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SYNTHESIS & INTEGRATION

Earth Stewardship: science for action to sustain the human-earth system

F. Stuart Chapin, III,[1,†] Mary E. Power,[2] Steward T. A. Pickett,[3] Amy Freitag,[4] Julie A. Reynolds,[5] Robert B. Jackson,[6] David M. Lodge,[7] Clifford Duke,[8] Scott L. Collins,[9] Alison G. Power,[10] and Ann Bartuska[11]

[1]*Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, Alaska 99775 USA*
[2]*Department of Integrative Biology, University of California, Berkeley, California 94720 USA*
[3]*Cary Institute of Ecosystem Studies, Box AB, Millbrook, New York12545 USA*
[4]*Nicholas School of the Environment and Earth Sciences Marine Laboratory, Duke University, Beaufort, North Carolina 28516 USA*
[5]*Department of Biology, Duke University, Durham, North Carolina 27708 USA*
[6]*Nicholas School of the Environment and Department of Biology, Duke University, Durham, North Carolina 27708 USA*
[7]*Environmental Change Initiative, University of Notre Dame, Notre Dame, Indiana 46556 USA*
[8]*Ecological Society of America, 1990 M Street, NW, Suite 700, Washington, D.C. 20036 USA*
[9]*Department of Biology, University of New Mexico, Albuquerque, New Mexico 87131 USA*
[10]*Department of Ecology and Evolutionary Biology, Cornell University, Ithaca, New York 14853 USA*
[11]*U.S. Department of Agriculture, Washington, D.C. 20250 USA*

Citation: Chapin, III, F. S., M. E. Power, S. T. A. Pickett, A. Freitag, J. A. Reynolds, R. B. Jackson, D. M. Lodge, C. Duke, S. L. Collins, A. G. Power, and A. Bartuska. 2011. Earth Stewardship: science for action to sustain the human-earth system. Ecosphere 2(8):art89. doi:10.1890/ES11-00166.1

Abstract. Human activities affect Earth's life support systems so profoundly as to threaten many of the ecological services that are essential to society. To address this challenge, a new science agenda is needed that integrates people with the rest of nature to help chart a more sustainable trajectory for the relationship between society and the biosphere. This paper describes Earth Stewardship, an initiative of the Ecological Society of America to provide the scientific basis for actively shaping trajectories of social-ecological change to enhance ecosystem resilience and human well-being. Principles for moving toward these goals include simultaneous attention to multiple scales and issues; consideration of both ecological and socioeconomic consequences; alignment of incentives with stewardship behavior; strengthening peoples' connections to valued places; and using demographic transitions as new opportunities for stewardship. Past experience provides guidelines for fostering Earth Stewardship. Early attention to sustainable pathways before problems emerge generally provides more cost-effective solutions than attempting to remediate entrenched problems. Defining sustainable pathways by assessing tradeoffs among alternative options requires careful attention to fine-scale processes, interactions, and feedbacks and to larger-scale controls and constraints. Many opportunities occur locally, through development of practices that match the properties of resources with the needs of their users. Substantial challenges remain at larger scales, including maintaining the diversity, productive capacity, and resilience of nature, which are essential for long-term human welfare. The knowledge needed to inform stewardship requires an interdisciplinary science that draws on the observations, skills, and creativity of a wide range of natural and social scientists, practitioners, and civil society. New questions and solutions will emerge when these groups work together to formulate the issues, design the research, and co-produce the observations, knowledge, and concepts that form the basis for solutions. The goal of Earth Stewardship is not to protect nature from people; rather it is to protect nature for human welfare.

Key words: Earth Stewardship; Ecological Society of America; ecosystem resilience; ecosystem services; governance; human well-being; sustainability; worldview.

Received 6 June 2011; revised 14 July 2011; accepted 18 July 2011; **published** 8 August 2011. Corresponding Editor: D. P. C. Peters.

† **E-mail**: terry.chapin@alaska.edu

Introduction

Human activities have altered Earth's life support systems so profoundly as to modify, and often threaten, the ecological services that are essential to society (IPCC 2007, Rockström et al. 2009, Raudsepp-Hearne et al. 2010). A more sustainable trajectory for the relationship between society and the biosphere requires science that integrates human interactions with nature in an Earth-System context (MEA 2005, ICSU 2010, MDG 2010).

This paper describes an Earth Stewardship Initiative that is intended to provide the scientific basis for actively shaping trajectories of social-ecological change. This initiative builds on the Sustainable Biosphere Initiative (SBI), a "call-to-arms for all ecologists" made by the Ecological Society of America (ESA) (Lubchenco et al. 1991). The SBI proposed a research agenda focused on three priorities: global change, biological diversity, and sustainable ecological systems. The SBI called for strengthening the interactions of ecologists with the broader scientific community, as well as with mass media, educational organizations, policy makers, and resource managers to achieve a more sustainable biosphere. Responding to the SBI, ESA established what is now the Science Programs Office to foster policy-relevant science and expanded efforts of the Public Affairs Office to communicate sustainability concerns to ESA members, government, and the public. The SBI and subsequent applications of ecological understanding to societal issues underscored a commitment by many ecologists to make their science relevant to society.

The Earth Stewardship Initiative is a call to ecologists to use the integrative potential of their discipline along with the societal goals of sustainability science to help develop ecologically and societally sound options that enhance ecosystem resilience and human well-being (Box 1) (Power and Chapin 2009, Chapin et al. 2011). Earth Stewardship goes beyond sustainability science (Lubchenco et al. 1991, Clark and Dickson 2003, Matson 2009, Clark and Levin 2010) by articulating the science needed to actively shape trajectories of social-ecological change. This science requires partnerships among experts and practitioners of many disciplines and professions and draws on local knowledge of people who observe and seek ways to mitigate and adapt to social-ecological changes. The Earth Stewardship Initiative contributes to international efforts by the U.N. International Council of Scientific Unions (ICSU) to improve understanding of the Human-Earth System so as to reduce global environmental risks while meeting economic development goals (ICSU 2010, Reid et al. 2010).

Fundamental social-ecological research is essential to identify problems, to understand the processes and interactions that support life, and to solve problems, forecast the future, and meet crucial needs of Earth Stewardship. As Earth Stewardship advances, it should broaden the scope of ecology and integrate it with other sources of knowledge and understanding to stimulate new interactions and collaborations that add to basic research and better guide the actions needed to shape a sustainable future. This paper presents an initial set of goals, a set of principles and processes to move toward these goals, a suite of alternative approaches and visions for implementation, and examples of metrics to assess progress toward goals. This paper is intended for ecologists as a call-to-join-arms with other disciplines in the effort needed to actively shape ecosystem resilience and human well-being of a rapidly changing planet.

A Science of People with Nature

Goals and concepts

The twin goals of Earth Stewardship parallel those of sustainability science—the long-term integrity of the biosphere and human well-being. These mirror the U.N.'s Millennium Develop-

Box 1

Glossary of key terms as used in this paper. Many of these terms differ among disciplines in their definition or are unfamiliar to experts in certain disciplines and practices.

Adaptation: Adjustment by people and other organisms to a change in environment.

Earth Stewardship: Science that facilitates the active shaping of trajectories of social-ecological change to enhance ecosystem resilience and human well-being.

Ecosystem services: The benefits that people receive from ecosystems.

Geoengineering: Intentional management of the global environment to achieve a societal goal.

Governance: Pattern of interaction among people or groups, their sometimes conflicting objectives, and the instruments chosen to steer social and environmental processes within a particular policy arena.

Mitigation: Reduction in the exposure of a system to a stress or hazard.

Natural capital: Nonrenewable and renewable natural resources that support the production of goods and services on which society depends.

Nature: The structure, interactions, and feedbacks among organisms, including people, and their use of resources and interactions with their environment.

Resilience: Flexibility of social-ecological systems to adjust to unforeseen shocks and stresses and to sustain their fundamental function, structure, identity, and feedbacks as a result of recovery or reorganization in a new context.

Service-learning: A form of experiential education in which students engage in, learn from, and critically reflect upon activities that address human and community needs.

Sustainability: Long-term integrity of the biosphere and human well-being.

Well-being: Quality of life; basic material needs for a good life, freedom and choice, good social relations, and personal security.

Worldview: Framework by which a group interprets events and interacts with its social-ecological system.

ment goals, which are broadly accepted by governments throughout the world (Table 1, column 2) (MDG 2010). They also reflect the stewardship principles of the world's major religions (Table 1, column 3) (Lodge and Hamlin 2006, Kearns and Keller 2007), including those of many indigenous peoples (Berkes 2008), and therefore resonate with the moral views of broad segments of society. Specific goals (Table 1, column 1) will continue to evolve as collaborations develop and understanding evolves. The challenge comes in improving the understanding of the interdependence of human welfare with the capacity of ecosystems to provide goods and services essential to human thriving (MEA 2005, Raudsepp-Hearne et al. 2010, Reid et al. 2010). Without a full understanding of this interdependence, human welfare and conservation of nature often appear to compete with one another (Kareiva et al. 2008). If that were the case, it might be reasonable to give priority to human welfare. However, with increased understanding of the interdependence of people and the rest of nature, trade-offs that appear at first to exist can often be better managed, and win-win situations are more likely to emerge (Rosenzweig 2003, Lodge and Hamlin 2006, Power 2010).

People and nature have always been intertwined—people receive many services from ecosystems, and society, in turn, affects ecosystems, sometimes severely (Daily 1997, MEA 2005). How can human well-being and societies flourish, while reducing and remediating environmental degradation (Walker et al. 2009, Raudsepp-Hearne et al. 2010)? People's immediate desires often take precedence over their long-term needs, leading to unsustainable interactions with ecosystems (Speth 2008, WRI 2010). Stew-

Table 1. Goals and principles of Earth Stewardship, Millennium Development, and the Earth Charter. Earth Stewardship goals are a work in progress that will evolve as new collaborations develop and understanding emerges.

Earth Stewardship Goals	Millennium Development Goals†	Earth Charter Principles†,‡
Ensure equitable access to the basic needs for a good life (e.g., food, clean water, and health care) across countries, segments of society, and genders	1. Eradicate extreme poverty and hunger; 4. Reduce child mortality; 5. Improve maternal health 6. Combat AIDS/HIV, malaria, and other diseases	9. Eradicate poverty and hunger and reduce preventable diseases; 12. Eliminate discrimination, with special attention to the rights of indigenous people and minorities
Provide equitable access to opportunities for self-realization and for social and environmental stewardship	3. Promote gender equality and empower women	11. Affirm gender equality and empower women; 3. Build democratic societies that are just, participatory, sustainable, and peaceful; 13. Strengthen democratic institutions and access to justice; 16. Promote a culture of tolerance and peace
Reduce unnecessary consumption and close loops on energy and material cycling		7. Reduce unnecessary consumption and pursue quality of life
Foster an ethic of environmental citizenship built on sense of place and pride in cultural identity		2. Responsible citizenship for welfare of all people and the earth; 15. Treat all living beings with respect
Sustain social-ecological systems and the delivery of ecosystem services now and for future generations	7. Ensure environmental sustainability	4. Sustain resources, culture, and traditions for future generations; 5. Prevent environmental damage; 6. Protect and restore ecological integrity
Foster biological, cultural, and institutional diversity to maintain a diversity of options		1. Respect for human and biological diversity
Advance the study of sustainability through scientific, local, and traditional knowledge		8. Advance the study of sustainability through scientific, local, and traditional knowledge
Provide education for all, including education and outreach for sustainability	2. Achieve universal primary education	14. Provide education for all, including education and outreach for sustainability
Ensure equitable and sustainable economic activities and institutions	8. Develop a global partnership for development	10. Ensure equitable and sustainable economic activities and institutions

† Numbers refer to the numbered statements in the Millennium Development (MDG 2010) and Earth Charter (Earth Charter 2009) documents from which these points are paraphrased.

‡ Paraphrased from the Earth Charter. Each Earth Charter principle is cross-cutting, so this paraphrasing is only a rough approximation of the intent and breadth of the fully articulated principles (Earth Charter 2009).

ardship entails a more rational long-term view by people of their place in nature and therefore the ways in which they manage and otherwise interact with ecosystems (Head 2000)—"to watch and understand the land and use it respectfully forever" in the words of Canadian First Nations people (⟨http://www.nwtcimp.ca/⟩).

Meeting human needs without environmental degradation is more likely to occur when a broad spectrum of ecosystem services are sustained (Daily 1997, MEA 2005). These include the harvest of water, food, and fuel; the interactions among ecosystems that regulate water quality, climate, and spread of disturbance and disease; and the non-material spiritual, aesthetic, and cultural benefits that cause people to value nature and life. Human welfare is not in competition with nature; instead human welfare depends on nature. For example, 53% of surface-derived drinking water in the U.S. flows from forests, linking healthy, resilient forests to supplies of clean water (Brown et al. 2008).

Given the checkered history of past efforts to shape ecosystems, Earth Stewardship requires humility about the state of human knowledge, acknowledging the uncertainty of potential outcomes. Nonetheless, the widespread deterioration of many ecosystem services (MEA 2005) warrants cautious but proactive efforts to move toward more sustainable trajectories, learning adaptively from our successes and failures (Carpenter et al. 2009, Hobbs et al. 2011).

Box 2

Principles to enhance Earth Stewardship. These and other principles can be integrated in various combinations to foster stewardship, depending on social and political context.

1. Global problems require solutions at multiple scales.
2. Durable solutions must address interactions among multiple issues rather than focusing narrowly on a single sector or problem.
3. Aligning incentives with solutions motivates stewardship.
4. Decision-making that fosters stewardship must be compatible with both the ecology of the resources and the socioeconomic and cultural characteristics of associated human communities.
5. Sense of place, including local concern for aesthetic, cultural, and spiritual dimensions of ecosystems, is a valuable ecosystem service.
6. Some global changes, such as the demographic shift to cities, provide unprecedented stewardship challenges and opportunities.

Stewardship requires effective governance at scales ranging from individuals to the globe. People have historically interacted with nature most directly at local scales, providing opportunities to learn from the consequences of their actions (Ostrom 1990, 2009). However, the large-scale environmental changes resulting from widespread *unsustainable* behavior indicate a need for a human-Earth-system perspective that informs governance at local-to-global scales to foster learning and sustainable behavior (Ostrom 2005, 2010).

Principles for Earth Stewardship

Past efforts to foster sustainability show that Earth Stewardship is feasible but often is not achieved. We identify and illustrate six principles that can be integrated in various combinations and scales to foster stewardship opportunities (Box 2). The usefulness and effectiveness of each of these and other implementation principles depends on political realities and cultural and social context (Robbins 2004).

Global problems require solutions at multiple scales. Complex global problems such as climate disruption are difficult to address because existing institutions provide, at best, only partial solutions (Walker et al. 2009). Both the causes of problems and opportunities for progress occur at many spatial scales. Emissions of greenhouse gases, for example, are broadly embedded in the global economy, requiring global solutions. However, the actions of international institutions are often undermined by nations acting in their own self-interest. Incentive schemes that benefit participating nations are most likely to be successful (Walker et al. 2009). In addition, many sectors of government, industry, and civil society do not perceive the strong connection between climate change and their own well-being (Allen et al. 2009). International and national assessments provide the scientific basis for understanding these connections (IPCC 2007), and there is increased awareness of ways this information can be communicated more effectively to stakeholders (APA 2010, NRC 2010). In the U.S., which has failed to approve strong international accords for climate regulation, greatest progress has been made at local-to-regional scales. For example, the Regional Greenhouse Gas Initiative involves ten northeastern states in an effort to reduce power sector CO_2 emissions (⟨www.rggi.org⟩), and the Western Climate Initiative brings together seven western states and four Canadian provinces developing a variety of policies to reduce greenhouse gas emissions (⟨www.westernclimateinitiative.org⟩).

Durable solutions must address interactions among multiple issues rather than focusing narrowly on a single sector or problem. Single-issue management strategies focused on a single location or scale often have unintended and

Fig. 1. The Chicago Sanitary and Ship Canal, which links the Mississippi River and Great Lakes-St. Lawrence River watersheds. The canal, whose original purpose was to shunt Chicago's sewage from Lake Michigan to the Mississippi River watershed, now also supports commercial and recreational navigation, and allows dispersal of non-native species between the watersheds (Photo by Lindsay Chadderton, The Nature Conservancy).

irreversible consequences and costs (Rodríguez et al. 2006). Earth Stewardship needs are often the result of previous unsustainable human-environment interactions. In the 19th century, for example, a concentration of political power in Chicago enabled its leaders to build a canal that flushed sewage downriver toward St. Louis, providing Chicago with services of water quality, waste disposal, and improved water transport routes at the expense of downstream degradation of water quality, fisheries, wildlife, and human health (Hill 2000). In recent decades, improvements in water quality have mitigated much of this downstream damage, but have also facilitated the dispersal of invasive aquatic species between the Mississippi and the Great Lakes watersheds (Fig. 1; Jerde et al. 2011). Narrowly focused efforts to mitigate dispersal of these invasive species have had limited success at the cost of millions of dollars. However, the shortcomings of past decision-making have been recognized (City of Chicago 2003). Currently, two complementary efforts are analyzing how to solve the invasive species problem with as little disruption as possible and perhaps improvement in other ecosystem services. Both the U.S. Army Corps of Engineers (⟨http://glmris.anl.gov/⟩) and a foundation-funded effort led by the Great Lakes Commission and the Great Lakes and St. Lawrence Cities Initiative (⟨http://glc.org/ans/chicagowaterway.html⟩) are analyzing how the risk of biological invasions can be reduced while also protecting the value of waterway transportation, water quality, flood control, tourism, and recreational benefits. This alternative framework that more completely reflects costs, benefits, and tradeoffs among a full suite of ecosystem services at multiple spatial scales is far more likely than single-issue management to facilitate durable solutions that maximize ecosystem services and human welfare.

Aligning incentives with solutions motivates stewardship. The U.S. has a long history of incentivizing environmental stewardship. Valuation of ecosystem services allows policy-makers to offer incentives to land owners such as farmers for providing these services. Following the Dust Bowl of the 1930s, for example, soil conservation policies in the U.S. paid farmers to reduce soil erosion and maintain the navigability of rivers (Fig. 2). In this case, farmers benefited from direct payments in the short-term and from increased soil quantity and quality in the long term. Some ecosystem services are less easily quantified and valued, however, and in many cases the individuals that control the supply of the services are not the beneficiaries of the services. Valuation requires measuring the provision of the ecosystem

Fig. 2. Following the 1930s dustbowl, shown here in Texas in 1935 (left, historical photo courtesy of NOAA), farmers responded to incentives from the U.S. Soil Conservation Service by adopting practices to reduce soil erosion, like strip cropping on the contour (right), shown here in Iowa in 1999 (Photo by Tim McCabe, courtesy of USDA Natural Resources Conservation Service).

service, determining the market or non-market value of the service, and designing policy to manage the service (Polasky 2008). Some of the best examples of quantification of ecosystem services come from agriculture. Ecosystem services that increase agricultural productivity, such as pollination or biological control of pests, have been measured and valued in a number of systems. Pollinators moving into coffee plantations from forest fragments in a Costa Rican landscape, for example, significantly increased yields and quality of coffee (Ricketts et al. 2004). Natural pest control provides an estimated savings of $13.6 billion/yr in U.S. crops (Losey and Vaughan 2006). These examples illustrate the value of policies that conserve natural ecosystems in agricultural landscapes.

Decision-making that fosters stewardship must be compatible with both the ecology of the resources and the socioeconomic and cultural characteristics of associated human communities. Sustainable ecosystem management often requires decisions at multiple spatial scales (Sanchirico and Wilen 2005). National-level fisheries policy, for example, may empower community-based management that uses fine-scale ecological knowledge to respond to economic priorities at national or international levels (Fig. 3; Cudney-Bueno and Basurto 2009). Strong institutions at higher levels can facilitate adaptation to ecological conditions and social concerns at finer scales, while maintaining trust and stability (Basurto and Coleman 2010). Modeling suggests that fishery management decisions that allow fishers to harvest a variety of fish (a portfolio approach) from an ecosystem could have increased revenue and reduced variance in the Chesapeake Bay (Sanchirico et al. 2008). Matching the scale and adaptability of decision-making to the ecological and social dynamics will be critical to successful future management of ecosystem services.

Sense of place, including local concern for aesthetic, cultural, and spiritual dimensions of ecosystems, is a valuable ecosystem service. Sometimes, the grassroots support needed for environmental protection emerges when a community's sense of place is threatened (Windsor and McVey 2005). In the late 19th century, coal companies built towns in the Appalachian Mountains to house miners when it became apparent that power from coal would fuel major U.S. development. Many communities have persisted through evolving mining methods, each with increasing environmental impacts, as ecological services were traded for electricity,

Fig. 3. A fleet of fishing boats from the pen-shell fishery in Baja California, Mexico. This fishery is sustained by a high degree of community management enabled by legislation at the federal level (Photo by Xavier Basurto).

creating some of the biggest environmental injustices in history (McGinley 2004). Communities living near mountaintop removal sites today are deprived of clean drinking water as well as the mountain ecosystems that shape their identity (Fig. 4; Palmer et al. 2010). In this case, unusual stakeholder partnerships in Appalachian communities have paired environmentalists with religious groups and artists to protect the mountain ecosystem and save historic communities (Adriance et al. 2010). As a result of cases such as this, sense of place has been suggested as a measure of community sustainability (Stedman 1999).

Some global changes, such as the demographic shift to cities, provide unprecedented stewardship challenges and opportunities (Bettencourt et al. 2007). Protecting natural ecosystems in densely populated regions can guide urbanization in ways that support livelihoods and nature. Management of the New Jersey pinelands illustrates a partnership at local-to-national levels to conserve natural resources, while allowing regional development. The pinelands are a complex of low-nutrient, fire-prone ecosystems that harbor many rare and endangered species, are sensitive to eutrophication, and are threatened by groundwater extraction. Agricultural and urban development exceeding 10% of the pinelands area significantly degrades water quality (Zampella et al. 2007). Its lowlands have supported a relatively sustainable cranberry agriculture since the early 20th century (Fig. 5). The pinelands occupy a rapidly urbanizing corridor between New York and Philadelphia. This creates pressures for development and corresponding tradeoffs with traditional agriculture and conservation. In the 1970s, a rise in environmentalism at local-to-national scales and leadership by Brendan Byrne, an environmentally aware governor, led to the creation of a Pinelands Commission with ultimate authority over development decisions. Pineland municipalities supported the concept because they valued critical ecosystem services, including water quality, fire regulation, and quality of life, more than the additional tax base lost by constraining development. Scientifically based constraints on development also prevented a rise in property taxes, likely preserving cranberry agriculture and the livelihoods of economically disadvantaged people. Designation as a Biosphere Reserve by the International Union for the Conservation of Nature (IUCN) raised the visibility and long-term commitment by municipal, state, and national government to this

Fig. 4. Mountaintop removal site in Lincoln County, West Virginia after a year and a half of mining. The dramatic shift in landscape removes local citizens' sense of place defined by the Appalachian mountain forest ecosystem (Photo by Vivian Stockman, ⟨www.ohvec.org⟩, courtesy of SouthWings.org). Also shown are a natural ephemeral stream (left) and one created to replace it (Photos by Margaret Palmer).

regional management scheme. Analysis of land-use change in the Pine Barrens from 1979 to 1991 was consistent with land-use designations, demonstrating that the plan is working (Bunnell et al. 2003). Thus, protection of significant ecological, agricultural, scenic, and cultural resources in the pinelands region has fostered environmentally responsible suburban development in this section of the New York-Philadelphia urban corridor (⟨http://www.state.nj.us/pinelands/index.shtml⟩).

These case studies illustrate implementation principles and strategies that enhance opportunities for stewardship (Box 2). Early attention to sustainable pathways before problems emerge generally provides more cost-effective and less dire solutions than attempting to remediate

Fig. 5. Cranberries ready for harvest in a commercial cranberry bog in the New Jersey Pine Barrens. A partnership between federal, state and local jurisdictions governs land-use and protects historical agricultural practices throughout the region. Studies show that cranberry agriculture has little impact on streamflow and channel morphology in the Pinelands (Procopio 2010; Photo by John Bunnell).

entrenched problems. However, assessing the costs, benefits, and tradeoffs of alternative options in the face of uncertainty is challenging and requires careful attention to fine-scale processes, interactions, and feedbacks and to larger-scale controls and constraints. It also requires attention to the long-term consequences for people and nature framed in the political realities of the present (Leung et al. 2002, Yung et al. 2003). Some of the greatest challenges occur at large scales, where people, groups, and governments are less directly confronted by the consequences of unsustainable actions (Walker et al. 2009, Ostrom 2010). Unmet challenges include maintaining the diversity, productive capacity, and resilience of Earth's life support system, while meeting the needs of people in an equitable fashion.

Approaches to Earth Stewardship

Earth Stewardship requires a new cutting-edge science that blends disciplinary traditions, diverse ways of knowing, and new ways to identify scientific priorities (Palmer et al. 2005, Miller et al. 2008). Full engagement is most likely to emerge from collaborations that, from the beginning, engage all participants in conceiving the questions, designing the science, and participating in the research (Haberl et al. 2006, Miller et al. 2008, Collins et al. 2010). Research questions, if formulated together, are more likely to meet community needs, aid practitioners, and advance a comprehensive understanding of the linkages between nature and human welfare (Miller et al. 2008). New types of collaborations often reveal mismatched disciplinary norms, including desired outcomes, publication strategies, credit for work during the academic tenure process, philosophy of humans' role in conservation, jargon, foundation literature, funding sources, and power dynamics within the group. When these issues arise, a plan should be made to equitably merge these norms (Campbell 2005). Furthermore, new research methodologies and venues need to be explored to make interdisciplinary collaborations more enjoyable and effective (Rhoten 2003, Palmer et al. 2005).

Just as Earth Stewardship research must engage many academic disciplines, it should be informed by engaging those segments of civil society that are directly confronted by environmental and socioeconomic changes (Lubchenco 1998). Community-Based Research (CBR) (Cornwall and Jewkes 1995) is change-oriented research that engages local people in all stages of the research process, from selecting the questions and the research agenda to analyzing and interpreting data (Strand et al. 2003). Rather than a traditional model where "the community" is viewed as the source of problems and "the university" as the source of solutions, CBR democratizes both the creation and dissemination of knowledge. This bottom-up approach is more likely to engage diverse peoples in addressing ecological issues and to yield practical solutions appropriate for local communities. When done well, this approach strengthens both the interdisciplinary science and the sense of community that grow out of the partnership. Public concern about the deteriorating conditions of Chesapeake Bay, as one of many examples, has led to citizen science that documents sources of pollutants, engages students in environmental monitoring, and facilitates an open dialogue with decision makers about potential solutions (⟨http://www.nationalgeographic.com/field/projects/cbfieldscope.html⟩).

Human actions are strongly influenced by the perceptions and values that are embedded in worldviews. CBR strengthens the applicability of Earth Stewardship science by incorporating a broader range of worldviews into research design and data analysis. This connection is well recognized in studies of traditional cultures (Agrawal 1995) but is equally relevant to understanding climate-change perceptions across the U.S. political spectrum (Leiserowitz and Smith 2010) and distinctions between environmental and business perspectives of sustainability (Whiteman et al. 2004, Epstein 2008). Diversity in beliefs and experiences leads to different types of questions that may broaden the types of social-ecological information collected. In addition, the research results tend to be better accepted because the process breaks down the divide between a scientific authority and the community (Jasanoff 2004).

Earth Stewardship requires a change in academic culture to reward research that promotes interdisciplinarity and the greater good (Palmer et al. 2005, Limerick 2008, Taylor 2009) as well as the conventional measures of research productivity. This is particularly important in harnessing the enthusiasm and energy of graduate students and early-career professionals who will play critical roles in shaping and leading this new science both within and outside of academia. Professional societies such as ESA should leverage highly visible "calls to action" such as the Boyer report (Boyer Commission 1998) to push for increased institutional support for civically engaged research and teaching, including pedagogies of engagement such as service-learning (Peterson 2009). Such institutional support significantly increases the likelihood that faculty members will use their scholarship to address local community needs by working *with* communities rather than *in* communities (Taylor 2009, Reynolds and Ahern-Dodson 2010, Vogelgesang et al. 2010). Some universities have already begun to rethink the requirements for promotion and tenure, recognizing and valuing faculty who are civically engaged within a broader community (Brustein 2007).

Visions for Change

Defining the science necessary to chart a sustainable future is challenging. Stakeholders often differ in their vision of a desirable future, and the pathway to implementing any desired vision depends on context and scale. Nonetheless, several general paradigms (or visions) can be articulated that provide opportunities for inputs from multiple disciplinary and stakeholder perspectives to imagine broad categories of sustainable futures. We briefly summarize three paradigms, some of which are based on those developed by the Millennium Ecosystem Assessment (Carpenter et al. 2006), as a starting point for designing an Earth Stewardship research agenda.

An *economic development paradigm* seeks to identify the economic values of a broad spectrum of ecosystem services so that their benefits can be specified and compared when considering tradeoffs among alternative policies or actions. This requires improved understanding of the mechanisms by which the multiple dimensions of natural capital, e.g., soil fertility and species diversity, contribute to delivery of ecosystem services and to processes that degrade or enhance critical components of natural capital

(Daily et al. 2009). Over the long term, Earth Stewardship requires sustaining or enhancing the capacity of regional systems to deliver ecosystem services so that future generations have the opportunity to meet their needs (WCED 1987, Arrow et al. 2004, Chapin et al. 2009). Improved understanding is needed because many ecosystem services that could be monetized have not been, and those that cannot be monetized require non-monetary valuation mechanisms, both of which present obvious research opportunities (Swinton et al. 2007). Furthermore, stakeholders often differ in their assignment of values to those aesthetic, spiritual, and cultural services that are not readily monetized, and different factors shape changes in these values (Yung et al. 2003, Ardoin 2006). For example, how might sense of place and environmental citizenship be enhanced for people who have recently moved from rural areas to the city? Finally, we need to know much more about factors controlling the response of natural capital and ecosystem services to human actions and the tradeoffs associated with restoring those services that have been degraded (Raudsepp-Hearne et al. 2010).

A *technology paradigm* seeks to accelerate technological and design innovation for sustainability. This includes win-win technologies such as cover crops that enhance plant and microbial assimilation of nitrogen and reduce standing pools of nitrate (Drinkwater and Snapp 2007) or fertilizer additions that are carefully matched to crop nutrient demand (Vitousek et al. 2009), so as to reduce nutrient loss to aquatic ecosystems and to the atmosphere. Similarly, on-farm management practices that target "green water" (rainfall stored in soil moisture), such as modifying the tillage regime or mulching to reduce soil evaporation, can help mitigate predicted impacts of climate change on crop production (Rost et al. 2009). Design innovation includes intentional management of natural enemies as biological control to regulate the spread of pests and pathogens, and agroecology to design agricultural ecosystems and landscapes that sustain a broad suite of ecosystem services (Tscharntke et al. 2005, Landis et al. 2008, Gardiner et al. 2009, Power 2010). A design perspective also motivates research on ecological restoration and remediation to foster recovery in response to past disturbances (Hobbs and Cramer 2008) as well as more controversial conservation strategies such as assisted migration to conserve species threatened by changes in climate and land use (McLachlan et al. 2007, Thomas 2011).

At the extreme end of the spectrum for the technology paradigm are approaches that require global planetary management. Geoengineering to cool the planet in the face of climate change is one such example, with many of its direct and indirect effects and long-term consequences still uncertain (Royal Society 2009). Ignoring for the moment feasibility of these approaches, geoengineering through stratospheric dust seeding to cool the Earth by blocking solar radiation would require centuries-long management (Victor et al. 2009). An interruption of continuous dust seeding would cause extreme climate change within a year and likely be far more damaging to species and society than gradual climate change. It seems unlikely that people, as a global society, can "manage" climate collectively for centuries– maintaining a consensus across national boundaries through war, changes in government, and social and economic upheavals. Geoengineering to cool the Earth by removing carbon dioxide from air by planting trees, building industrial facilities (Jackson and Salzman 2010), or deep-ocean sequestration (Schrag 2009) can be tested and assessed at smaller scales but would require massive programs to offset current emission rates. Are we prepared to alter ocean productivity over a large enough scale to store billions of tons of carbon in ocean sediments?

An *adapting mosaic paradigm* seeks to enhance resilience, i.e., the flexibility of social-ecological systems to adjust to unforeseen shocks and stresses. This paradigm recognizes the uncertainty of future changes and social-ecological responses and seeks to maintain a diversity of future options rather than targeting specific outcomes. A diversity of species, landscapes, and cultures, for example, frequently contribute to resilience (Tilman et al. 1997, Chapin et al. 2000), although the underlying mechanisms and processes are too poorly known to be broadly predictive. Similarly, a suite of social processes and structures, including social innovation, bridging networks, and adaptive governance (Folke et al. 2005, Westley et al. 2006), provide guidelines for human dimensions of resilience

(Kenward et al. 2011).

These paradigms and visions are not mutually exclusive, and none is universally "best." Instead, each paradigm will likely be essential, with local context dictating the approach or combination of approaches that is most likely to sustain ecosystem resilience and human well-being. Management goals for local or regional social-ecological systems can be controversial, but in many cases they are not. All of the citizens of the arid and semi-arid portions of the western U.S. would prefer more water availability to sustain ground water and river flow through the prolonged summer drought, less risk of catastrophic fires, better public health, and more fulfilling lives for residents of their regions. Many northern Californians of diverse ethnic heritage would prefer that their communities remain embedded in the majestic forests that once cloaked the Coast Range and Klamath Mountains—redwoods are as iconic as salmon in these regions. It is becoming clear, however, that this region, as elsewhere in the American west, has been rendered brittle (Walker and Salt 2006) by clear-cut forestry followed by regional fire suppression. The relationship between the state of the forests, artificial regulation of river flows, and the widely shared goals of fire control, public health, cultural benefits, and prolonged stream flow through drought are emerging and could be further clarified with interdisciplinary research and informed policy decisions.

Assessment of Progress

Implementation of Earth Stewardship requires a clear articulation of public values, such as sustainability, that describe societal goals (Bozeman and Sarewitz 2011) and quantifiable metrics to assess progress toward those goals (Table 2). These metrics vary with scale but share common components such as quantifiable improvements in ecosystem services and improved access to these services. Environmental stewardship has both ecological and human dimensions. In general, then, an Earth Stewardship perspective requires metrics that are more integrative of human welfare than those traditionally used by ecologists. Ideal metrics would capture the net outcome, considering all ecosystem services, of management decisions or policy frameworks that require trade-offs among ecosystem services.

The Millennium Development Goals provide a good example of ambitious goal-setting and metric-based assessments of progress. The eight goals (Table 1, column 2), which have a target "completion" date of 2015, have been accepted by almost 200 nation-states. One goal, to "Ensure Environmental Sustainability," includes plans to reduce biodiversity loss and to halve the proportion of the population without access to safe drinking water and basic sanitation, but begs for a metric that accounts for trade-offs in water management for different ecosystem services (Jackson et al. 2005, Lodge 2010). Reduced rates of deforestation and the proportion of species threatened with extinction are two of many metrics that are used as benchmarks for success. As a positive sign of improvement, the official rate of tropical forest clearing in Brazil in 2009 was the lowest rate since the government started monitoring deforestation in 1988.

Social-ecological milestones, and measurements that tell us whether we are progressing towards or away from our goals, are clearest when we agree on the desired states for particular ecosystems. Globally, the goal of restoring the concentration of CO_2 in Earth's atmosphere to 350 ppm has gained worldwide traction from citizens of 181 nations (⟨http://www.350.org⟩). How to accomplish this and over what timescale it might be feasible remain highly problematic (Solomon et al. 2009).

Conclusions

Despite the enormity of the challenge, past experience provides guidelines for progress toward Earth Stewardship, i.e., to develop ecologically and societally sound options that enhance ecosystem resilience and human well-being. Given the inherent uncertainty and current rapid changes in the Human-Earth System, there is no simple formula to enhance Earth Stewardship. Instead, multiple principles and approaches must be employed. For example, potential solutions should consider multiple problems and sectors simultaneously through institutions at many scales rather than addressing each problem separately without attention to unintended side effects. Aligning incentives with stewardship behavior of individuals, groups,

Table 2. Examples of studies that provide metrics to document progress toward or away from stewardship goals. Stewardship goals are from Table 1.

Social-Ecological System	Stewardship Goal	Metric	Reference
Sustainable development projects	Ensure equitable access to the basic needs for a good life	Poverty reduction; biodiversity increase; area protected for conservation	Goldman et al. 2008, Tallis et al. 2008
New Jersey Pinelands	Provide equitable access to opportunities for self-realization and for social and environmental stewardship	Range of household incomes; range of occupations; local conservation engagement; area of rural livelihoods and conservation easements	This paper
Cities	Reduce unnecessary consumption and close loops on energy and material cycling	Reduced thermal and CO_2 emissions (soon detectable by satellite); use of organic wastes for fuel	Murphy and McKoegh 2004, Pahl 2007
Native American communities in ancestral lands	Foster an ethic of environmental citizenship built on sense-of-place and pride in cultural identity	Increased human health and general well-being by engaging in outdoor stewardship and harvest of traditional foods and other cultural resources	Berkes et al. 2000, 2009, Lake et al. 2010
Southwestern short-grass prairie ranches	Sustain social-ecological systems and the delivery of ecosystem services now and for future generations	Increase cover by native short-grass prairie and associated biotic diversity; reintroduction of fire as a management tool; conservation easements that prevent ranch conversion to developments	Sayre 2005
Urban neighborhoods	Foster biological, cultural, and institutional diversity to maintain a diversity of options	Numbers of neighborhoods with organized plans and local resources (equipment, emergency medical training, planned evacuation routes)	Ebi et al. 2004
Farm	Advance the study of sustainability through scientific, local, and traditional knowledge	Reduced nutrient leaching to ground and surface water; reduced aerial emissions of nitrogen gases from fertilized fields; reduced pesticide impacts on beneficial organisms; increased soil carbon	Lal 2008, Matson 2009
Chesapeake Bay	Provide education for all, including education and outreach for sustainability	Number of citizen science projects; funding for projects to reduce nutrient inputs	This paper
Ocean fisheries in vicinity of marine protected areas	Ensure equitable and sustainable economic activities and institutions	Increasing catches over prolonged (5–10 yr) time, particularly near protected reserves	Kaplan et al. 2009

businesses, and nations facilitates this process. Given the interdependence of people and ecosystems, potential solutions must be consistent with the properties of both ecological and social dimensions of a system, including peoples' concerns for aesthetic, cultural, and spiritual dimensions of valued places. Stewardship should be forward-looking: Many recent trends, such as demographic transitions from rural to urban areas, provide opportunities for novel ways to enhance human well-being, while maintaining or enhancing ecosystem resilience.

The knowledge needed to inform stewardship requires science that integrates people with the rest of nature and draws on the observations and skills of a wide range of natural and social scientists, practitioners, and civil society. In some cases, such as the U.S. National Environmental Policy Act, much of the policy framework is in place to implement this science. Earth Stewardship is a call-to-arms for ecologists to forge collaborations with other experts, practitioners, and the public. The following areas appear particularly promising as collaborations to develop the interdisciplinary science that must eventually be integrated in support of Earth Stewardship:

1. The mismatch between what "is" and what "ought to be" often reflects differences in core values and power relationships among stakeholder groups (Robbins 2004, Lodge and Hamlin 2006, Bozeman and Sarewitz 2011). Aligning goals with application requires open and iterative sharing of evidence and discussion among experts and stakeholders as well as continual assessment of progress.
2. People are social beings who generally conform to the norms of groups with whom they identify. Research on the origin, maintenance, and spread of norms that either foster or erode stewardship behavior could inform strategies to strengthen citizenship for environmental and social justice. This requires input from social psychologists, sociologists, and others.
3. The relation between people and their environment is governed by a broad array of rules, ranging from formal laws to informal norms that govern human behavior (Ostrom 2005). Feedbacks between human institutions and the ecosystem services that people want must be better understood (Raudsepp-Hearne et al. 2010, Horan et al. 2011). Careful institutional analysis would improve understanding of current behavior and decision-making around the environment and could define conditions and incentives that would foster a more forward-looking and problem-solving ethic of Earth Stewardship (Walker et al. 2009). This requires input from political scientists, geographers, economists, and others.
4. Some of the greatest insights for patterns and practices that foster sustainable solutions come from practitioners with experience in resource management and urban and regional design. Engagement of resource managers, city and regional planners, and other practitioners will facilitate the solution-focused approaches needed for Earth Stewardship.

Earth Stewardship is *the* central challenge facing society in the 21st century and beyond. Addressing it will require innovation that draws on the hearts and minds of people from a wide range of disciplines and practices. Such innovation and integration can drive the success of Earth Stewardship for generations to come.

Acknowledgments

We thank the Center on Global Change and Nicholas School of the Environment at Duke University for supporting the workshop that initiated this article.

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