Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment

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The Millennium Ecosystem Assessment (MA) introduced a new framework for analyzing social–ecological systems that has had wide influence in the policy and scientific communities. Studies after the MA are taking up new challenges in the basic science needed to assess, project, and manage flows of ecosystem services and effects on human well-being. Yet, our ability to draw general conclusions remains limited by focus on discipline-bound sectors of the full social–ecological system. At the same time, some polices and practices intended to improve ecosystem services and human well-being are based on untested assumptions and sparse information. The people who are affected and those who provide resources are increasingly asking for evidence that interventions improve ecosystem services and human well-being. New research is needed that considers the full ensemble of processes and feedbacks, for a range of biophysical and social systems, to better understand and manage the dynamics of the relationship between humans and the ecosystems on which they rely. Such research will expand the capacity to address fundamental questions about complex social–ecological systems while evaluating assumptions of policies and practices intended to advance human well-being through improved ecosystem services.

Sustainability science is motivated by fundamental questions about interactions of nature and society as well as compelling and urgent social needs (1). Research topics transcend the issues of traditional academic disciplines and focus instead on complex interactions of people and nature (2). Progress in sustainability science does not resemble the usual paths of scientific inquiry, where action lies outside the domain of research (3). Instead, scientific inquiry and practical application are commingled. By the turn of the century, fundamental research questions of sustainability science were stated (3). At about the same time, the policy and science communities undertook a massive synthesis of scientific knowledge about global ecosystems and their capacity to support human well-being, the Millennium Ecosystem Assessment or MA (www.MAweb.org).

The MA combined the applied and basic motives of sustainability science. It challenged the research community to synthesize what was known about sustainability science in policy-relevant ways. The results exposed strengths and gaps in the underlying science (4). Since the completion of the MA in 2005, ongoing research has revealed new possibilities for measuring and projecting the effects of policy choices and human actions on the structure and processes of ecosystems, the services they provide, and human well-being. New developments are evident on diverse fronts, such as ecosystem services (5), land use dynamics (6), governance of common-property resources (7), connections of human and earth system history (8) and earth system modeling (9). At the same time, demand from the policy community for this information is expanding.

Progress in this fast-moving field is revealing new challenges in the basic science needed to assess, project, and manage flows of ecosystem services and changes in human well-being. This article highlights salient research needs in light of recent progress. We begin with a brief summary of the MA as a basis for understanding the gaps that it exposed. We then turn to research priorities, based on findings of a joint study conducted in 2007 and 2008 by the International Council of Science, the United Nations Educational, Scientific, and Cultural Organization, and the United Nations University (10). We stress the urgency and importance of accelerated effort to understand the dynamics of coupled human–natural systems.

Millennium Ecosystem Assessment

The Millennium Ecosystem Assessment (11–15) used a new conceptual framework for documenting, analyzing, and understanding the effects of environmental change on ecosystems and human well-being. It viewed ecosystems through the lens of the services that they provide to society, how these services in turn benefit humanity, and how human actions alter ecosystems and the services they provide. The focus on eco-

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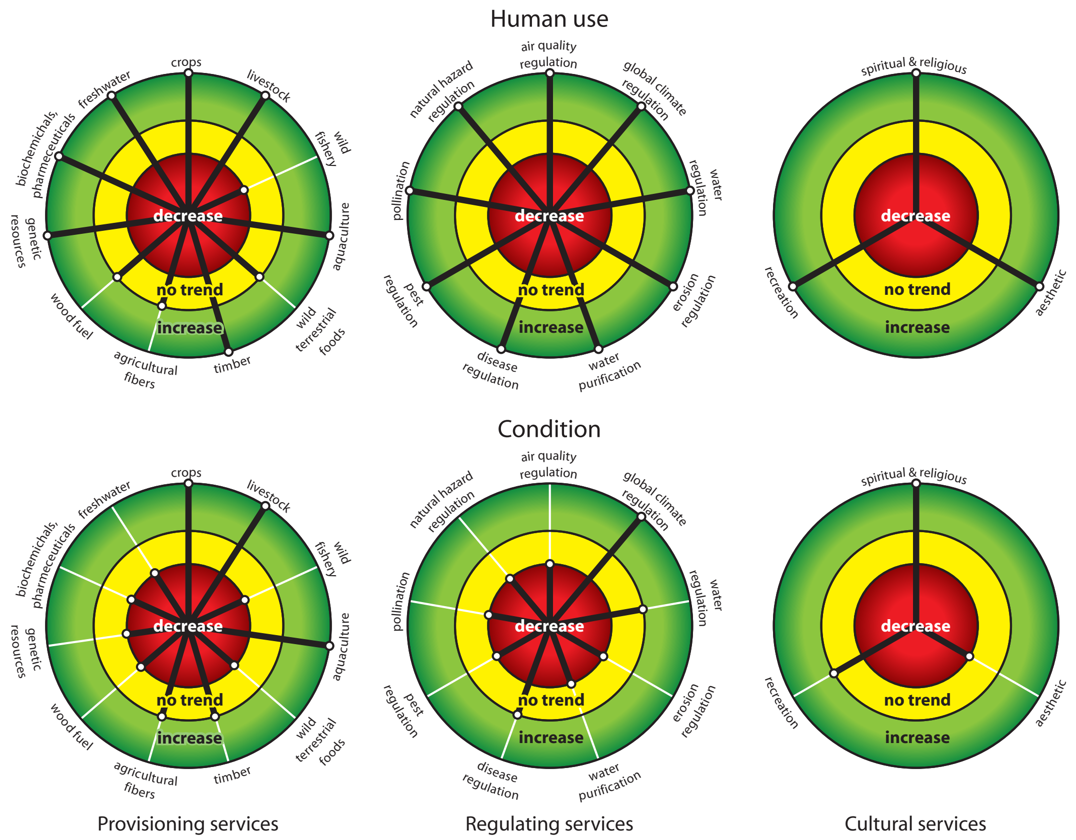

Fig. 1. Trends in human use (*Upper*) and condition (*Lower*) of ecosystem services. Provisioning, regulating, or cultural ecosystem services are shown in *Left*, *Center*, and *Right*, respectively. Length of black radial lines shows the degree of change in human use or condition of the service. Modified from data in Table C.1 of ref. 12.

system services has been adopted widely among the scientific and policy communities and has resulted in new approaches for research, conservation, and development (5).

MA findings showed that human use of ecosystem services is expanding, commensurate with growth in earth's human population and expansion of consumption (Fig. 1). Human use is increasing for all ecosystem services studied, except for wood fuel, agricultural fibers, wild terrestrial foods, and wild-caught fishes [but see recent evidence of declining trends for some recreational use (16)]. Improvements in life expectancy and reduction in poverty over the last few decades have been predicated on human efforts to enhance the provision of food (crops, livestock, cultured fish). Even as these services have increased, most of the other services have decreased during the past 50 years (12). The decline of regulating services is of special concern because it foreshadows future declines in other ecosystem services (12, 13). Indications are that the future trajectory will continue to be unfavorable unless society takes action to combat the adverse trends (13). All of the major drivers, climate change, land use change, invasive species, overexploitation, pollution, population increase, and economic growth, continue to grow, and the trends have taken us beyond the bounds of human experience. Thus, society faces a challenge of unprecedented proportions.

Global degradation of ecosystem services has many causes, including dysfunction of institutions and policy, gaps in scientific knowledge, unpredictable events, and other factors. We often do not know if, or why, policy instruments have succeeded or failed. The MA made a thorough effort to assess the effects of policies on ecosystem services and human well-being (14). However, rigorous evaluation requires appropriate reference systems and before–after data that are often absent. We lack basic information on the dynamics of social–ecological systems and the relationships of ecosystem services to human well-being. We first highlight some key needs in these topic areas. Then we consider critical research needs for place-based research, evaluation of ongoing management programs to learn by doing, and monitoring of social–ecological systems. We conclude that most management of ecosystem services is grounded in assumptions that have not yet been vetted by evidence. Evaluation of assumptions, policy instruments, and practices is sorely needed.

Dynamics of Coupled Social–Ecological Systems

Synthesis of knowledge about social–ecological systems was a daunting task for MA. Participants had to address the effects and interactions of multiple global drivers, differing spatial extents and turnover times of key ecological and social processes, and connections of individual actions, institutional responses, and ecological changes across these multiple dimensions of scale (Fig. 2 and ref. 17). Global biophysical and social drivers affect both ecological and social aspects of regional systems (*Left* and *Right* sides, respectively, of Fig. 2). Within a given region, scales of both space and time must be considered. Changes in social–ecological dynamics can be understood through relationships of slow and fast variables (components of the system with longer vs. shorter turnover times, respectively). Diverse human actors respond to ecosystem services, environmental factors, and social factors, and they influence institutional re-

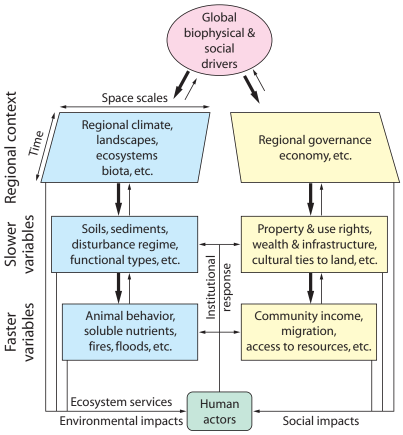

Fig. 2. Conceptual framework for integrated analysis of coupled social–ecological systems, highlighting key issues of space and time scales, social–ecological interactions, dynamics of individual actors, and institutional responses. Modified from ref. 17.

sponses that feed back to components of the regional system. Long-term trends, thresholds of nonlinear change, and resilience of ecosystem services are related to the feedbacks among slow and fast variables.

The relevant information needed to analyze social–ecological systems is both vast and fragmented, encompassing most of the natural and social sciences as well as the humanities (e.g., through roles of cultural ecosystem services). The MA was able to bridge among islands of solid knowledge, and advances are ongoing. Nonetheless, future assessments modeled on the MA would benefit from concerted effort to understand effects of biodiversity in social–ecological context, improve quantitative modeling across a range of social–ecological topics, address nonlinear and abrupt changes, and improve assessment and communication of uncertainty.

Analyze Biodiversity Effects in Social–Ecological Context. Biodiversity embraces a host of structural features of ecosystems: heterogeneity of genomes, species, or ecosystems on landscape units; variety of ecological functions; or variety of responses to environmental shocks, for example. The MA showed that genetic and species diversity is declining at high rates compared with the norm over geologic time and that landscapes have become more homogeneous as more of the terrestrial land surface is converted to human uses (12). These losses diminish options for management and increase vulnerability of ecosystem services. For example, heterogeneity in the responses of species to fluctuating environments can reduce the variability of services provided by an ensemble of species, so loss of this type of diversity may decrease reliability of services (18, 19). Many studies have documented effects of biodiversity on ecosystem processes and services, but most of these studies have addressed effects of species richness in small-scale, short-term experiments that do not resemble real-world ecosystem management (20, 21). Only a few aspects of stability or resilience have been studied experimentally, and often theories and experiments are mismatched so the tests are inconclusive (22). Since the MA, researchers have developed more comprehensive research frameworks for quantifying connections of biodiversity and ecosystem services for spatial extents and time frames useful in management (23).

Biodiversity effects must be understood in social–ecological context. Drivers that affect biodiversity (however it is defined) also have direct effects on ecosystem services, and these changes in ecosystem services may then evoke feedbacks through human responses. For example, a road network that alters species richness and fragments a landscape will at the same time have direct impacts on hydrology and landscape nutrient cycles and thereby alter water supply and water quality independent of any direct impacts of species richness on freshwater resources. Moreover, human responses to the road network will have further effects on ecosystem structure, hydrology, nutrient cycling, and freshwater resources.

Studies that isolate biodiversity effects from this crucial context are incomplete for understanding how policy affects ecosystem services. It is rare to find a linear causal path from changes in drivers → biodiversity → ecosystem processes → ecosystem services → human well-being → human responses → feedbacks to drivers and biodiversity. Instead, causal patterns are much more complex. Linkages may jump forward or backward over steps (e.g., drivers may affect human well-being without affecting biodiversity or ecosystem services, or ecosystem processes may feed back directly to drivers, independent of human intervention). Moreover, feedbacks may be different at particular locations or over particular time scales. The MA subglobal assessments (15) are replete with examples of complex feedbacks that cannot be represented as simple causal chains. For example, the Caribbean Sea Ecosystem Assessment (CARSEA) showed how coral reef biodiversity (of species and spatial heterogeneity) is embedded in complex linkages of indirect drivers (urbanization, investment in unsustainable tourism, international shipping practices, fragmentation of authority among 22 island states), direct drivers (land and sea use, coastal pollution, fish harvest, climate change, river discharge, alien species introductions), ecosystem services (principally ecotourism and fish harvest), and amenity values measured as jobs, GDP, and investment (24). In this context, no simple policy lever can change outcomes. Instead, CARSEA focused on a suite of interventions, including institutions for international coordination among the island states, economic policy instruments for marine conservation, monitoring, and regular assessment to adapt policy to changing circumstances.

Future research should focus on controls of ecosystem services themselves, addressing the effects of multiple drivers, structural factors including biodiversity, and human feedbacks. Such research would directly address needs for information about how drivers and management interventions change ecosystem services. It would evaluate not only the direct effects of biodiversity, but the role of biodiversity in modifying the effects of drivers on ecosystem services. These effects are the essential ones for understanding changes in ecosystem services and projecting the consequences of policies intended to improve ecosystem services.

Match Quantitative Models to Conceptual Goals. Explicit models of coupled social–ecological systems are essential for research, synthesis, and projection of the consequences of management actions. Useful models may be qualitative relationships, toy heuristics, or complex simulation tools. Whatever the format, models are used to clarify spatial boundaries of systems, units of analysis, time horizons, inputs and drivers, key components of the system and their relationships, and outputs. Therefore, the MA used a diverse array of models to describe systems, synthesize information, interpolate within the historical record, and project future outcomes (12, 13). These models provided crucially important information. Yet, there were gaps (13). The MA used only peer-reviewed published models. Although this practice enhanced the credibility of results, it made the analyses more cumbersome and precluded quantitative analysis of some important questions.

Integrated, quantitative models of social–ecological systems do not match the scope of existing conceptual and qualitative models. Existing models of ecosystem services were developed to address particular sectors (e.g., agriculture, marine fisheries, land use, water supply) or particular intersections of issues (e.g., biodiversity and land use change). Moreover, models for sectors must be coupled with projections from other models of climate, demography, macroeconomic development, and other drivers to assess or project ecosystem services. It would be far better to have models that correspond in scope and content to the conceptual frameworks used by the MA or future assessments. Integrated models should be built from scratch to address the scales and drivers that are directly relevant for the question at hand, rather than patching together existing models aimed at disparate scales and objectives. There is ongoing progress toward models that better match conceptual frameworks for ecosystem assessment (25–29). Nonetheless, a great deal of work is needed. This model development should be done in a research setting, not under the stringent time constraints of an assessment.

Address Nonlinear and Abrupt Changes. A recurring theme of the MA was "the absence of theories and models that anticipate thresholds, which once passed yield fundamental system changes or even collapse" (13, Chapter 4, p. 107). Some important ecosystem services subject to nonlinear changes include dryland agriculture, fisheries, and freshwater quality (13). Once degraded, these services may recover slowly or not at all. Slow recovery and irreversibility translate into long-term losses of ecosystem services and persistent problems for managers aiming to sustain human well-being. Social systems are also subject to rapid massive changes (30), and the interactions of social and ecological thresholds have scarcely been explored (31). Research is needed to build the empirical base for understanding thresholds of massive persistent changes in social–ecological systems, the factors that control probabilities of such changes, and leading indicators of incipient thresholds (32). Further work is needed to develop policy approaches that build resilience for massive changes that are hard to predict and have long-lasting consequences (33, 34). Current research on resilience addresses questions about avoiding dangerous thresholds, destabilizing degraded system states as a prelude to restoring systems, adapting to unpredictable change, and transforming brittle systems to more adaptable ones (32–34).

Expand the Scope of Probabilistic Analysis. Many decision analyses require estimates of the probabilities or uncertainties of outcomes. In most cases, the MA addressed uncertainty by stating the degree of scientific consensus or the team's degree of confidence about conclusions. Only rarely was it possible to estimate uncertainties by using rigorous quantitative methods. Yet any decision to mitigate the risks of ecosystem change depends on our capacity to predict the consequences of mitigation actions with some stated degree of confidence. Research should seek to enhance our capacity to identify the outcomes of current activities and to compute probabilities for the different outcomes.

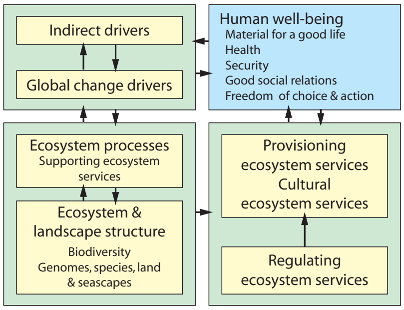

Fig. 3. The overarching feedback loop considered by MA involved indirect drivers (such as economic growth or social values that affect human well-being but do not directly affect ecosystems), direct drivers that directly alter ecosystems (such as human-driven land use change or natural volcanic eruptions), ecosystem structure and processes, ecosystem services, and human well-being. Modified from ref. 35.

Many of the environmental challenges that we face are unprecedented in human history (8, 9, 12), so we lack relevant data for prediction. In such cases it is important to expand the scope of questions being asked, in the hope that important possibilities are not overlooked. For this purpose, the MA used scenarios at global and local scales (13, 15). Use of scenario methods should be expanded, and tools for coupling scenarios with quantitative models should be improved. Scenarios also provide a tool for communicating uncertainties and complexity among diverse groups of experts and stakeholders.

Relationships of Ecosystem Services and Human Well-Being

Connections among ecosystem services and aspects of human well-being were core topics for the MA. The main feedback loops are evident in even the most simplified versions of the MA conceptual framework (Fig. 3 and ref. 35). This diagram represents a specified region over a specified time interval. The situation becomes vastly more complicated when feedbacks are considered among regions, across spatial extents from local to global, or across time horizons as when short-term decisions affect long-term flows of ecosystem services (13).

Simplified as it is, Fig. 3 nonetheless depicts the main interactions that must be considered to understand the relationships of ecosystem services and human well-being. The MA defined well-being as a multivariate state comprising 5 dimensions: basic material for a good life, health, security, good social relations, and freedom of choice and action. Poverty was defined as the extreme deprivation of well-being. The 5 dimensions are qualitative and situation-dependent and must be studied by using surrogates or correlates that are expressed as indicators. Any discussion of indicators immediately evokes debate about weights and preferences. For example, the Human Development Index [HDI (36)] assigns equal weight to 3 variables (life expectancy, literacy, and GDP). However, any weighting structure is likely to be criticized by some, because assigning weights is a value-dependent process. Yet, one must start somewhere, and the alternative is no indicators at all. The MA used many indicators of human well-being, reflecting the diverse literature that was synthesized by the project.

Even when indicators are defined, significant challenges remain. Quantification of tradeoffs among ecosystem services and their interactions with human well-being are among the most pressing areas for research.

Quantify Tradeoffs of Ecosystem Services. There is great enthusiasm for win–win solutions in the conservation-and-development debate, despite counterexamples (5, 37–39). The unfortunate reality is that in an increasingly resource-constrained world, increases in one ecosystem service or human activity typically result in the reduction in other services or activities (39). The general increase in provisioning services over the past century has been achieved at the expense of decreases in regulating and cultural services, and biodiversity (12, 40, 41).

Making these tradeoffs explicit is a core function of ecosystem assessments. Economic analysis is often used to quantify tradeoffs. A principal reason for the decline of ecosystem services is because their true values are not considered in economic decision making (12). Most decisions are based on market prices, but for many ecosystem services no markets exist, and decision makers have no clear signal for the value of the services. Understanding the true social value of nonmarketed ecosystem services depends on the ways that services are used by different stakeholders. There are a number of existing methodologies for estimating the value of specific nonmarketed ecosystem services, yielding shadow or accounting prices for those services. However, new methodologies need to be developed to derive the value of the ecosystem configurations that deliver different bundles of services (42).

Tradeoff analysis prompted the MA to quantify and determine the value of services, insofar as possible. Economic analysis of tradeoffs employs the marginal value, or the value of a small increment or decrement of that service from its current supply. When tradeoff decisions are made within a well-informed, relatively homogeneous decision-making community, where the loss of one benefit is balanced by the gain of another, the community can be assumed to make nuanced value-based judgments regarding such tradeoffs without technical interventions. However, a large number of ecosystem service tradeoffs fail this test. The affected parties are neither homogeneous nor well-informed. In many cases, there is a disconnection between the location where the benefits are derived and the location where the costs are borne; for instance, better catchment management is a cost to highland people, but a benefit to downstream lowlanders. Increasingly, people live in cities, whereas the ecosystem services on which they depend (but of which they are largely unaware) are generated far away from cities. A special but prominent case of tradeoff asymmetry involves intergenerational inequities, where actions taken in the present result in a loss of ecosystem services in the future. The notion of a discount rate is often used to address this tradeoff, but many outcomes are critically dependent on the precise value adopted for this discount rate, which is highly contested. There is an active debate about whether far-future effects should be discounted at all, particularly where future losses may be severe and irreversible (43).

If people's preferences over two or more services are known and can be expressed accurately in the same units of value, for instance, in monetary terms, then making the tradeoff decision is (at least conceptually) straightforward and involves a simple cost–benefit calculation. Although the denominator of economic value need not be in monetary terms (for instance, for diseases and natural hazards it is often expressed in disability-adjusted life expectancies) much effort goes into estimating the "dollar value" of nonmarketed ecosystem services. In some particular cases, research has quantified tradeoffs among two or more ecosystem services in the context of policy options (5). For example, incentives to induce joint management of landscape carbon sequestration and biodiversity have been evaluated (44).

The experience of the MA was that such economic valuation was hard to achieve with consistency and confidence for multiple ecosystem services in diverse locales. In very many cases, the information needed to monetize the services does not yet exist, and some ecosystem services, in particular cultural services, do not lend themselves to economic valuation in any event. In particular, peoples' preferences over the range of services offered by ecosystems may not be known. This is often the case where the services are public goods. Multicriteria analysis may then be used to uncover the tradeoffs between services that groups of people are willing to make (45). In the absence of information on preferences, a useful contribution can still be made by describing (and where possible, quantifying) the causal chain by which value is delivered, even without the final step of imputing monetary value. Even a narrative description of the pathway of impact is an advance over having no information at all, and many decisions are made without having all of the factors in common-denominator form. An important piece of qualitative information is the shape of the curves relating various levels of activity and the corresponding levels of delivery for key services. From these, it is often possible to agree on certain thresholds that should not be exceeded (46).

Evaluate Interactions of Ecosystem Services with Other Determinants of Human Well-Being. Even though all human life ultimately depends on ecosystem services, the relationships of incremental changes in ecosystem services to human well-being are difficult to discern. Many kinds of capital, including natural capital, contribute to human well-being (47). The components of human well-being may be strongly influenced by other factors, such as national politics or social values, independent of any direct effects of ecosystem services. Research is needed to understand how changes in ecosystem services interact with other determinants of human well-being.

In addition, research is needed to understand the effect of changes in ecosystem services on wealth and poverty. Poverty is frequently quantified by using the poverty datum line, the minimum income required to purchase a person's basic nutritional needs (12). This income threshold is then transformed to reflect the purchasing power in the respective countries. However, ecosystem services are often outside the market economy, affecting human well-being in multidimensional ways. So too are the ecosystems that support those services. They are part of people's wealth. Indeed, access to the benefits offered by ecosystems in communal ownership is frequently much more important to the poor than to the rich. Compounding this problem is the fact that people often benefit from ecosystem services produced elsewhere and that managers of remote ecosystem services may not be compensated for them. Research is needed to clarify how changing flows of ecosystem services affect the most vulnerable members of society.

From Theory to Practice

The fundamental challenge is to understand the dynamics of ecosystem services and human well-being as they interact from local to global scales in the context of multiple changing drivers. What combinations of ecosystem services can flow sustainably from a particular landscape? How do changing land use, nutrient mobilization, species composition, and climate affect flows of ecosystem services? For a given landscape, what drivers can be managed, and how? What mixes of ecosystem services do people prefer? How do human choices and actions affect local flows of ecosystem services and spill over to affect other regions? When do human actions aggregate to cause consequences for larger regions or the earth system? What institutions, incentives, and regulations are effective in sustaining flows of ecosystem services? Such questions are emblematic of the challenge before us.

The gaps in knowledge that exist today cannot be addressed through uncoordinated studies of individual components by isolated traditional disciplines. Instead, a new kind of interdisciplinary science is needed to build understanding of social–ecological systems. At the broadest scale, the research that is needed overlaps with the program of Earth System Science (48). To understand changes in ecosystem services, the interactions of social and ecological constituents of the earth system must be considered. Discipline-bound approaches that hold one component constant while varying the other lead to incomplete and incorrect answers. Although many important questions of basic interdisciplinary science must be addressed, here we are most concerned with the problem-solving aspects of social–ecological research (1). We focus on the need for networked, place-based long-term social–ecological research, opportunities to learn from existing programs, and needs for improved monitoring.

Place-Based, Comparative, Long-Term Research. Productive research on social–ecological systems must ground concepts and theories in real-world observations and analysis. There are long traditions of empirical field research in both natural and social sciences. Regardless of the disciplinary origins, successful projects share common features: (*i*) study designs address specific research questions within an overarching conceptual framework; (*ii*) contrasts that reveal key insights emerge from comparisons among places or regions, across spatial extents from local to global, and across periods of time; (*iii*) comparisons are guided by models that bridge observations to concepts and theories; (*iv*) consistent datasets are maintained by using easily repeatable methods. To understand changes and interactions of ecosystem services, contrasts across locales, scales, and time periods are particularly important. To achieve this capacity, study designs must be coordinated across a network of places. This does not mean that each place implements the same design. It does mean that at each place the design allows for comparisons across the network of places and opportunities for unique place-specific research. Such research must be guided by a conceptual framework that can be applied at multiple scales and accounts for interactions across scales (6, 15, 35). Networked research also demands consistency in data collection across places and through time, as well as shared, transparent, interoperable capacity for information management, analysis, modeling, and synthesis.

Some of the most important questions for place-based research address the connections of ecosystem processes and institutions across local, regional, and global scales (Fig. 4). The MA found that some losses of ecosystem services were related to mismatch between the scales of ecosystem processes and the scales at which institutions were effective. In other cases, governance and feedback control mechanisms, prices, property rights, sanctioning systems, and the like, seem to operate at scales that conform to those of ecosystem services. Conceptual frameworks for multiscale systems of governance and economics offer a range of ideas for matching the scales of ecosystem governance to those of ecosystem dynamics and providing institutions with the fluidity needed to track long-term change in ecosystems (7, 33, 49). Clearly, however, successful governance of ecosystem services requires more than just scale-matching. Coordinated stewardship of multiscaled ecosystem services is hard to achieve in practice (50).

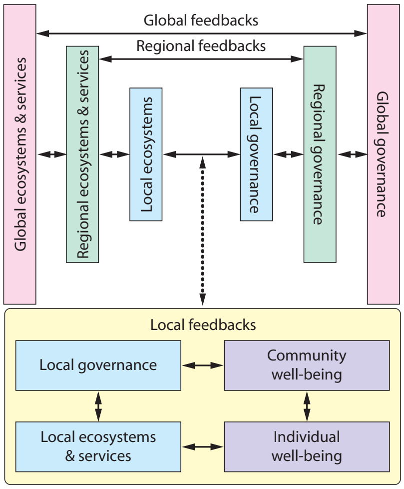

Fig. 4. Governance and ecosystem services are interlinked at multiple scales, in ways that may or may not be effective for building or maintaining ecosystem services and human well-being.

Learn from Existing Management Programs. Conservation organizations, global institutions, and governments are increasingly engaged in projects intended to improve human well-being in concert with ecosystem services. In view of the current state of knowledge, such projects must be regarded as hopeful hypotheses to be tested rather than guaranteed prescriptions for success. Yet, only rarely is the success of these projects evaluated by using appropriate data and indicators (51, 52). Recent studies, for example, reviewed the conditions that lead to success or failure of incentives for conservation (53), showed that fisheries with property rights systems such as tradeable catch shares are less prone to collapse than open-access fisheries (54), and quantified the effects of protected-area networks in decreasing deforestation (55).

Considering projects for development and conservation, the most extensive use of consistent records may be those of the World Bank, where ≈18% of development projects have included "environment and natural resources management" as a major theme (39, 56). Of the projects that were evaluated between 1998 and 2006 and included both environmental and human development goals, only 5 of 32 (16%) documented substantial gains in both environmental and poverty mitigation outcomes. Evidently, win–wins are possible but not common. Unfortunately, the available information is insufficient to reveal which practices lead to success or failure. Outcomes could be explained by project design or implementation, unavoidable tradeoffs among ecosystem services, or uncontrolled factors such as armed conflict or weak rule-of-law. It is impossible to tell from available data.

Ongoing and future projects are an opportunity to learn the factors that influence the outcomes of programs intended to improve ecosystem services and human well-being. What must be added is a framework for assessing changes in social–ecological systems, by using metrics and indicators that can be collected consistently and compared across the range of cases. The cost of implementing such a framework will be small compared with the cost of the projects themselves. The potential benefit is huge from assessing changes in ecosystem services and human well-being associated with conservation and development projects. If the failure rate is as high as suggested by the World Bank sample, there are enormous gains to be had from improving the design and implementation of development projects.

Upgrade and Maintain Monitoring Systems. The MA made extensive use of the world's storehouse of long-term data on social–ecological variables. Nonetheless, the scarcity of such data made it difficult to evaluate trends and draw conclusions about relationships of social–ecological variables (4). Despite improvements in monitoring technology, in some cases the currently collected data are of lower quality than historical data. Fundamental research on sustainability and sustainable practices depends on reliable, ongoing monitoring of social–ecological systems.

Improved monitoring of ecosystem services could build on a number of existing programs. We offer 3 examples at different scales. For the United States, the Heinz Center's recently released report, *The State of the Nation's Ecosystems*, shows what can be accomplished, what gaps remain, and what must be done to secure an adequate monitoring program in the future (57). For the continent of Europe, the Advanced Terrestrial Ecosystem Analysis and Monitoring program (www.pik-potsdam.de/ateam/) has mapped and quantified ecosystem services (27). The Global Earth Observation System of Systems (GEOSS; www.earthobservations.org) provides access to data and analysis tools in 9 core areas (disasters, health, energy, climate, water, weather, ecosystems, agriculture, and biodiversity). Although all of these areas pose challenge for data gathering, analysis, and modeling, biodiversity is particular demanding because it involves the variety of kinds, spatial patterns, and interactions of biotic systems at multiple levels of organization (genes, species, ecosystems, and landscapes or seascapes). The technical problems of comprehensive biodiversity monitoring appear tractable but will require concerted international effort (58, 59).

Critical data needs include (*i*) comprehensive time series information on changes in land cover and land use, biotic systems, and changes in use and ecological characteristics of oceans; (*ii*) locations and rates of desertification; (*iii*) spatial patterns and changes in freshwater quantity and quality, for both ground and surface waters; (*iv*) stocks, flows, and economic values of ecosystem services; (*v*) trends in human use of ecosystem services; (*vi*) changes in institutions and governance arrangements; and (*vii*) trends in components of human well-being (particularly those not traditionally measured, such as access to natural products that are not marketed). In addition to these core global datasets, indicators are needed to bridge raw observations to scientific hypotheses or policy questions. Ideally, the set of indicators would be broad enough to address a range of sustainability issues, small enough to be manageable, and simple enough to be applied consistently and affordably in different regions over long periods of time. Clear guidelines are needed for estimating and communicating uncertainties. The indicators should be relevant for projecting future changes in ecosystem services and human well-being. At present, we lack agreement on a set of indicators that meets these criteria and serves the needs of researchers and decision makers. The research and policy communities need to work together to design a set of appropriate indicators and implement the sustained monitoring programs that will be needed to ensure the availability of data and indicators for the long run.

From Assumptions to Evidence

Earth's life support systems and society have entered an era of enormous change. In the last 50 years, ecosystems and their services have changed more than any previous period in human history (12). Further huge changes are inevitable, as human population increases 2 to 5 more billions by midcentury, human per-capita consumption continues to expand, drivers of ecosystem change intensify, and feedbacks among ecosystem services and human well-being become stronger and more complex (13). A number of existing policies and practices can mitigate damage to ecosystem services (14). Although these policies and practices are not widely adopted at present, some offer the prospect of a better path through the ongoing transitions.

The policy and science communities offer a hopeful vision that human well-being can be enhanced through certain approaches, including those that improve or maintain ecosystem services. Indeed, there are encouraging case studies from scattered locations and times. Yet, evidence suggests that success and failure are context-specific and that no policy or practice is a panacea (60). In any particular situation, available options must be evaluated, selected, implemented, tested, and then replaced or modified in an ongoing search for better outcomes. Global rehabilitation of ecosystem services and human well-being is therefore a long-term, spatially complex experiment that requires continuous innovation and learning. Many elements of the experimental design are based at present on assumptions rather than data-based outcomes. The people who are affected and those providing resources for this experiment are increasingly asking for evidence of improvement in ecosystem services and human well-being. Actions will have to be backed up by data and analysis that evaluate how global policies and practices are benefiting people and nature.

To this end, it is imperative that the policy and science communities establish a capacity to create and implement policies for social–ecological systems, predict consequences, and evaluate outcomes. Basic research on social–ecological systems must be expanded to build this capacity, and more appropriate, integrated approaches to research must be developed. This research must build on existing disciplinary strengths, bridge disciplines effectively, and create new areas of knowledge that are needed to build resilient social–ecological systems. Key results of this research must be applied promptly, and monitoring programs must be put in place to evaluate outcomes. Such a massive effort in social–ecological science is unprecedented in human history, yet it is commensurate with the problems we face and with the potential of sustainability science.

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