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Coupled Human and Natural Systems

Humans have continuously interacted with natural systems, resulting in the formation and development of coupled human and natural systems (CHANS). Recent studies reveal the complexity of organizational, spatial, and temporal couplings of CHANS. These couplings have evolved from direct to more indirect interactions, from adjacent to more distant linkages, from local to global scales, and from simple to complex patterns and processes. Untangling complexities, such as reciprocal effects and emergent properties, can lead to novel scientific discoveries and is essential to developing effective policies for ecological and socioeconomic sustainability. Opportunities for truly integrating various disciplines are emerging to address fundamental questions about CHANS and meet society's unprecedented challenges.

INTRODUCTION

Coupled human and natural systems (CHANS) are systems in which human and natural components interact. Although humans have interacted with the biophysical environment since the beginning of human history, the scope and intensity of these interactions have increased dramatically since the Industrial Revolution. Historically, most human-nature interactions took place at the local scale, although there were some large-scale human migrations and other broad activities, such as trade and wars. Today, interactions between human and natural systems at the regional, continental, and global scales have emerged as special concerns because human activities are globally connected.

Although human-nature interactions have long been recognized (1–9), the complex patterns and processes involved in such interactions have not been well characterized, let alone fully understood (10, 11). Traditional research in the social and natural sciences informs the current interest in CHANS. However, social scientists have often focused on human interactions, minimizing the role of environmental context or perceiving environmental influences to be constant, whereas ecologists have traditionally focused on pristine environments in which humans are external and rarely dominant agents. Although disciplinary research continues to be important to advance disciplinary inquiries into many aspects of human and natural systems, it is not effective to study human and natural systems separately when addressing social-ecological and human-environment interactions (12–16).

The importance of developing a new integrated framework to study CHANS is recognized in a growing set of interdisciplinary research programs (see examples in Table 1). These projects go well beyond what was commonplace in ecological and social sciences research just a decade or two ago. The human and natural domains are no longer viewed as separate but rather as connected and embedded entities in webs of interactions. For instance, the Millennium Ecosystem Assessment (17) explicitly integrated social and ecological systems by analyzing the global status, trends, and future scenarios of 24 selected ecosystem services and more than 70 policy instruments for addressing them. Results from CHANS research have been published in various outlets, and a few interdisciplinary journals, such as *Ambio*, have been unusually receptive to such findings (18–21).

The science of CHANS builds on but moves beyond previous work (e.g., human ecology, ecological anthropology, environmental geography). First, CHANS research focuses on the patterns and processes that *link* human and natural systems. Second, CHANS research, such as integrated assessment of climate change (22), emphasizes reciprocal interactions and feedbacks—both the effects of humans on the environment and the effects of the environment on humans. Third, understanding within-scale and cross-scale interactions between human and natural components (e.g., how large-scale phenomena emerge from local interactions of multiple agents and in turn influence local systems) is a major challenge for the science of CHANS. Although each of these three aspects has been addressed in some studies on human-environment interactions (23, 24), the science of CHANS promotes the integration of all these aspects. Such integration is needed to tackle the increased complexity and to help prevent the dreadful consequences that may occur due to the fundamentally new and rapid changes, because the magnitude, extent, and rate of changes in human-natural couplings have been unprecedented in the past several decades, and the accelerating human impacts on natural systems may lead to degradation and collapse of natural systems which in turn compromise the adaptive capacity of human systems. Constructing approaches that emphasize an integrative framework and comprehensive methods for understanding complexities of human-nature interactions is an urgent and growing priority (10, 24–28) (Table 1).

In this article, we synthesize major characteristics of complex organizational couplings (among organizational levels), spatial couplings (across space), and temporal couplings (over time) of CHANS. To demonstrate practical values of studying these complex characteristics, we discuss their implications for sustainable environmental/natural resource management and governance. To guide future research efforts, this article illustrates several main opportunities and challenges in studying CHANS. Although some discussion in this article is brief due to space limitation and some issues in this article have been discussed in other contexts, integrating all relevant important topics in one article provides a holistic view of the relationships among CHANS complexities, implications, and prospects.

ORGANIZATIONAL COUPLINGS

Reciprocal Effects and Feedbacks

Coupled human and natural systems can be conceptualized as entities with nested hierarchies (15, 29). In CHANS, people and nature interact reciprocally across diverse organizational levels (30). They form complex webs of interaction that are embedded in each other.

Humans depend on nature for a wide array of ecosystem services (31, 32), including potable water, clean air, nutritious food, raw materials, and medicine. Many aspects and processes of nature upon which humans depend, however, are threatened or have disappeared due to human action or inaction (17). For example, humans have significantly altered between one-third

Table 1. Representative programs on studies of coupled human and natural systems.*

Program Name	Dynamics of Coupled Natural and Human Systems	Beijer International Institute for Ecological Economics	Resilience Alliance	Intergovernmental Panel on Climate Change	Millennium Ecosystem Assessment
Focus	Complex interactions among human and natural systems at diverse spatial, temporal, and organizational scales	Ecological economics	Research on the dynamics of complex adaptive systems in order to discover foundations for sustainability	Assessment of scientific, technical, and socioeconomic information to understand climate change, its impacts and choices for adaptation, and mitigation	An international program assessing conditions and consequences of ecosystem change for human well-being and options for responding to those changes
Major funding source	U.S. National Science Foundation	Kjell and Märta Beijer Foundation	Diverse grants from private foundations	World Meteorological Organization and United Nations Environment Programme	Multiple sources
Duration	2000–present	1991–present	1999–present	1988–present	2001–2005
Source of information	http://www.nsf.gov/geo/ere/ereweb/fund-biocomplex.cfm	http://www.beijer.kva.se/	http://www.resalliance.org	http://www.ipcc.ch/	http://www.MAweb.org

* This list omits an enormous number of local, regional, national, and global projects (e.g., ozone hole, melting Greenland, shutting off Gulf Stream, worldwide shifts in phenology of rivers, ice, and plants and animals) that are making significant contributions to the understanding of coupled human and natural systems.

and one-half of the land surface (5). More than half of all accessible surface freshwater is used by humans (33), and groundwater supplies are increasingly scarce. Fishing has had a substantial impact on populations of large marine fishes (34). Invasive species have been increasing numerically and spatially via intentional and unintentional human introduction. Human activities, such as use of land, oceans, and fresh-water, have markedly changed land cover, biogeochemical and hydrological cycles, and even the climate system (5, 22, 35, 36). Human influence is now so pervasive that it dramatically alters the evolutionary trajectories of many other species (37). Even areas explicitly buffered from human impacts, such as protected areas (e.g., nature reserves), are the outcome of human decisions and are influenced by global responses to human disturbances, such as climate change. Development has generated enormous benefits for humanity and improved human well-being (17), but gains through inappropriate practices (e.g., undervaluation and overexploitation of ecosystem services) have also increased risks and impaired numerous ecosystem services essential for human survival and development (31, 32). To offset the loss of some ecosystem services, humans have attempted to replace them with engineered solutions (e.g., aquaculture or levees for wetlands) and restore them (e.g., tree planting to retain nutrients and water, increasing native cover to resist invasion by exotic species (38)). However, restoration may be much more costly than preventing the loss of the services in the first place.

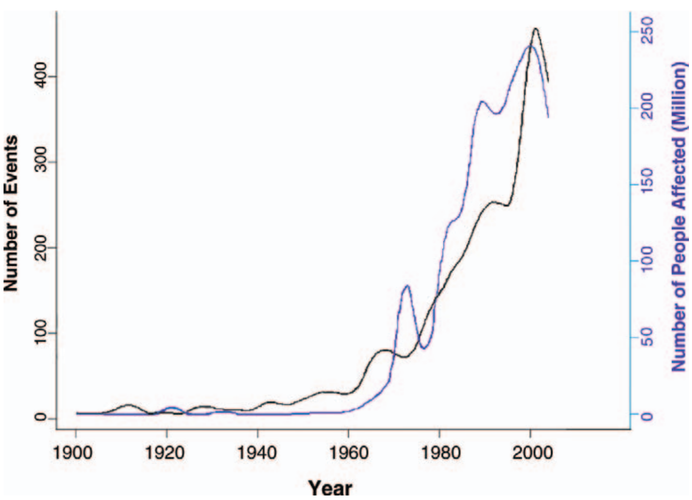

Figure 1. Changes in the numbers of natural disasters and people affected (modified from Centre for Research on the Epidemiology of Disasters (91)).

Natural processes can devastate human systems through environmental degradation and disasters, such as earthquakes, floods, volcanoes, heat waves, droughts, hurricanes, tornadoes, landslides, and diseases (39) (Fig. 1). At the global level, environmental deterioration now forces more people to cross national borders than wars, and environmental refugees may reach 50 million within the next 5 y (40). The impacts of disasters range from interruption of people's work and life routines, through social conflicts, economic losses, destruction of such infrastructure as roads and buildings, to the spread of disease and death. The 2005 Hurricane Katrina in the US Gulf region that was responsible for more than 1200 deaths and estimated damages of more than $200 thousand million (41) and the 1998 flood in China that killed at least 2000 people and affected more than 240 million are just two recent examples (42). Furthermore, human-nature interactions often vary across social groups: the elderly, the poor, and the young tend to be more vulnerable to natural disasters.

Feedback loops in which humans both influence and are affected by natural patterns and processes are typical of CHANS (28, 43). These loops can be positive or negative (44) and can lead to acceleration or deceleration in rates of change of both human and natural components as well as their interactions (10). For example, many human activities, such as greenhouse gas emission, have increased notably since the beginning of the Industrial Revolution, often growing exponentially (45). In return, the impacts of these activities on human well-being (e.g., greenhouse effects) have also increased remarkably.

Indirect Effects

Many human-nature interactions occur indirectly due to the production and use of human-made (manufactured and synthesized) products, such as electronic appliances, furniture, plastics, airplanes, and automobiles. These products insulate humans from the natural environment, leading them to perceive less dependence on natural systems than is the case, but all manufactured products ultimately come from natural systems. Estimation of embodied energy (energy used by all processes

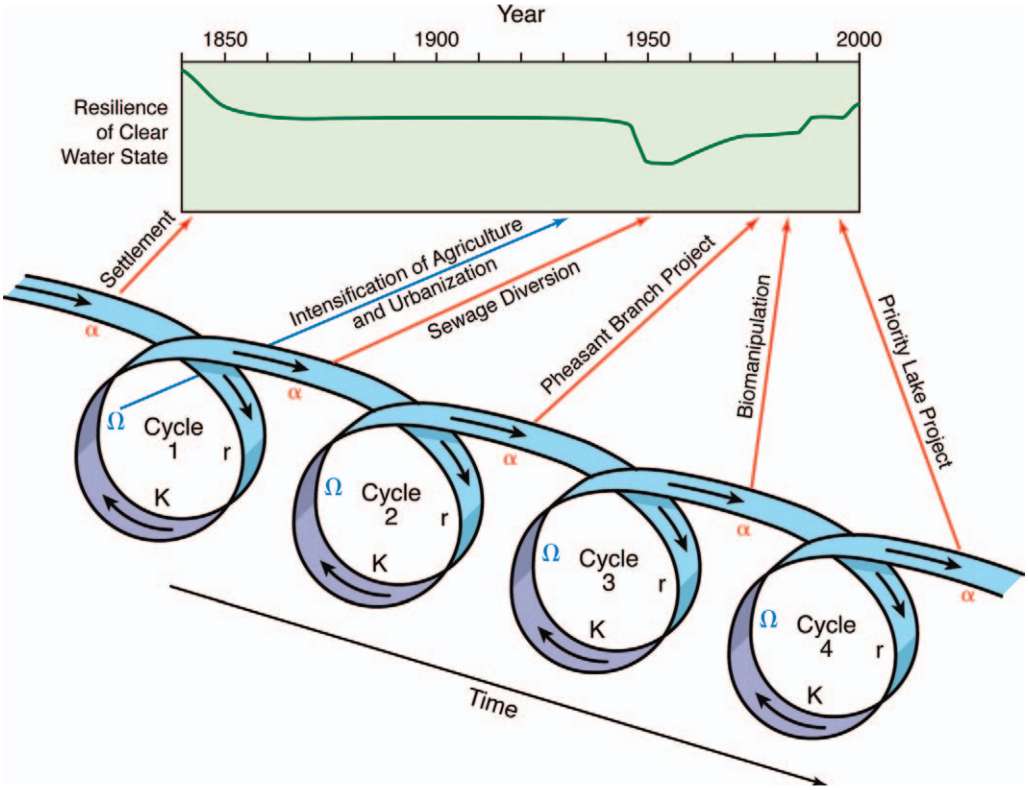

Figure 2. Resilience of clear water state showing four cycles under management and human influences on Lake Mendota, Wisconsin, US. Each cycle goes through four phases: rapid growth and exploitation (r), conservation (K), collapse or release (Ω), and renewal or reorganization (α). (Source: Carpenter et al. (160)).

related to the production of a good) permits assessment of some otherwise unrecognized or underestimated human links to the natural world (46). Generally, there is a direct relationship between the number of steps required to make a product and the amount of embodied energy of that product. For example, among 107 building materials surveyed (47), differences in embodied energy coefficients varied by as much as 10 000-fold per unit mass, ranging from <0.1 MJ/kg in natural materials, such as virgin rock and sand, to approximately 200 MJ/kg in human-made aluminum.

A different category of indirect effects is caused by alteration of ecosystem dynamics and services after human use or modification of a few species. For example, the extermination of sea otters (a keystone predator) in Alaska triggered reorganization of coastal marine ecosystems, including decreases of most species dependent upon kelp forest habitats (48, 49).

Emergent Properties

Coupled human and natural systems exhibit many emergent properties, unique properties not belonging to human or natural systems separately but emerging from the interactions between them. For instance, spatial distribution and quality of panda habitat result from human activities (e.g., timber harvesting, fuel wood consumption) and natural processes (e.g., forest succession) (50). Coupled climate-economy models have shown that the discount rate emerges as the key to the sustainability of human development scenarios, a property that would not emerge so clearly in stand-alone models (51).

Figure 3. World total merchandise trade (US dollars at current price, based on data from the World Trade Organization (161)).

Vulnerability

Vulnerability is the degree to which CHANS are likely to experience harm due to changes in internal and external variables (52), including local and regional factors, as well as global forces (e.g., climate change, globalization of trade, mobility of people [e.g., tourists] and their spread of infectious diseases) (53). It may result from the human (e.g., infectious diseases) and natural components (e.g., the rise of water level due to a flood) and/or the interplays between human and natural systems (e.g., overfishing coupled with disease and a hurricane triggering the collapse of a diverse coral reef ecosystem (54)). Eventually entire CHANS can become vulnerable to disturbances and feedbacks between human and natural systems (55).

Thresholds and Resilience

Thresholds are transition points between alternate states or regimes (56, 57). When ecosystems are degrading, effects on human well-being may not be apparent until ecological changes reach thresholds (17). Resilience is the ability of CHANS to retain similar structures and functioning after disturbances for continuous development (58–60) (Fig. 2). Subtle losses of resilience can set the stage for sudden, surprising, and large changes in ecosystems that are difficult or impossible to reverse (61–64). Among the 64 examples analyzed in a recent study, nearly 40% of the regime shifts were irreversible (59). Such shifts have had substantial impacts on CHANS, including water, fisheries, dry land agriculture, and pastoral systems around the

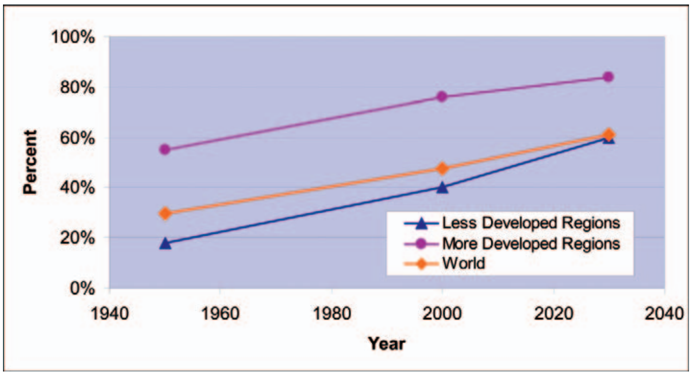

Figure 4. Percent urban population in more developed regions, less developed regions, and the entire world (based on data from Hodgson (162)).

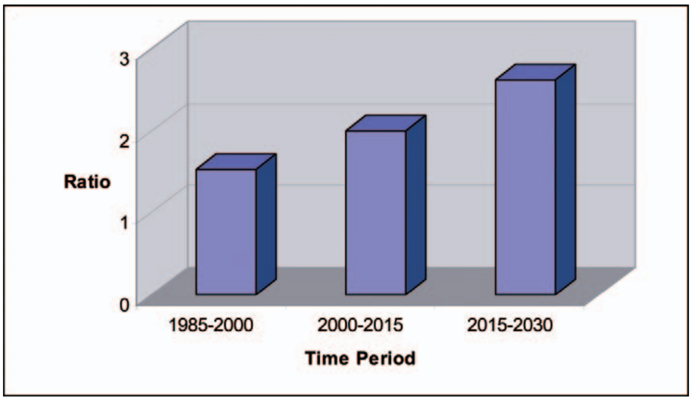

Figure 5. Ratio of growth rates of human population size and number of households (based on data from the United Nations Centre for Human Settlements (Habitat) (163)).

world (17). Thresholds and resilience are also faced with more uncertainty due to the interactions among increasingly important but imperfectly understood drivers, such as governmental policies (65), climate change, and new technology (e.g., nanotechnology, biotechnology).

SPATIAL COUPLINGS

Couplings across Spatial Scales

Couplings within and among CHANS take place across nested multiple spatial scales, ranging from local to global. Local couplings are influenced by broad-scale processes that in turn act in the context of still larger-scale processes and ultimately global-scale processes. Global couplings are in part generated by the synergistic and cumulative effects of local processes (e.g., greenhouse gas emission, biodiversity loss, deforestation, overfishing of localized stocks), which repeat throughout much of the globe and contribute to stress on global or regional systems (e.g., emission of ozone-depleting substances into the atmosphere, discharge of heavy metal pollutants into the Great Lakes and the oceans). Global or regional couplings also occur due to human activities over long distances (e.g., international trade; Fig. 3) and large-scale natural processes (e.g., hurricanes, tsunamis, atmospheric movement of pollutants). Increasing globalization of human activities and rapid movements of people as well as their goods and services suggest that mankind is now in an era of novel coevolution of ecological and socioeconomic systems at regional and global scales (66).

Couplings beyond Boundaries

Human-nature interactions occur beyond political or ecosystem boundaries through such processes as trade and animal migration. Both markets and governance can cause decisions made in one place to influence people and ecosystems far distant. The global movement of people, goods, and information has transformed the context within which modern interactions occur. As goods and people move from continent to continent, so do invasive species, pests, and microbes. Thus, couplings at one location also spill over to other locations (42). People in cities receive food from rural areas at the expense of nutrient depletion and soil erosion in rural areas (67). Climate change driven by emissions from rich countries increases disease incidence and mortality in poor countries (68). In developing countries, exporting of raw materials and finished products to developed countries might increase vulnerability of humans to environmental stressors and cause social unrest and degradation of ecosystem services essential for the local population (21). Furthermore, the manufacture of many export products generates substantial pollution and high levels of risk to workers in developing countries (42). Because exports of raw materials often fetch low prices, the economic benefits may not match the costs in loss of ecosystem services in the long run. On the other hand, pollution (e.g., CO_2, other greenhouse gases) from developing countries affect developed countries as well, although the average per capita amount of CO_2 emission in developed countries is much higher than that in developing countries (42). Food production in one region may affect food production in another due to changes in the hydrological cycle (69). In short, effects of distant people on local natural systems and effects of distant natural systems on local people are common across the world.

Heterogeneity

Couplings between human and natural systems vary across locations, as is evident in a comparison of rural and urban areas. Approximately half of the current global population lives in urban areas (Fig. 4). Cities consume 60% of the water tapped for use by people and emit 78% of the anthropogenic carbon (70). Although the average urban population density is higher than in rural areas, the average urban household size (number of people in a household) is lower and per capita efficiency of resource use in smaller households is lower than in larger households (71). Most food, energy, and other materials used by urban residents are brought in from distant places (20). For example, the inhabitants of Hong Kong need approximately 2000 times the city's built area to provide ecosystem goods and services to maintain their current quality of life (72).

Couplings are more indirect and global in developed countries than in developing countries. This is partially because a higher percentage of the human population lives in urban areas in developed countries (almost 80%) than in developing countries (approximately 40%) (Fig. 4). Furthermore, developed countries import a substantial fraction of raw materials from developing countries. For example, Japan is the world's largest importer of timber from tropical countries while maintaining its own forest cover (64% of the Japanese land mass remains in forests).

Although 37% of the world's population lives within 100 km of the coast (73) (twice the world's average density), humans have more direct couplings with terrestrial and freshwater systems than with marine systems because almost all people live in terrestrial ecosystems with embedded freshwater systems. However, human use of terrestrial and freshwater systems affects marine systems (e.g., discharge of pollutants to the marine systems). For instance, in 2003 alone, 20 of China's 867 main wastewater outlets discharged approximately 880 million tonnes of sewage water (containing 1.3 million tonnes of pollutants) from land into the sea (74), not to mention the pollutants that enter the waterways from nonpoint sources and land-use change.

TEMPORAL COUPLINGS

In recent years, scholars have suggested that humans have entered the anthropocene era, a term that emphasizes human dominance of biospheric processes (45). Key human drivers of environmental change became much stronger over the last half of the 20th century as the human population grew exponentially and the number of households (a basic socioeconomic unit) increased faster than the number of people (Fig. 5) (71, 75). Furthermore, the scale of human production and consumption has also grown much faster than the population, especially in rapidly growing countries, such as China and India (76).

Massive Increases in Human Impacts on Natural Systems

Over the past 50 y, humans have changed ecosystems more than in any other period of human history (17) and have rapidly increased ecological footprints (77, 78), and these impacts have been projected to grow by about 2% per year between 2001 and 2015 (79). Humans continue to "simplify and homogenize" landscapes and seascapes around the world. Although there are cases in which humans have made landscapes more heterogeneous and have increased biodiversity, the overwhelming trend has been in the opposite direction (80). For instance, overfishing with accompanying pollution and habitat destruction in coastal waters has simplified ecosystems and has made them respond to external influences in unpredictable manners as the buffering mechanisms and resilience in the earlier systems have been degraded (81). The global climate changes that are at least partially attributed to human activities have made many plants and animals "victims" (82, 83). Furthermore, there may be a declining baseline expectation with regard to diminishing ecosystem conditions as people habituate to ever-degrading ecosystems (84).

Although humans have always depended on natural systems, this reliance is increasingly at risk because there are more people, per capita use of resources has increased, and many ecosystem services critical to human well-being are now degraded (35). Furthermore, humans now use more artificial products (including at least 10 million compounds) than in the past (85). For example, such compounds as steroids, antibiotics, hormones, and other active ingredients in prescription and over-the-counter drugs are commonplace in US streams (86).

Rising Natural Impacts on Humans

Changes in natural systems also have increased human vulnerability in many places and constrained options for human livelihoods (87, 88). Since 1900, the total numbers of natural disasters and affected people have increased almost exponentially (Fig. 1), largely because of increased population density, especially in disaster-prone areas, such as lowlands and coastal communities. Hurricane intensity has increased in the past three decades in both the Atlantic and Pacific, coincident with warming of the sea surface significantly associated with human forces (89, 90). In northwestern China, dust storms increased from an average of once every 31 y between AD 300 and 1949 to once almost every year since 1990 (42). As natural disasters increase, the social and economic costs for emergency and humanitarian aid have skyrocketed (91).

Many gains in economic development come at the cost of degrading the capacity of ecosystems to provide services now and in the future (10, 17, 92). For example, food production in dry land ecosystems that are home to about 2 thousand million people is threatened by declining water resources, deteriorating soils, and climate change (17). In the Argolid valley of Greece, there is not enough water to continue irrigating the citrus crops that were planted in the valley about 40 y ago. The water table in parts of the valley has dropped up to 7 m a year. Now water is pumped at the valley's edge from depths as great as 400 m. Throughout the world, the effects of ecosystem degradation on human well-being are a growing obstacle to achievement of the Millennium Development Goals (93), such as poverty reduction and human development (17), although it is not clear whether environmental impacts of increases in economic activity are surpassing the offsetting effects of improvements in resource efficiency.

Legacy Effects

Legacy effects are the cumulative and evolving impacts of past interactions in CHANS on current and future conditions. They vary in duration and intensity, depending on such factors as disturbances (94), physical and biological conditions (95, 96), and socioeconomic status. For instance, among the legacies of former land use that have been surprisingly influential in explaining the current condition of the landscape are the historical effects of humans on the age, size, and species structure of forests (97).

Time Lags

There are varying intervals of time between human-nature interactions and their ecological and socioeconomic effects. In some cases, the linkages between human and natural systems unfold slowly and the changes are not detectable. In other cases, there is simply a lack of research and monitoring necessary to learn that systems are changing, and in still other cases, humans may not have perceived the linkages. For example, the promulgation of chlorofluorocarbons (CFCs) as refrigerants, fire retardants, and cleaning agents led to depletion of stratospheric ozone and increased exposure of many ecosystems to UV-B radiation. However, for many years lack of knowledge of the adverse effects of CFCs precluded decisions limiting their manufacture and use; indeed, at the time of their introduction, CFCs were seen as a boon to public health, because they displaced dangerous ammonia-based refrigeration (98). Greenland ice sheet collapse could have been entrained by a changing climate a long time before it can be easily discerned (99). The time lags between human decisions and their environmental effects, or between environmental changes and consequences to humans, complicate attempts to understand and manage these interactions.

Increased Scales and Pace

Human-nature interactions in the past were usually at the local scale, with a few exceptions, such as long-distance human migrations. They now occur increasingly at the regional, continental, and global scales. Interactions between human and natural systems, such as urbanization, have also increased in pace. For instance, London increased from 1 million to 8 million inhabitants in 130 y (from 1801 to 1930) (100), but Mexico City achieved this growth in only 30 y (from 1940 to 1970) and doubled again to 16 million in only 26 y (from 1970 to 1995) (101, 102). In the meantime, environmental impacts on urban residents due to such factors as pollution and shortage of resources (e.g., water) also increased. Furthermore, the emergence of novel diseases and the re-emergence of old diseases (e.g., tuberculosis) have accelerated. Such diseases as SARS have spread faster than in the past because the speed of transportation systems allows the virus to reach almost every corner of the globe within days, a process that would have taken weeks, months, or even years a century ago (103).

Escalating Indirect Effects

Indirect interactions between human and natural systems have become more common and more pronounced due to rapid urbanization, among other reasons. Over the last 5 decades, the proportion of people in urban areas has increased from 30% to 50% (Fig. 4). By 2030, the proportion of urban residents is projected to exceed 60% (Fig. 4). As a result, a smaller proportion of people are directly engaged with the ecosystems that provide critical resources while more people consume manufactured products made in and transported from distant places. With a more than 10-fold increase in population over the past century, urban regions are increasingly the primary drivers of natural resource consumption, atmospheric and water pollution, climate change, and threats to biodiversity. The impact of these urban areas as a point source environmental hazard is expected to grow because the expected net population growth in the next 30 y (approximately 2 thousand million people) will be concentrated in urban areas (104). However, it is not clear whether the total environmental impact would be less if the increased population were to spread across rural areas.

IMPLICATIONS OF COUPLED HUMAN AND NATURAL SYSTEMS FOR MANAGEMENT, GOVERNENCE, AND POLICY

Coupled human and natural systems challenge traditional planning and management assumptions and strategies for natural resources and the environment. By and large, most policies in place today will not lead to sustainable outcomes (93). Some emerging new policies, for example, ecosystem-based management in oceans and coupled land-sea ecosystems, seem to move in the direction of sustainability and need to be encouraged, implemented, monitored, and revised if necessary (105). The success or failure of many policies and management practices is based on their ability to take into account complexities of CHANS. For instance, without considering cross-boundary effects, forest harvests in the upper reaches of river basins often result in serious soil erosion and floods downstream (e.g., the 1998 huge flood in the Yangtze River Basin in China) (42). Assumptions regarding climate variability and extreme events that do not take into account the uncertainty often result in lack of preparedness and effective response (e.g., Hurricane Katrina). In contrast, the Montreal Protocol is a remarkable success story in part because it recognized the time lag in the effects of CFCs and thus had motivated global action to prevent deterioration of the ozone layer before significant impacts on human and natural systems were evident (106). These experiences suggest that characteristics of CHANS be considered in natural resource planning and management.

First, hubris in human attitudes toward natural systems is an impediment to progress. A shift from the idea that “humans can conquer nature” to “humans coevolve with nature” would help facilitate improved management (107, 108). So too would more attention paid not only to immediate outcomes but also to resilience that is essential to maintain functioning systems over time. Emergent properties, reciprocal effects, nonlinearity, and surprises should be routinely taken into account in planning and management practices (109, 110). The inherent limitations of humans’ predictive ability dictate that uncertainty must be incorporated into decision making (110–112). Scenario building provides a strategy to explicitly consider plausible futures when irreducible uncertainties are present (113). Changes in response to various exogenous stressors and internal dynamics of CHANS are inevitable, so strategies that enhance the adaptive capacity of CHANS while preserving key aspects of their structures and functioning are essential (114). More effective technologies could be used to enhance resilience, reduce vulnerability, and minimize human impacts on natural systems below critical thresholds to prevent harmful feedbacks to human systems. The increasing prevalence of indirect interactions between people and nature (e.g., global trade) makes environmental management increasingly complex. The roles of government are critical: well-designed regulations, policies, incentives, and governance structures can stimulate involvement of diverse populations in the understanding and management of CHANS.

Managing CHANS effectively requires not only consideration of all major natural components but also coordination of human components as well as their interactions. Although development-as-usual has initial economic benefits, traditional development strategies need to be altered, and transforming them into sustainable practices is urgent, because the magnitude and scale of human disturbances are too vast and have led to irreversible unsustainability in many circumstances. In the transition to sustainability, those not yet enjoying the fruits of development need help (in the forms of resources, information, technology, etc.) from those who have benefited from development so that overall efficiency of resource use and socioeconomic equity can be enhanced. A lack of coordination of human activities can result in “tragedies of the commons” (115), such as a crash in the Chinook salmon population in Lake Michigan due to communication breakdown among managers and fishermen and disjointed efforts to control fishing (116). Fortunately, after the collapse, management agencies adjusted their mode of independent operation to an integrated loop of involvement, consensus building, and decision making, involving managers and stakeholders in states bordering the lake (116). Ecosystem measures (e.g., the forage base) that assisted in guiding salmonid stocking rates were also considered (117, 118). This new approach appears to have been highly successful in that both the number and the health of fish caught have been improved.

Second, as human action is more tightly linked across the globe, local economic decisions are increasingly shaped by conditions and processes half a world away (e.g., soybean production in Brazil for export to China and Chinese products sold in Europe and North America). Globalization, the connectivity and synchrony of many interactions, is changing the roles and responsibilities of governments at all levels through both decentralization of decision making and tighter linkages through international accords. Financial deregulation and free trade may weaken the power of nation states (119, 120) and strengthen the power of international corporations, international policy bodies (e.g., the World Trade Organization), and, in some cases, local governments and enterprises. That 51 of the largest 100 economic entities in the world are corporations, not nations (121), has profound effects on regulation and management of CHANS. Localization of policy design is important because CHANS are very context specific and strategies that work well in one place may fail in another. However, they must also take into account global and regional dynamics that shape the responses of local CHANS. In areas in which hazards are common and the human population is at risk (e.g., many coastal regions), previously unthinkable strategies (e.g., retreating from the coast and returning some areas of New Orleans to natural systems, abandoning agriculture in areas where it is unsustainable) must be explored and new development models implemented (e.g., eliminating subsidies for coastal development).

Third, the ever-changing nature of CHANS implies that management systems should be dynamic, but inertia tends to dominate the social, political, and economic structures involved in many aspects of natural resource management (109). In many countries, natural resource policies and laws (e.g., mining law and subsidies, water law, public lands leasing) currently in effect have their origins in a paradigm of exploration and exploitation of natural resources (122). Special interest groups are often able to maintain the status quo even when it leads to environmental degradation and socioeconomic costs to others. Cultural inertia may make it hard to perceive needed changes, whereas sometimes cultural change can be quite rapid. A balancing act is required to ensure that institutions and decision-making processes retain their flexibility without becoming faddish (110, 123, 124). Time lags and legacy effects dictate that both patience and foresight are necessary for environmental restoration and to avert future problems. Overcoming years of environmental insults in CHANS, such as the Everglades of the US, will not happen overnight. The anticipation of future effects, as was evident in the Montreal Protocol, also is essential.

Despite the obvious importance of using information from CHANS studies for policy making, governance, and management of natural resources, recognizing the incompleteness of knowledge about CHANS and the inevitability of surprises is vital. The negative consequence of inherent uncertainty and the increasing likelihood of surprises can be minimized by 3 approaches: *i)* maintaining margins of safety to account for uncertainties (e.g., in calculating fisheries quotas), *ii)* factoring in insurance as a hedge against disasters (e.g., adding in a buffer of additional area in calculating the size of marine reserves (125)), and *iii)* ensuring adaptive mechanisms. These approaches are all essential elements of a strategy to effectively manage CHANS (126), including the commons (124, 127–129). The greatest likelihood of success will entail developing strategies of policy analysis and implementation that approach decisions with humility and emphasize the need to learn through time (15, 130).

CHALLENGES AND OPPORTUNITIES

The need for research and management that treat all human-environment and social-ecological systems as CHANS or parts of CHANS is increasingly recognized. This recognition comes with a number of challenges and opportunities. Although humans are integral components of ecosystems (4), they are still not fully represented in ecological science (131–133). Although theoretical frameworks that integrate humans into ecological studies exist, they are not sufficiently quantified and applied (44, 134, 135). Thus, it is crucial to re-examine (and revise if necessary) current ecological theory to address ecosystems coupled with humans that shape ecological patterns and processes. Likewise, it is also essential to reconsider (and alter if necessary) existing socioeconomic theory to recognize the increasing roles of natural systems in socioeconomic patterns and processes. Making such revisions and meeting the challenges below are critical for better understanding CHANS and for implementing government policies and management programs that ensure socioeconomic and ecological well being in the future.

Linking Coupled Human and Natural Systems across Scales

Studying CHANS requires a new paradigm that emphasizes hierarchical couplings of natural and human systems across organizational, spatial, and temporal scales. The approach is not simply larger-scale analysis, as with previous global modeling efforts (e.g., World Dynamics (136), Limits to Growth (137)). Rather it stresses the nesting of local systems in regional and global systems, the cumulative effects of local processes on global processes, the differential coupling of human and natural systems at each scale, the embedding of smaller-scale processes in larger scale processes, and the influences of larger-scale processes on smaller-scale processes. In particular, the new approach to studying CHANS integrates methods at multiple scales and continually evaluates how small-scale phenomena are embedded in broad-scale processes and how broad-scale phenomena emerge from and influence the small-scale structure and functioning of CHANS (15, 138). Understanding even the most local human-nature interactions requires "progressive contextualization" in which local actions are understood in terms of landscape, regional, and national factors, which in turn depend on global forces (139, 140). For example, the vulnerability of a community to natural hazards depends not only on local topography and subsistence activities but also on the state of the regional economy, the ability of relief to reach distressed localities, and ultimately global climate changes. This embedding requires studies of couplings between human and natural systems at multiple organizational and spatial scales simultaneously. The same problem occurs with regard to time scales as well; it is essential to understand not only the daily interactions between humans and their environments but also the dynamics and interplay of the slower processes at the scales of decades to centuries.

Integrated Tools

Tools, from mathematical and statistical models to computer simulation models, geographic information systems, and remote sensing, are useful in understanding the structure, functioning, and dynamics of CHANS. Models capable of integrating various multidisciplinary techniques and data show particular promise for understanding CHANS, such as integrated assessment of climate change (141–145). One interesting example of such an integrated approach to modeling is the agent-based models of land-use change (146, 147), which utilize a collection of agents to represent human decision making, combined with other tools (e.g., geographic information systems) that capture socioeconomic and biophysical processes across a landscape (146). These integrated tools, including integrated assessment of climate change, agent-based models, and other bottom-up models, such as pattern-oriented models that use observed patterns to optimize model structure (148), should be further developed to better understand changes in CHANS across multiple spatial, temporal, and organizational scales; make predictions or evaluate short- and long-term consequences of various management and policy scenarios; and develop hypotheses regarding complexities of CHANS that can be tested empirically.

Long-term data are of particular importance for CHANS work because understanding reciprocal causation between human and natural systems cannot be done with cross-sectional data alone. Support for collection of data to develop time series was not available until recently, and most data still are collected and analyzed for either human or natural systems at local scales, not for the articulation of both simultaneously at multiple scales. Satellite imagery plays a key role in identifying land-cover and land-use changes, as well as many human features, such as household locations on the landscape (149–151). With an ongoing large international effort (The Global Earth Observation System of Systems), existing and new satellite resources including hardware and software are being assembled to make them compatible. This effort will help ensure that long-term, reliable, and high-quality data will be open and freely available to answer many CHANS questions, such as those regarding climate change and pulse of Earth. However, relevant social and economic observations should also be made so that the remote sensing data can be used to achieve the overarching goal of understanding CHANS from a truly interdisciplinary perspective.

Comparative Studies and Portfolios

To date, much CHANS research has been site specific or at best compares a handful of sites. Such work is necessary but insufficient for understanding how CHANS work. A single site or even a small set of sites cannot adequately capture regional and global variations in types of ecosystems, climatic regimes, political and economic contexts, or culture. Coupled human and natural systems programs must include not only site-specific studies but also planned comparisons across sites and macrolevel analysis with existing and emergent data. It is also essential to go beyond existing CHANS programs, such as the Dynamics of Coupled Natural and Human Systems at the US National Science Foundation (Table 1), develop bigger and more comprehensive portfolios with larger funding and coordinated comparative projects, and establish a global collaboratory for CHANS research across local, regional, national, and international levels.

Collaborations among All Fields Relevant to Coupled Human and Natural Systems

Understanding of CHANS requires effective nurturing of interdisciplinary research. Coupled human and natural systems scientists face formidable tasks and have several needs: *i)* both disciplinary and integrative data collected across multiple scales, *ii)* new analytical approaches to connect constantly moving dots, and *iii)* strong communication skills for the team approach essential to CHANS research. Gone are the days of the solo scientist: researchers must learn the languages of multiple disciplines. Such programs as the Integrative Graduate Education and Research Traineeship Program of the US National Science Foundation should be further developed and expanded to train young and midcareer scholars in team building; leadership; and appreciating the multiple mindsets, paradigms, and different assumptions of disciplinary backgrounds, especially between the social and natural sciences.

Despite some notable achievements in interdisciplinary research, the promise of working across disciplines has not been uniformly realized and the barriers (e.g., reward system, institutional structure) to sustained successful collaboration remain very high (26, 152–154). Fortunately, there are some "real world" practitioners who clearly recognize the need for interdisciplinary perspectives on challenges in the business, civic, and other arenas. Many funding agencies also recognize the value of interdisciplinary approaches and are allocating significant research dollars for cross-program initiatives and multiagency cooperative programs (Table 1). Top-level administrators at many universities are strongly urging interdisciplinarity, but many midlevel administrators, such as department chairs, remain discipline oriented for various reasons (e.g., budgetary structure, self-identity within the university system, ranking within their fields). Importantly, although university programs are ranked according to individual disciplines, there is no equivalent ranking of interdisciplinary programs, such as CHANS, or even environmental science. However, the pursuit of interdisciplinarity will continue to grow and will be a major factor in differentiating individual researchers, departments, and even universities from one another. Although this structural change for interdisciplinary research is a larger phenomenon and requires institutional and cultural changes, each CHANS researcher can move the field forward not only through individual and small team research projects but also by supporting efforts in universities and in funding agencies to advance interdisciplinary work.

Beyond the Ivory Tower

Coupled human and natural systems researchers should be responsive to the needs of society by integrating basic understanding of CHANS with practical solutions to societal problems (e.g., poverty reduction specified in the UN Millennium Goals). Many research questions must be reformulated and answered to produce more "usable" knowledge for sustainable ecological and socioeconomic benefits and to assess complex characteristics, such as how human interactions with the environment generate emergent behaviors and feedback loops (28, 110). In urbanizing regions, for example, it is necessary to ask how social and ecological patterns and processes arise, how they are maintained, how they evolve (44), and how they can be sustainably managed.

Coupled human and natural systems scientists should also do a better job of communicating knowledge about CHANS more directly and effectively with a variety of audiences, such as the private sector, politicians, managers, media, and the general public (155, 156). Most midcareer and even senior CHANS researchers do not have such communication skills but can benefit from training programs, such as the Aldo Leopold Leadership Program (157). Furthermore, emerging literature (158, 159) provides a model for interaction between scientists and other stakeholders.

CONCLUDING REMARKS

Coupled human and natural systems are experiencing unprecedented rapid changes and progressively tighter couplings at multiple scales. Tackling the escalating complexity of CHANS not only will be an unparalleled interdisciplinary challenge for scientists but also is critical for shaping the future of Earth upon which humans ultimately depend. Better understanding and quantifying CHANS across various scales require much more integrated efforts by researchers from all relevant disciplines simultaneously. Putting the knowledge gained from such integrated studies into socioeconomic and environmental decision-making processes is essential for achieving productive and sustainable CHANS.

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