in these mountains varies from about 3,000–48,000 $Mg \cdot ha^{-1} \cdot y^{-1}$ (74), values that dwarf average landslide erosion rates along forest roads in unstable terrain in the northwest USA (60 $Mg \cdot ha^{-1} \cdot y^{-1}$), which were sufficient to suspend forest-logging operations on federal lands due to concerns over aquatic habitat (40). Surface erosion from and along these roads, although significant, is typically <10% of the landslide erosion. Oftentimes, >80% of the landslide and surface-eroded sediments directly reach stream and river systems (Fig. 3*B*) (76).

Thus, a more sustainable approach to rural road development in Yunnan would be to consider potential landslides as the primary sediment source and to evaluate alternatives for road location, construction, and structural and nonstructural protection against end uses and socioeconomic benefits. Many newly constructed roads in northeastern Yunnan are inoperable during wet seasons or require

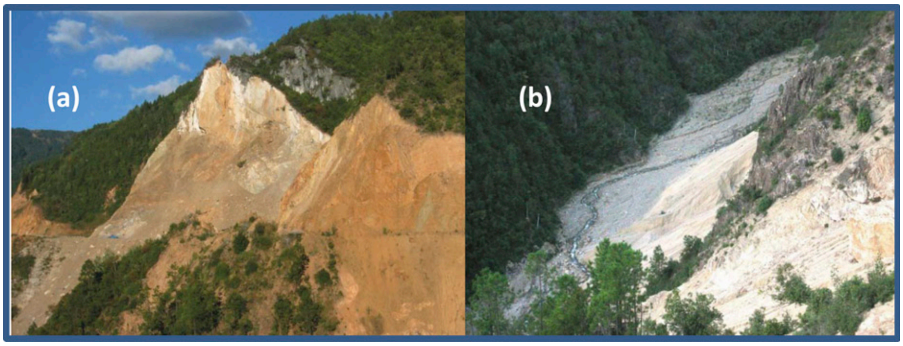

Fig. 3. Landslides along a road constructed in 2002 in the upper Mekong River basin near Weixi, China, northwest Yunnan Province. (*A*) A large landslide originating in the cutslope of the road killed six people traveling in a minivan. (*B*) Most of the sediment from the cutslope failure and shallow fillslope landslides directly entered the stream channel, posing a future threat for episodic evacuation. Reproduced with kind permission from Springer Science+Business Media: from ref. 76, figure 2a, Springer Science+Business Media B.V. 2010.

extensive maintenance to remove landslide sediment, which eventually makes its way into rivers. In the worst cases, mountain road construction is abandoned, leaving no access and a legacy of sedimentation problems. Examples of landslide-related deaths along these lightly traveled mountain routes have already been reported (76). Current development is paying little attention to road location or construction methods to control the mass wasting of rock and soil (40). These secondary roads are typically constructed with hydraulic shovels, back hoes, or indiscriminate blasting, and the excavated material is simply disposed of onto slopes below the road. Much of the terrain is very steep (>30°) with few breaks in gradient, and thus once a landslide initiates along a road there is little chance of sediment entrapment on the slope. Until urgent attention is directed toward this problem, local residents and downstream communities will bear the burden of such unsustainable practices, not to mention damage to fragile terrestrial and aquatic habitats.

This example shows how ecosystems could be pushed to tipping points because of poor management decisions. Consequences that have appeared or could develop include (*i*) extensive road-related landslides and surface erosion that progressively strip soil to the point where vegetation is altered and habitation downslope is unsafe; (*ii*) degraded water quality exerting long-term downstream impacts; (*iii*) catastrophic debris flows in sediment-laden headwaters; and (*iv*) impacts on livelihoods or economies of downstream water users. An effective sustainability assessment before extensive road construction and other land development activities in this mountainous region should include landslide hazard assessments and analysis of potential trigger mechanisms with probability thresholds for different road locations and construction methods (Fig. 4). Acceptable levels of landslide and surface erosion need to be articulated, as well as thresholds that equate to tipping points, that is, where site productivity, human welfare, ecological attributes, or river conditions are severely impacted in the long term. Management activities (e.g., road building) could be constrained to options that would not approach tipping points.

Cases That Would Have Benefited from Considering Ecosystem Resetting. ***Cascading effects of linked episodic disasters and urban development, Tohoku, Japan.*** The complex cascade of damage in the Pacific coastal region of Tohoku, Japan, was initially triggered by the March 11, 2011, Great East Japan Earthquake. This was the largest earthquake ever measured in Japan in terms of ground motion, magnitude ($M = 9.0$), shaking duration, and magnitude and number of aftershocks. Much of the coastal damage occurred when a huge tsunami, with run-up heights exceeding 39 m in some areas, struck within 30–40 min of the earthquake (29) (Fig. 5*A*). Even with the most advanced tsunami warning system in the world, a large percentage of the 20,000+ lives lost in this disaster was directly attributed to tsunami impacts. The tsunami inundated dikes and breakwaters along the coast, bringing into question the protective value of such countermeasures for truly episodic events. On one hand, it can be argued that these countermeasures (although breached) ameliorated the extent of tsunami damage; on the other, a case can be made that

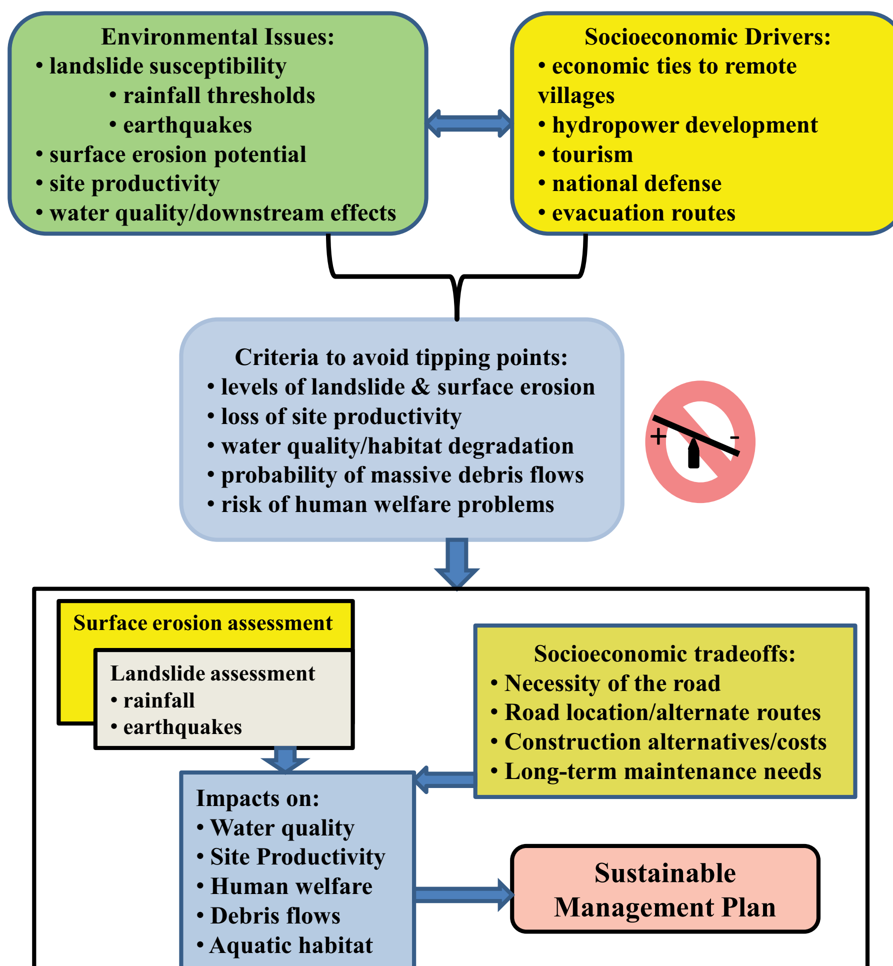

Fig. 4. Sustainability assessment example in ecosystems of northwestern Yunnan, China, where extensive road networks are being proposed in steep terrain with protected river basins.

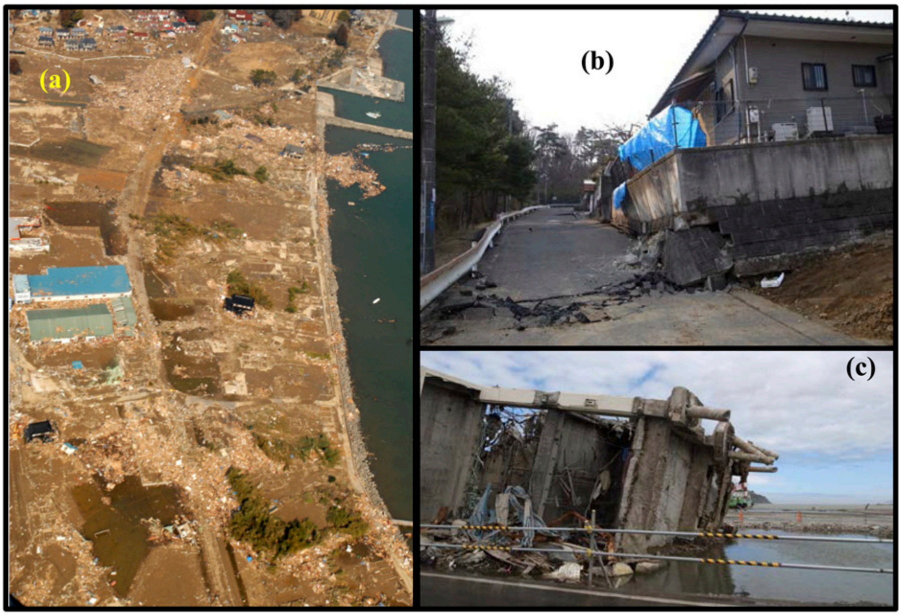

Fig. 5. Ecosystem impacts and urban/residential damage caused by the March 11, 2011, earthquake (M = 9.0) and tsunami off the east coast of Japan. (*A*) Tsunami damage and potential ecosystem changes along the coastline north of Sendai (US Navy photo; D. McCord). (*B*) Homes and roads built on valley fills in Sendai destroyed by slope collapse (valley fill-type landslide). (*C*) Overturned reinforced concrete building with a pile foundation in Tohoku Prefecture, an example of a complex disaster where earthquake shaking liquefied the foundation ground and subsequent tsunami waves overcame resistance to pull-out forces.

such measures may lead to a false sense of security for residents and that emphasizing disaster prevention education is more effective, particularly in a nation where residents are aware of such hazards (29).

Along with the lives that were lost during this composite disaster, extensive infrastructure damage occurred including roads, railways, artificial fills, lifelines, and earthen dam collapse, and some 76,000 homes were destroyed (Fig. 5). Although reinforced concrete structures mitigated some of the damage (77), the combination of earthquake and subsequent tsunami waves liquefied foundation materials and actually toppled many reinforced structures (Fig. 5*C*). Associated "natural" disasters affected by the earthquake/tsunami included fires, landslides, and debris flows. The largest long-term consequence of the disaster is the accident at the Fukushima Nuclear Power Plant No. 1. After the earthquake, the two most-affected nuclear reactors were shut down successfully; however, earthquake damage to the electrical feeder lines required that backup generators supply power to emergency cooling systems for the reactors. Within less than 1 h, the backup generators were inundated by the tsunami surge, causing power loss to the cooling systems. Subsequent actions taken to deal with the system failures resulted in a release of radioactive material into the environment. The regional deposition of radioisotopes may have long-term implications for agricultural production and land use throughout coastal Fukushima Prefecture and neighboring regions (78). Furthermore, evidence exists that cesium has penetrated the bark of Japanese cedar (the most important regional commercial tree species) to the extent that it may have contaminated wood to be used in housing and furniture construction. The Fukushima government is attempting to mitigate economic impacts of the disaster by supporting the local forest industry, thus exacerbating this contamination problem.

This catastrophic set of disasters underlines the necessity for concurrent hazard analysis in sustainability assessments and decision making. The cumulative cascade of disasters—earthquakes, tsunami, landslides/debris flows, fires, radioactive releases from damaged power plants—emphasizes the need to base environmental safeguards on joint probabilities of the occurrence of multiple, interrelated hazards in dynamic settings. Siting criteria and contingency plans for facilities such as nuclear power plants that pose severe environmental risks if compromised must carefully consider the range and interaction of geohazards. Whereas the vulnerable subduction zone off Japan's east coast is known for its earthquake potential, the combination of episodic effects that occurred on March 11, 2011, together with power outages, were not anticipated in the siting and emergency planning of the Fukushima power plants. The radioactive releases that followed now bring into question the need for contingency planning that could anticipate such human and environmental exposures (in time and space) and how to proceed with managing contaminated areas (79, 80). By reinterpreting planning and response strategies based on experiences gained during this multifaceted disaster, decision makers can learn ways of promoting more sustainable approaches of mitigating risk (37). Although human health must be of paramount concern, related issues include soil and water contamination and equitable compensation to owners of contaminated areas, as well as science-based decisions on future land-use trajectories in affected regions. In hindsight, sustainability assessments in tectonically active coastal settings should consider such low-frequency, high-magnitude events and weigh the risks of siting vulnerable facilities there. Additionally, assessments must evaluate long-term ecosystem changes that follow uplift, subsidence, coastline alterations, and sedimentation (81, 82).

In the shadow of the damage caused by tsunami waves, more than 200 residential lots in Sendai City were impacted (Fig. 5*B*). Among these, at least 50 residential lots were damaged by landslides in the urban region, and several hundred houses were destroyed by landslides, all of which were associated with artificial landforms, especially valley fills (embankments), created during residential development on slopes (83) (Fig. 5*B*). Infrequent, very large magnitude earthquakes ($M \geq 8$) have occurred off the eastern coast of Japan, but smaller major earthquakes ($M \geq 7$) have struck much closer to the mainland with greater frequency and caused more severe damage in this urban region. In particular, the 1978 Miyagi Prefecture Off Shore Earthquake ($M = 7.4$) disaster was the first case of a modern urban complex affected by a major earthquake (84). Before this earthquake, Japan had experienced several decades of postwar growth (1954–1973) that affected socioeconomic conditions and increased the demand for labor and housing in large cities, such as Sendai City. Concurrently, energy sources evolved from charcoal to fossil fuels, eliminating harvesting of forests around the urban area. Even after the 1978 earthquake, Sendai City continued to expand in response to population growth, especially during the bubble economy from the mid-1980s through the early 1990s, with large numbers of residential lots being constructed on surrounding hillsides. Crests of hills were removed and valleys were filled by soils from cuts and industrial waste. The poor quality of fills and degraded subsurface water drainage were major contributors to the widespread valley fill landslides that occurred in the urban region during the 2011 earthquake (83). In contrast, smaller cities in Japan experienced less population growth, thus precluding the need for extensive fill construction for residential lots on hillsides. As such, the population dynamics and urban development in the Tohoku region during the past half-century were reflected in the distribution of urban landslides induced by the 2011 earthquake

(83). Current government relocation of coastal communities to inland hillsides is designed to provide safe residential/business sites as well as bolster the devastated local economy. However, cuts and fills used to implement this massive relocation exemplify how power relations and mismatches of informational flows create a scenario where government decision makers ignore lessons from past experiences instead of retaining this knowledge and acting accordingly (37). The disproportional number of landslides that occurred in artificial valley fills during the 1995 Kobe earthquake further highlights the need to avoid residential fills and opt for more sustainable alternatives such as building "contour line cities," with houses distributed along topographic contours to reduce the cascading linkage between development and landslides in hilly urban regions (85).

Repeated natural disturbances affecting ecosystem structure, Papua New Guinea. Continual natural disturbances (e.g., earthquakes, volcanism, tectonic uplift, landslides) in the mountains of Papua New Guinea have created an ecosystem in a kind of "dynamic equilibrium." An estimated 8–16% of New Guinea's tropical forests are disturbed every century by earthquakes and related landslides (86). Earlier studies in a portion of this terrain revealed that large single earthquakes in 1935 ($M = 7.9$) and 1970 ($M = 7.0$) denuded 8% and 25% of affected forested areas (130 and 60 km^2), respectively (87, 88). An additional 3% of the New Guinea landscape is disturbed by landslides not associated with earthquakes—mostly initiated by the high rainfall (2,500–6,000 $mm \cdot y^{-1}$) that exhibits strong but spatially variable seasonal cycles. Natural episodic disturbances maintain large areas of successional forest that, in the absence of these disturbances, would eventually be replaced by other tree species (86). Extraction of natural resources further exacerbates terrain instability and resultant forest composition. Timber harvesting, mining, energy development, and associated infrastructure all affect the stability of steep slopes (40).

Because earthquake-initiated landslides are more common on steep hillsides and ridgelines (40), these sites are where vegetation disturbance is most prominent. Rainfall-initiated landslides typically occur on steep slopes, as well as in concave depressions (hollows) where shallow groundwater concentrates (40), but not along ridgelines. The ecosystem resetting associated with these different mechanisms and topographic features, therefore, should be included in sustainability assessments.

The juxtaposing forces and influences of rapid tectonic uplift and denudation by mass erosion and other surficial processes are evident in the development of drainage networks in this geologically youthful terrain. The early phase of rapid tectonic uplift creates a pre–steady-state evolution of topography in Papua New Guinea that can be characterized by the following sequences in the Finisterre Mountains: (*i*) watershed initiation in isolated gorges in terrain with subdued relief where drainages are created by dissolution processes and tectonic uplift dominates erosion; (*ii*) watershed expansion where mass wasting (landslides controlled by groundwater seepage) rapidly supplies sediment to streams, which accelerates channel erosion, lowers valleys, and steepens topography; (*iii*) tributary expansion by slope-clearing landslides along valley sides; and (*iv*) stream entrenchment due to runoff concentration and associated fluvial incision of landslide scars and deposits (89). Each unique setting must be recognized in sustainability assessments of land use in this dynamic terrain, especially in how management decisions affect stream channel morphology, erosion, and sediment transport. Treating responses to management decisions similarly for these different geomorphic settings is fraught with problems.

Summary

Ecosystems are impacted by natural and anthropogenic stressors. Resilience in these systems accommodates certain levels of both stressor types and should be considered to properly frame ecosystem assessments. A more difficult issue occurs when stressors push systems to tipping points, causing a regime shift. Whereas chronic anthropogenic activities such as progressive soil degradation, land-cover change, and air pollution are often linked to tipping points (25, 39), natural changes can also push systems to their limits (16, 24). Recognizing tipping points and implementing strategies to avoid (in terms of anthropogenic stressors) or cope (in the case of natural stressors) is a challenge that requires thorough understanding of ecosystem processes and responses to stressors. Cumulative-effects analysis can help separate effects of anthropogenic activities from those of natural processes and is useful in sustainability assessments (90).

The most difficult ecosystems to assess for sustainability are those predisposed to episodic natural disasters—major earthquakes, tsunami, large landslides, widespread wildfire, and volcanic activity—that can reset entire systems for long periods. Oftentimes, major events initiate a cascade of linked disasters, as in the case of the 2011 Great East Japan Earthquake, where tsunami, fires, landslides, fillslope collapses, radioactive releases, and associated health effects occurred. Such disasters are often devastating because lack of warning inhibits response, and the infrequent nature of these events precludes the incorporation of past episodes into contemporary decision making (14, 37). Capturing the probability of ecosystem resetting in sustainability assessments is necessary, as evidenced by recent disasters throughout Asia and North America.

A paradigm shift is required for us to embrace concepts of sustainability and explore the consequences of decision making that affects human and ecosystem integrity. Harmonizing environmental, economic, and social opportunities for the benefit of present and future generations creates an opportunity to understand the influence of inherent chemical, geophysical, and social attributes and stressors on human health and ecological integrity. It is further recognized that whereas underestimating the impact of certain stressors and related exposures may result in contamination or adverse health effects, overestimating the potential hazards could create an economic burden on communities. Land-management and regulatory agencies often rely on indicators of sustainability in ecosystems (3, 91, 92), but it is important to understand how anthropogenic and natural ecosystem processes force changes in system behavior as well as the goods and services they provide (16, 24, 90).

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