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Ecology for transformation

Stephen R. Carpenter[1] and Carl Folke[2]

[1]Center for Limnology, University of Wisconsin, Madison, WI 53706, USA
[2]Center for Transdisciplinary Environmental Research and Department of Systems Ecology, Stockholm University, SE-10691, Stockholm, Sweden

Ecology has a key role in our understanding of the benefits that humans obtain from ecosystems (i.e. ecosystem services). Ecology can also contribute to developing environmentally sound technologies, markets for ecosystem services and approaches to decision-making that account for the changing relationship between humans and ecosystems. These contributions involve basic ecological research on, for example, the resilience of ecosystem services or relationships of ecosystem change to natural disasters. Much of the necessary work involves interdisciplinary collaboration among ecologists, social scientists and decision makers. As we discuss here, ecology should help formulate positive, plausible visions for relationships of society and ecosystems that can potentially sustain ecosystem services for long periods of time.

Introduction

Ecology has become a global science over the 20 years since the inaugural issue of *TREE* [1,2]. Massive assessment projects, such as the Intergovernmental Panel on Climate Change (http://www.ipcc.ch/), have evolved as processes for bringing scientific information into political discussions (see Glossary). Such assessments aim to summarize scientific consensus (on widely confirmed results as well as on uncertainties and areas of disagreement) in a form that is relevant to, but does not prescribe policy.

Ecology is the centerpiece of the most recent synthesis of this kind, the Millennium Ecosystem Assessment (MA, http://www.MAweb.org), which focuses on ecosystem services (Box 1) [3–6]. According to the MA framework [7], these include provisioning services (e.g. food, fiber and fresh water), regulating services (e.g. water and air purification, climate regulation and soil development), cultural services (e.g. educational, recreational or spiritual values of ecosystems) and supporting services (e.g. primary production and nutrient cycling). Underpinning all of these is species, ecosystem and landscape biodiversity [7]. However, the findings of the MA show that 14 out of 24 identified ecosystem services are in decline. Only four ecosystem services are increasing: production from crops, livestock and aquaculture, and carbon sequestration in terrestrial ecosystems. Moreover, degradation caused by land-use change, nutrient mobilization and other drivers is intensifying [7–9]. These adverse changes coincide with an increasing demand for ecosystem services, which is set to increase further as the human population, economic activities and per-capita consumption grow over the coming decades. The social, economic and ecological drivers behind those changes are complex and interwoven in the global system [7–11].

As well as the clear warnings of adverse trends, the MA offers hope. Research has identified characteristics of social–ecological systems that seem to be resilient and capable of ongoing renewal (Figure 1), and environmentally sound technology might reduce adverse impacts of

Corresponding author: Carpenter, S.R. (srcarpen@wisc.edu).
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Glossary

Adaptive governance: institutional and political frameworks designed to adapt to changing relationships between society and ecosystems in ways that sustain ecosystem services; expands the focus from adaptive management of ecosystems to address the broader social contexts that enable ecosystem-based management [12,13].[12] [13]

Adaptive management: a systematic process for continually adjusting policies and practices by learning from the outcome of previously used policies and practices [60]. In active adaptive management, management actions are treated as a deliberate experiment for purposes of learning.[60]

Assessment: a structured process for synthesizing technical information in a way that is useful to policy but does not prescribe particular policies [7].[7]

Ecosystem services: benefits that people obtain from ecosystems [7].[7]

Institutions: rules and norms that guide how people within societies live, work and interact. Formal institutions are codified rules such as the constitution, organized markets, or property rights. Informal institutions are rules governed by social or behavioral norms of a family, community or society [28].[28]

Market, for ecosystem services: an institution for buying and selling an ecosystem service. Markets exist for some ecosystem services (e.g. food and forest products) and are emerging for other ecosystem services (e.g. carbon sequestration or pollutant emission quotas).

Property rights: rights to specified uses of an ecosystem service, perhaps including the right to exchange the services in markets [28]. Property rights are generally divided into private, common, or state, or combinations thereof. Open access is a situation with a lack of well-defined property rights [61].[28] [61]

Regime shift: rapid reorganization of a system from one relatively unchanging state to another [22].[22]

Resilience: magnitude of exogenous change or disturbance that a system can experience without undergoing a regime shift under specified conditions, functions or processes; the degree to which the system can organize itself (versus lack of organization, or organization forced by external factors) and the degree to which the system can build and increase the capacity for learning and adaptation [23,31,33,46].[23] [31] [33] [46]

Scenario: a plausible, simplified, synthetic description of how the future of a system might develop, based on a coherent and internally consistent set of assumptions about key driving forces and relationships among key variables [28].[28]

Social–ecological system: integrated system of ecosystems and human society with reciprocal feedback and interdependence. The concept emphasizes the 'humans-in-nature' perspective [15].[15]

Technology, environmentally sound: a technology that provides the same benefits as other technologies but with less adverse effects on ecosystems [28].[28]

Traditional ecological knowledge: the cumulative body of knowledge, practices and beliefs about ecosystems developed by a society and handed down through generations [15].[15]

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Box 1. Ecosystem services

By the 1970s, researchers had begun to focus on the ecological life-support systems and services provided by ecosystems to humanity [3,5]. de Groot [6] used the term 'environmental functions' instead of services and, more recently, Daily [18] edited the popular book *Nature's Services*. The field of Ecological Economics developed the concept Natural Capital [62,63] to address non-renewable resources, renewable resources and ecosystem services (the latter two are generated by ecosystems) and to make social scientists and, in particular, economists aware of the significance of ecosystems and their services. Controversy was sparked when Costanza *et al.* [50] attempted to set a dollar value on 17 ecosystem services, evaluated worldwide.

Ecosystem services were adopted as a central concept by the MA [7], which focused on three categories of ecosystem services that directly affect humans (Figure I). Provisioning ecosystem services are the products that humans obtain from ecosystems, such as food, fuel, fiber, fresh water and genetic resources. Regulating services are benefits that humans obtain from natural regulation of ecosystem processes, including maintenance of air quality, climate regulation, erosion control, disease control and water purification. Cultural services are the nonmaterial benefits that humans obtain from ecosystems through spiritual enrichment and educational, recreational and aesthetic experiences. All of these services depend on biodiversity and the processes routinely studied by ecologists, such as primary production and nutrient cycling.

The identification and quantification of ecosystem services is important because many ecosystem services are not apparent to the average person or decision maker. Regulating services are particularly likely to be ignored, even though they are often crucial for the resilience of other ecosystem services. Cultural services are generally known and appreciated, and are often protected by parks or reserves. Provisioning ecosystem services are generally known and often are traded in markets. However, unless the markets are constructed properly, the prices will underestimate the true social value of the ecosystem services [64]. The improvement of markets for ecosystem services is a major area of research in ecological economics as well as innovation in the business world [7]; see for example the Katoomba Group's (http://www.katoombagroup.org/) Ecosystem Marketplace (http://www.ecosystemmarketplace.com/).

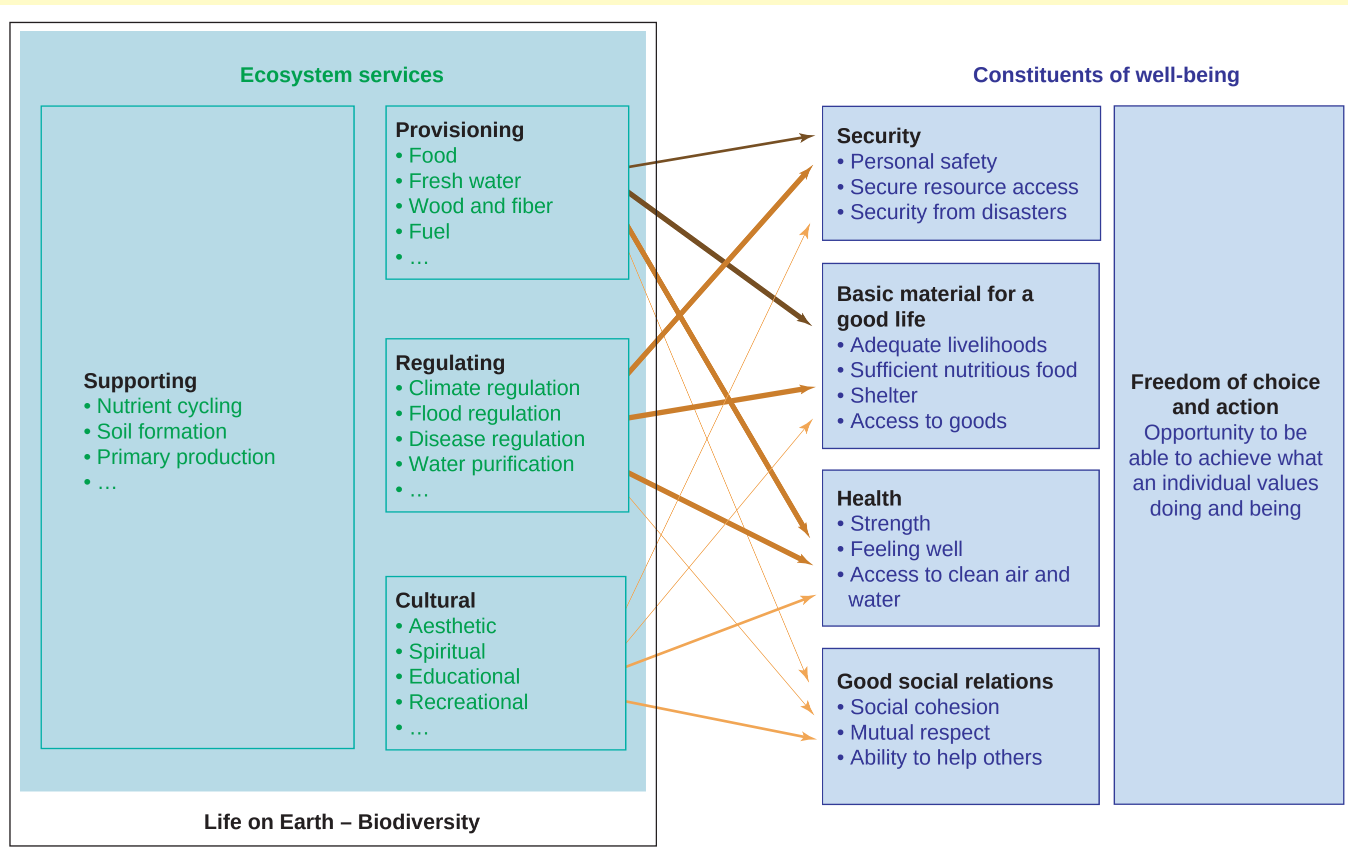

Figure I. Linkages of ecosystem services to human well-being. Arrows depict the connections of ecosystem services to human well-being that were investigated by the MA [28,64]. Arrow width denotes the intensity of the linkage between ecosystem services and human well-being (narrow, weak; mid-width, medium; or wide, strong), and arrow color denotes the potential for mediation by socioeconomic factors (light-brown, low; mid-brown, medium; or dark-brown, high). For example, if it is possible to purchase a substitute for an ecosystem service, then there is high potential for socioeconomic mediation. Reproduced with permission from [7].

agriculture on biodiversity and water quality, for example [9]. Improvements in construction practices and energy technology also offer opportunities to mitigate human-caused environmental change [7]. Most ecosystem services are not marketed, even though economic studies propose that properly constructed markets would support strong conservation measures [7]. Certain institutional and political frameworks, collectively known as adaptive governance [12,13], align property rights of resource users to evoke sustainable use of ecosystem services and appear to be successful in managing ecosystem services [7]. The frameworks also distribute authority among institutions nested across a range of spatial scales, similar to the multiple scales of ecosystem processes [13]. They preserve and use memories of past crises to address present ones, synthesize diverse forms of knowledge (e.g. technical and traditional knowledge), and seek innovative approaches [13]. Diverse ecosystems, culture and

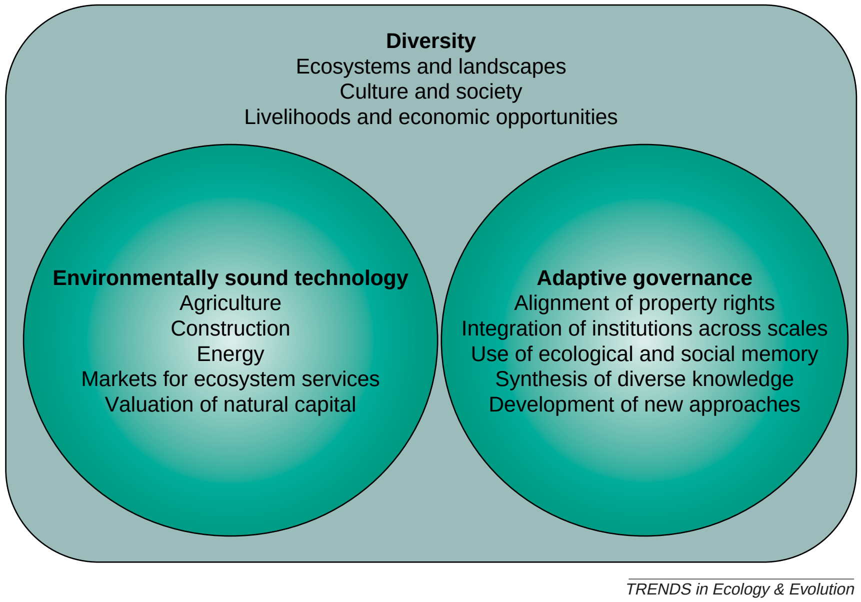

Figure 1. Characteristics of resilient social–ecological systems.

livelihoods seem to be a necessary background condition for environmentally sound technology (including markets) and adaptive governance.

If these characteristics of resilient social–ecological systems could be implemented more widely, the situation could improve, although such a global transformation is an enormous challenge [14]. Here, we offer suggestions for how ecologists can contribute to such a transformation. An expanded role for ecology will require changes in the way that we conduct science as most of the necessary research on ecosystem services involves interdisciplinary collaboration among ecologists and social scientists. To address the condition and future of ecosystem services, ecologists must acknowledge the human dimension of ecosystem dynamics and consider social and economic driving forces and their interaction with changes in ecosystems [15,16].

Improve approaches for assessing ecosystem services

To manage ecosystem services, one must know what they are, as well as their location, abundance, rates of renewal and resilience. The basic science of identifying, quantifying and forecasting ecosystem services is thus an important challenge for interdisciplinary research [16–20]. The need for such information is likely to increase if more ecosystem services are traded in markets. Participants in a market for ecosystem services (e.g. forest products, potable fresh water or sequestration of carbon) must evaluate and verify inventories and supply rates, project future supply and demand, and assess risks. Markets for ecosystem services are therefore likely to increase demand for ecological information and drive improvements in technology for ecosystem measurements.

Assessments of ecosystem services rely on a variety of indicators. Because ecosystems are endlessly changing, indicators focused on static or steady-state behavior are of limited use. Instead, they should represent aspects of change and therefore provide forward-looking perspectives on how ecosystem services might change in the future [20]. As an example, regime shifts in ecosystems can produce large (and often unexpected) changes in ecosystem services [7,21,22], such as the eutrophication of lakes, degradation of rangelands, shifts in fish stocks, breakdown of coral reefs and persistent drought [23]. Indicators that focus narrowly on the flow of the ecosystem service itself (e.g. livestock yields from a rangeland) might miss impending regime shifts (e.g. collapse of grazing owing to replacement of grasses by woody vegetation) [24]. Regime shifts result from crossing thresholds in slowly moving variables, such as soil nutrients or abundance of long-lived species [22,23,25]. Indicators of potential regime shifts must therefore be based on the long-term observation of variables that are sensitive to changes in thresholds; for example, changes in the variance of long-term observations often predict ecosystem regime shifts [26].

Uncertainty is inescapable in assessments of ecosystem services [17,20,27], given that ecosystem dynamics are complex and multicausal, and causes can be remote in space and time from the events that we wish to anticipate [20]. Scientific knowledge of the conditions and trends of ecosystems is far from complete, and ecosystem change has both random and predictable components. Current changes in ecosystems have no historical analog and past changes are, at best, an unreliable guide to the future [8]. Human volition creates uncertainty, because the future is subject to human choices that have not yet been made, and the very process of thinking about the future can affect these choices [28]. Thus, some aspects of future ecosystem services are ambiguous, because their appropriate probability distribution is not known, much less the related parameters [29]. Considerable work is needed on the identification of uncertainties and ambiguities in ecosystem services, on quantifying uncertainties where possible, on communicating this understanding to general audiences. Ecologists must help build an understanding of uncertainty into the governance structures that make ecosystem management possible.

Role of ecology in natural disasters

Ecosystem degradation can exacerbate the human consequences of natural disasters [7]. The role of ecosystem changes, such as wetland loss, deforestation, canalization of rivers and loss of coral reefs, was evident during the 2004 Asian tsunami and the 2005 hurricane in New Orleans, USA [30]. The capacity of ecosystems to mitigate natural hazards such as floods, droughts, storms and tsunamis appears to be decreasing, although there is considerable variability among regions [7].

Whereas some connections of ecosystem change to disasters are evident, we have little quantitative information with which to measure the disaster risks associated with ecosystem change. Fundamental research is needed in this area. Such research could improve planning to avoid or mitigate future disasters, improve quantitative risk assessment, and make it possible to address ecosystem services using insurance markets.

Understand the resilience of ecosystem services

Resilience is the capacity of a system to renew and sustain specified conditions or processes in spite of exogenous disturbances or changes in driving forces [15,31–33]. From its origins in ecology [23,34], resilience has been extended to interdependent social–ecological systems [15,31,32]. Because it is related to the distance of a system from a critical threshold, resilience changes over time and can therefore be managed [31]. In ecosystems, it is often related to slowly-changing biogeochemical pools, long-lived organisms, or biodiversity. In lakes, for example, resilience of water quality to fluctuating phosphorus inputs depends on slow changes in the mass of phosphorus in lake sediment, and resilience of fish production depends on biomass of long-lived, slowly-growing predatory species [22].

Work on biodiversity suggests that the persistence of functional groups of species contributes to the performance of ecosystems and the services that they generate [35]. Functional groups of species and their interactions in the larger landscape or seascape are sources of renewal and reorganization for ecosystem resilience in the face of change [33,35,36]. For example, large trees serve as biological legacies after fires and storms in forest ecosystems [37]. In coral reefs, grazers connect a wide range of spatial scales from cm^2, such as amphipods and sea urchins, to thousands of km^2, such as green turtles [38]. By operating at different spatial and temporal scales, competition among grazers is minimized and the robustness over a wider range of environmental conditions is enhanced. Within a functional group, variability in the responses of species to environmental change appears to be important for ecosystem resilience [39–41]. Such response diversity [38] has a significant role in the capacity of ecosystems to renew and reorganize into desired states following disturbance [23].

We are just beginning to understand the ecological basis of resilience and its connections to ecosystem services (Figure 2). The MA made an important contribution by identifying ecosystem services that regulate climate, floods, diseases, water and air quality, and so on [7]. However, the connections of these regulating ecosystem services to resilience are not well understood. The reliability of ecosystem services appears to depend on

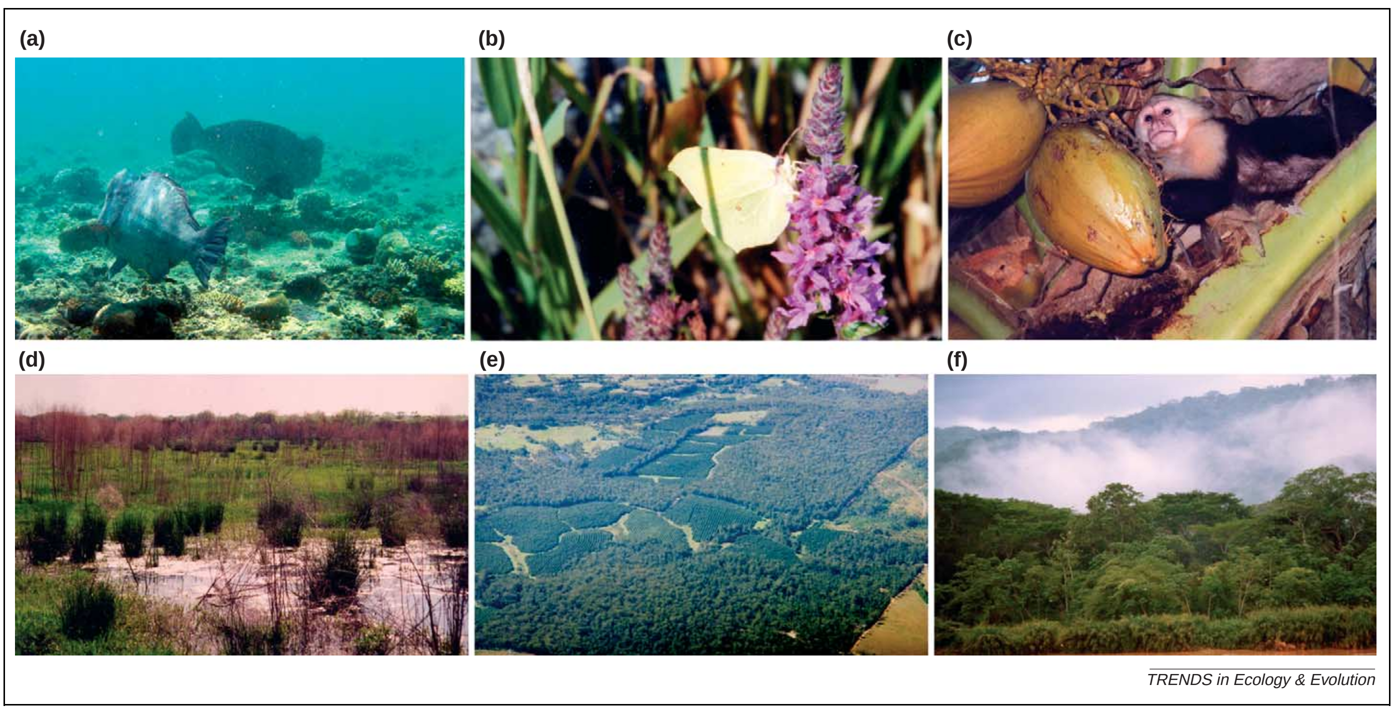

Figure 2. Regulating ecosystem services [6]. **(a)** Grazing fish help keep the substrate accessible for coral recruits; **(b)** pollination by insects supports food production and cultural services of terrestrial ecosystems; **(c)** seed dispersal by mobile link species, such as monkeys, facilitates ecosystem reorganization following disturbance; **(d)** wetlands filter runoff and reduce the influx of nutrients and sediment to lakes, rivers and coastal areas; **(e)** regrowing forests sequester carbon; and **(f)** water vapor from trees contributes to local climate regulation. Reproduced with permission from Terry Hughes (a) and Carl Folke (b–f).

Box 2. Scenarios for future relationships of societies and ecosystems

Scenarios emerged as a planning tool for business, military and strategic applications during the 20th century [28]. Since the 1970s, they have been used for global environmental analyses by groups such as the Stockholm Environment Institute (http://www.sei.se/ [59]) and the Intergovernmental Panel on Climate Change [65]. Scenarios are similar to the modeling approaches used in adaptive management [45] and appear to be used more frequently in local or regional environmental planning [66,67]. As global environmental scenarios became more sophisticated, the demand for detailed ecological information increased [57]. The MA addressed this need for a structured analysis of the future of ecosystem services [7] and policies for proactive management of ecosystem services are the focus of two of the MA scenarios: 'TechnoGarden' and 'Adapting Mosaic' [28].

Adapting Mosaic

Adapting Mosaic considers the consequences of adaptive governance developing in hundreds of autonomous regions around the world (Figure I). Some experiments fail and others succeed, while globalized communication rapidly spreads information about successful practices. There are notable successes in building resilience and improving ecosystem services in many regions. However, these are accompanied by failures in managing some global problems, such as climate and pelagic marine fisheries, and by breakdowns in regions where adaptive experiments fail.

TechnoGarden

TechnoGarden considers a world in which environmentally friendly technologies are used in agriculture, construction and energy, and ecosystems are engineered and intensively managed. Efficiencies improve the delivery of ecosystem services and make it possible to set aside more land and ocean for parks and reserves (Figure I). However, these benefits are accompanied by risks and occasional catastrophes associated with large intricate projects and rigid control of ecosystems. The highly engineered systems provide ecosystem services efficiently, but cannot always cope with unexpected disturbances.

The scenarios explored by MA do not offer an optimal solution. Instead, each illustrates the advantages and disadvantages of a coherent approach to ecosystem services. The logical consequences of alternative sets of policies are explored, thereby providing a basis for discussion and decision among alternative policies and practices for addressing ecosystem services.

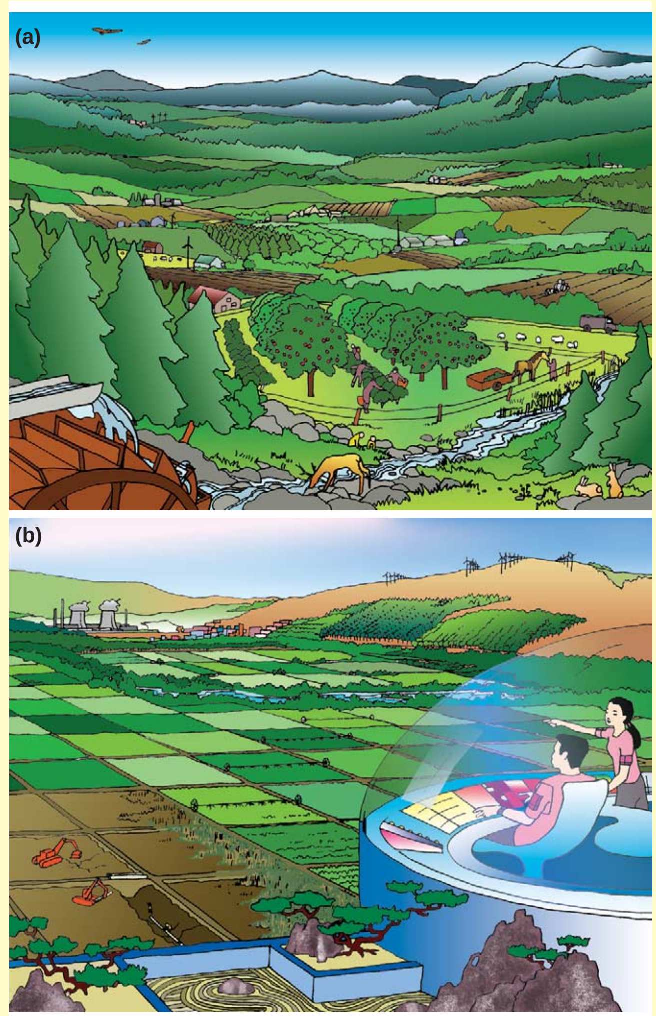

Figure I. Artist's rendition of a rural landscape in the Adapting Mosaic scenario **(a)** and TechnoGarden scenario **(b)**. Reproduced with permission from [28].

resilience, which itself depends on features of ecosystems in complex ways. Elucidating these linkages is an important research challenge.

Contribute to adaptive governance

Because the relationship between ecosystems and society is changing continuously, it is difficult to predict the consequences of management actions; therefore, it is misleading to view ecosystem management as the solution to a problem [42–44]. Instead, management actions should be viewed as experiments that can improve knowledge of social–ecological dynamics if the outcome is monitored and appropriately analyzed [45,46]. Adaptive environmental management (AEM) is a formal process for conducting and interpreting ecosystem management experiments [15,45]. Its success or failure appears to depend on the institutional and political processes that govern the project [46,47]. Because of the key role of governance in ecosystem management, researchers have introduced the concept of adaptive governance to study the structures and processes by which humans make decisions and share power in the process of managing ecosystem services [12,13]. Political scientists [12] use a biological analogy to explain adaptive governance: 'Devising effective governance systems is akin to a coevolutionary arms race. A set of rules created to fit one set of socioecological conditions can erode as social, economic, and technological developments increase the potential for human damage to ecosystems and even to the biosphere itself. Furthermore, humans devise ways of evading governance rules. Thus successful commons governance requires that rules evolve.' In this quote, 'commons' is a broader concept than the open-access resource used in Hardin's parable of the tragedy of the commons [48] and includes common-pool resources such as forests, migrating fish stocks, or irrigation systems [12].

Ecological knowledge is crucial for adaptive governance [12,13]. Ecological insights are required, for example, in measurement of ecosystem services, in the development of proper indicators of the capacity of ecosystems to produce services in the future, and in helping to resolve resource conflicts in efficient, inexpensive ways. However, technocratic approaches in which ecologists do the science first and confront others with already established frameworks are likely to fail [13,49,50]. Adaptive governance expects ecologists to be more than passive providers of information and, in addition, to participate in social processes for ecosystem management [51–53]. For example, ecologists have served as bridges between different social networks, therefore contributing to collaborations that proved crucial for improved management of ecosystems [51,54].

Develop positive visions for the future

There is no lack of information in our current globalized society. Overwhelming information flow makes it difficult for people to grasp the broader situation. Thus there is risk that people, particularly in urban areas (approaching half of the human population [7]), will become alienated from their dependence on ecosystem services. This problem cannot be overcome by more information alone. Instead, we need integrated information in the form of visions for positive change in the approaches of society toward ecosystem services (Box 2).

Such approaches to ecosystem services often seem frozen until a crisis occurs [23,44,46,55], and the perception of that crisis can create opportunities for reorganizing the relationships of society to ecosystems [15,46]. At such times, barriers to action might break down, if only for a short time, and new approaches have a chance to change the direction of ecosystem management. To succeed, a particular approach or vision must be well-formed by the time the crisis arises, because the opportunity for change might be short-lived.

Ecologists can help to create visions for the future that involve new approaches for the relationships between humans and ecosystems [20,50,56,57]. Scenarios with positive visions are quite different from projections of environmental disaster (Box 2). Doom-and-gloom predictions are sometimes needed, and they might sell newspapers, but they do little to inspire people or to evoke proactive forward-looking steps toward a better world. Transformation requires evocative vision of where we can go. In fact, we need multiple visions of better worlds to compare and evaluate the diverse alternatives available to us (e.g. *Ecotopia* [58], *Great Transitions* [59], *TechnoGarden* [28] or *Adapting Mosaic* [28]). Although we cannot predict the future, we have much to decide. Better decisions start from better visions, and such visions need ecological perspectives.

Conclusions

The role of ecology in policy-relevant research is evolving rapidly. Here, we have focused on two exciting and important research areas: innovation of environmentally friendly technology, including markets for ecosystem services, and adaptive governance. In both of these areas, ecological expertise is needed to identify and quantify ecosystem services, to understand how they might change in the future, and to help envision more resilient social–ecological systems. The transformation to more-resilient relationships of society and ecosystems cannot occur without ecological knowledge. This emerging role of ecology will transform the discipline by expanding transdisciplinary collaborations among ecologists, economists and social scientists. Ecological advances have often emerged from collaborations with biogeochemistry, climatology, evolution, genetics, hydrology and other disciplines. Emerging collaborations with economics and social science form one of the most exciting frontiers of research, a frontier that creates fundamental information for the transformation of the relationship of society with nature.

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