# Top 40 Priorities for Science to Inform US Conservation and Management Policy

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*To maximize the utility of research to decisionmaking, especially given limited financial resources, scientists must set priorities for their efforts. We present a list of the top 40 high-priority, multidisciplinary research questions directed toward informing some of the most important current and future decisions about management of species, communities, and ecological processes in the United States. The questions were generated by an open, inclusive process that included personal interviews with decisionmakers, broad solicitation of research needs from scientists and policymakers, and an intensive workshop that included scientifically oriented individuals responsible for managing and developing policy related to natural resources. The process differed from previous efforts to set priorities for conservation research in its focus on the engagement of decisionmakers in addition to researchers. The research priorities emphasized the importance of addressing societal context and exploration of trade-offs among alternative policies and actions, as well as more traditional questions related to ecological processes and functions.*

*Keywords: conservation, decisionmakers, ecosystems, natural resource management, priority setting*

**Policies that address conservation and management of** natural resources reflect societal values, and scientific information is essential to the development and implementation of effective policies and management actions. To enhance the availability of policy-relevant scientific information and to maximize the capacity to predict the effects of alternative policies and actions, decisionmakers and scientists must identify the most pressing research questions and focus their limited financial resources and scientific abilities accordingly.

The United States is experiencing rapid ecological and social change. Ongoing changes in land use, climate, nutrient cycles, and species distributions are geographically extensive and of considerable magnitude (e.g., Brown et al. 2005, Serreze 2010). These changes are creating new combinations of biological and physical conditions (e.g., Knick et al. 2005, Scheffer et al. 2009) for which there exist no historical analogues on which to base predictions. At the same time, changes in human demographics are reflected in shifting societal values regarding natural resources.

Scientific research creates opportunities to identify and use existing information, close knowledge gaps, and increase communication among diverse creators and users of knowledge (Ruckelshaus and Darm 2006, Mawdsley et al. 2009). Considerable opportunities exist to support decisionmaking through scientific inquiry that is aligned with medium- and long-term policy priorities. The probability that research will deliver benefits to society further increases when decisionmakers have reasonable expectations of what types of information science can provide, and when they are able to apply and evaluate scientific research (Sarewitz and Pielke 2007).

Substantive communication among producers and users of knowledge also is essential for developing credible, relevant, and legitimate institutional and technological solutions to conflicting demands for conservation and resource management (Cash et al. 2003, Sarewitz and Pielke 2007). We used a participatory approach to identify key research questions in the biological, physical, and social sciences whose answers are most needed by those responsible for managing ecosystems in the United States. Participatory approaches may establish a foundation for joint fact-finding, a process through which diverse and sometimes adversarial parties collaborate to identify, define, and answer critical scientific questions that inform policy development (Karl et al. 2007).

Accordingly, we sought input from decisionmakers and their advisers in the public sector, science and policy

*BioScience* 61: 290–300. ISSN 0006-3568, electronic ISSN 1525-3244.  doi:10.1525/bio.2011.61.4.9

specialists in the nongovernmental and private sectors, public and private funders of research, and academic and other researchers. The process we followed built on previous priority-setting exercises for the United Kingdom (Sutherland et al. 2006, 2010), Australia (Morton et al. 2009), and the world (Sutherland et al. 2009), and was conducted in parallel with a Canadian exercise (Rudd et al. 2010). Our approach was distinct from previous priority-setting exercises in that questions or issues were not identified primarily by researchers but by scientifically oriented individuals responsible for development and implementation of policy and funding of research. Our hope is that this US-focused effort will directly and indirectly spark research that will inform domestic and international policy. A key outcome of the process was a set of 40 research questions that, if answered, will increase the effectiveness of policies related to conservation and management of natural resources. Collectively, the questions constitute an agenda for scientific inquiry that is designed to serve the needs of decisionmakers.

## Participatory process

From September 2009 to May 2010, the first seven listed authors organized a participatory process to identify research questions in the natural and social sciences with high relevance for decisions about conservation and management of natural resources in the United States (defined for this exercise as the 50 states, the District of Columbia, and the adjacent waters over which the United States has jurisdiction) within the next 10 years. The process had three phases: (1) preliminary consultations with senior decisionmakers and science advisers, (2) solicitation of potential research questions from a broad community of scientists and decisionmakers, and (3) collaborative refinement of submitted questions by a diverse set of workshop participants to identify a final set of the "top 40" research questions. We selected 40 as a target number of questions because it was (a) tractable given the time available for workshop discussions, (b) an appropriate sample size for future exploration of relative priorities among sectors on the basis of surveys, and (c) ideally would resonate with the public as an important set of questions without being highly exclusive.

**Consultations with senior decisionmakers and science advisers.** In September and October 2009, four of the authors (EF, DEB, JAH, JMS) interviewed nine current and former senior decisionmakers and science advisers. The interviews helped us refine the scope of the project and identify mechanisms for enhancing the practical application of the results. Several of the nine had been associated with more than one type of organization; we were not aware of all associations throughout their careers. Of those associated with US federal agencies at some point during their career (the US Fish and Wildlife Service, Environmental Protection Agency, National Marine Fisheries Service, Bureau of Land Management, Forest Service, and US Geological Survey), some served in Republican and others in Democratic administrations. Three individuals had associations with nongovernmental organizations. At least two individuals had associations with academic institutions. At least one individual had a previous association with a state agency, a funding organization, or the private sector.

These key informants identified energy development and impacts of climate change on policies for management of species, their habitats, lands, and waters as the primary issues they are now confronting and expect to face over the next 5 to 10 years. They identified scientific gaps, including knowledge of local and regional effects of climate change; ways to translate scientific data into information on trade-offs among different ecological, economic, and social values; spatially extensive land-use change; and the impacts of emerging chemicals and other stressors on natural resources. They also identified the need for scientists to more effectively communicate the ways in which their work can inform specific policy and management options and trade-offs.

**Solicitation of research questions.** The seven organizers invited 70 leaders of government agencies, nonprofit organizations, trade associations, and related groups in natural resource management, 59 of whom responded to and 35 of whom accepted the invitation, to a workshop in Washington, DC, in February 2010 to identify policy-relevant research questions related to conservation and management of natural resources. Participants collectively had expertise in policy formulation, application of science to policy, and funding of scientific research at different levels (e.g., federal, state, local) and branches (e.g., executive, legislative) of government and different types of public and private organizations (e.g., government, nongovernmental organizations including academia, professional scientific societies, charitable foundations). Participants were invited as individuals rather than as representatives of an organization.

Before the workshop, the seven workshop organizers and 35 participants solicited questions from within their organizations, from other colleagues, and in public forums (e.g., e-mail listservs). For approximately six weeks in December 2009 and January 2010, we received candidate questions through a Web site. Responses were anonymous unless the respondent chose to provide an organizational affiliation or name.

The organizers provided the 35 participants with a set of six ideal criteria for framing questions. Those who visited the Web site were presented with these criteria before they could submit a question. The criteria required that questions (1) were answerable through a realistic research design by a single project team or a moderately sized program supported by a research laboratory or funder; (2) were answerable on the basis of facts rather than value judgments; (3) were of a spatial and temporal scale that realistically could be addressed by a research team; (4) were not answerable by "yes," "no," or "it all depends"; (5) if related to effects and actions, contained a subject of the action, an action, and a measurable outcome; and (6) if answered, would increase the effectiveness of policy regarding and management of species, ecosystems, and ecological processes in the face of climate change and other stressors. Climate change was identified explicitly because it was mentioned by the majority of those we interviewed. The category "other stressors" was identified explicitly in the hope of encouraging respondents to consider a wide range of stressors.

We received 531 questions from a total of 374 individuals, some of whom may have participated in other parts of the process. These individuals were affiliated with a minimum of 109 different organizations, including at least 26 federal, 15 state, and 1 municipal agencies or consortia; 17 nongovernmental organizations of diverse prominence and scope; 12 universities; nine professional societies; six private companies or firms; four museums; and two charitable foundations.

**Culling and refining research questions.** In advance of the February 2010 workshop, the 35 participants identified questions that did not meet the ideal criteria. If a simple majority of participants noted that a given question did not meet the criteria, the question tentatively was discarded. The list of discarded questions was circulated to all participants to provide an opportunity for reconsideration. The result was 271 research questions that were provided to workshop participants.

The dates of the workshop (8–10 February 2010) coincided with two winter storms that delivered the greatest recorded amount of snow in any consecutive seven-day period in Washington, DC. These circumstances disrupted travel and Internet service for a number of participants. We held the workshop as planned and created several mechanisms for remote participation. A total of 27 individuals, including organizers (who primarily served as facilitators), ultimately participated in the workshop. During the workshop, participants in three sets of three concurrent, thematic small-group discussions developed 36 priority questions and 18 possible alternates on the basis of the list of 271 retained questions. At this stage, the criteria for questions were treated as aspirational and were not strictly enforced. A plenary session refined the 36 proposed questions and filled gaps from the list of alternates to reach the target of 40 questions. The workshop attendees subsequently refined the questions through e-mail correspondence. A subset of the most active participants joined the seven organizers as authors of this article (listed alphabetically, beginning with AMB).

None of the 40 questions is identical to any question submitted on the Web site, given that before, during, and after the workshop, participants reduced the original set of questions through an iterative process of voting and discussion in person and through e-mail. During this process, related questions frequently were grouped. At all stages, participants edited questions to improve syntax and clarity and to eliminate subjective language. Because we aimed for concise, straightforward phrasing, terms could not always be defined or context presented in the question itself. Therefore, participants decided to provide brief explanations or refinements to accompany each question in this article. Points to be included in the accompanying text were identified during the workshop and subsequent e-mail discussions. The authors selected references to substantiate those points. The questions were not easily grouped thematically because many issues overlapped.

The final list of questions is the result of the process, not the opinions of the organizers. The list inevitably reflects the initial contributed questions, the perspectives of individual participants, and the processes followed (Sutherland et al. 2009). We attempted to minimize the effect of individual preferences by canvassing a large number of people to produce the initial questions and by convening a large group with diverse expertise to engage in a structured and inclusive process of question refinement. We believe it is reasonable to expect that another group of approximately equal size and expertise would highlight a similar set of issues.

## Consensus priorities

In the following questions, we define ecosystems as including individual species, assemblages or communities of species, and ecological processes. We define ecosystem resilience as the maximum perturbation that an ecosystem can withstand without shifting to an alternative state (Groffman et al. 2006). The 40 questions were not ranked in order of priority.

**1. What quantity and quality of surface and groundwater will be necessary to sustain US human populations and ecosystem resilience during the next 100 years?** Connections between surface and groundwater are poorly understood, as are effects on terrestrial and freshwater ecosystems of groundwater removal (Sophocleous 2002) or changes in quantities and timing of flow. Controversies over flow requirements for pelagic fishes in the San Francisco Estuary (NRC 2010), which affect the allocation of water to the agricultural industry in California's Central Valley, exemplify the immediate ecological, economic, and social relevance of this topic.

**2. How do different strategies for ecosystem management across the gradient of development intensities affect human health in urban areas?** It is widely recognized that the status and trend of ecosystems and human health are tightly linked (McMichael 1997). Human health in urban areas can be affected by air quality, water quality and quantity, and major natural and human disturbance events both in nearby, high-density areas and in more distant, relatively rural areas.

**3. How do different strategies for growing and harvesting biomass or biofuel affect ecosystems and associated social and economic systems?** The production of biomass energy is expanding rapidly. Feedstocks range from intensively cultivated crops (e.g., corn) to native perennial grasses (e.g., switchgrass [*Panicum virgatum*]) to wood remnants from logging. Different feedstocks and different growing and harvesting technologies have different ecological effects on sequestration of carbon (Tilman et al. 2006), soil fertility, and quality of habitat for different species.

**4. How do different strategies for managing forests, grasslands, and agricultural systems affect carbon storage, ecosystem resilience, and other desired benefits?** As part of a strategy to reduce carbon emissions, management practices that favor carbon storage may be emphasized. However, a number of these practices may decrease ecosystem resilience and other ecosystem services (Groffman et al. 2006). Moreover, the social effects of efforts to mitigate climate change may be unequal. Evaluation of the outcomes of alternative strategies at different spatial and temporal scales may inform development of policies for simultaneously achieving climate mitigation, conservation, and human-development goals.

**5. What are the relative ecological effects of increasing the intensity versus spatial extent of agricultural and timber production?** Intensification is intended to provide humans with a consistent amount of food and wood products while leaving more land available to meet other societal demands, including maintenance of natural ecosystems (Matson and Vitousek 2006). In some cases, however, intensification displaces humans, leads to extensive agriculture elsewhere, and increases local inputs of pesticides, fertilizers, and water. Understanding trade-offs between intensive and extensive production is necessary to inform agricultural and forestry policies.

**6. How do different agricultural practices and technologies affect water availability and quality?** Agriculture and associated irrigation systems can modify factors including flow, sedimentation, nutrient loading, and runoff of pesticides, all of which have the potential to affect both surface and groundwater. Effects may be local or, when aggregated across extensive areas, can lead to phenomena such as dead zones in nearshore marine systems. Even if a waterway is considered unsuitable for human consumption under the Clean Water Act, exceedances of metals, nutrients, toxic algae, and pesticides may have sublethal effects on aquatic species. Improved knowledge of the societal and ecological benefits and costs of given agricultural practices can inform revisions or implementation of legislation such as the Federal Insecticide, Fungicide, and Rodenticide Act.

**7. What are the ecological and economic effects of different methods of restoring forests, wetlands, and streams?** Effects of different restoration methods often are not well understood because methods for measuring effectiveness have not been standardized. For instance, only 10% of more than 37,000 entries in a major national database on river and stream restoration projects appeared to incorporate collection of monitoring data, and few of that subset assessed the effects of restoration activities (Bernhardt et al. 2005). More than 40% of the projects in the database had no associated information on costs, and 20% did not have stated restoration goals. Different methods of ecological restoration affect the return on society's investment in restoration in economic terms (Aronson et al. 2010).

**8. What are the potential effects on ecosystems of developing new sources of renewable and nonrenewable energy?** Exploration of new sources of energy is driven by increasing energy use and demands for reducing emissions of greenhouse gases and increasing domestic production of energy. Little is known about the ecological effects of extracting and utilizing different spatial and temporal configurations of renewable and nonrenewable energy sources. For instance, decisions about where to situate energy facilities or crops for biofuels involve consideration of trade-offs among land and water use, ecosystem structure and function, and effects on specific taxonomic groups (e.g., Kuvlesky et al. 2007).

**9. How do population dynamics respond to the independent and interactive effects of multiple stressors?** The responses of particular species to a given stressor, such as habitat loss, drought, invasion of a nonnative species, or harvest, often are fairly well known. By comparison, mechanistic understanding of how species respond to the cumulative effects of multiple stressors and their interactions is limited. Lack of knowledge constrains robust assessments of cumulative effects required under policies such as the National Environmental Policy Act (NEPA) and the Endangered Species Act (ESA) for public and private organizations.

**10. How is the productivity of soil in a given region affected by different policies and stressors?** The Conservation Reserve Program, enacted in part to protect highly erodible soils, has been one of the federal government's largest conservation investments over the past 25 years, with conservation payments to landowners exceeding $40 billion. As markets for farm commodities are altered by energy and climate policies, the role of soil conservation programs also may change (Morgan et al. 2010). Mandates and incentives for biofuels may induce landowners to return Conservation Reserve Program acres to production, alter traditional crop rotation patterns, and reduce the amount of residuals left on the ground after harvest. Nevertheless, markets for carbon sequestration credits may lead to new soil management and tillage practices that improve the fertility of agricultural lands.

**11. What are the aggregate effects on ecosystems of current-use and emerging toxicants?** Tens of thousands of toxicants (pollutants of anthropogenic origin such as metals; polychlorinated biphenyls; and other petroleum hydrocarbons, pharmaceuticals, and nanoparticles) regularly enter all types of ecosystems. Each contaminant can be toxic to individuals or can aggregate to higher trophic levels. The number and diversity of pesticides and synthetic hormones (e.g., Kidd et al. 2007) in current use have greatly expanded during the past 50 years. Compared with legacy organochlorines such as DDT (dichlorodiphenyltrichloroethane), these chemicals generally are less persistent, more difficult to measure, and more likely to have sublethal than lethal effects. Toxicological information often is not transferred effectively to managers.

**12. How do demographic and cultural shifts in the human population of the United States shape conservation values, attitudes, and behaviors?** Demographic and cultural attributes of the United States are changing rapidly in response to immigration, urbanization, technology-enabled work patterns, and aging of the "baby boomer" generation (defined by the Census Bureau as individuals born between 1946 and 1964). These shifts may redefine the way that society conceives of the environment at different spatial scales and within different political jurisdictions. Values, attitudes, and experiences influence perceptions of threat (Stern 2000) and may in turn affect public support for design and implementation of environmental laws and policies.

**13. How do the social and economic impacts of US conservation policies vary spatially, temporally, and among social groups?** Social effects of conservation policies and practices are not well understood, especially in the United States. Cases such as restoration of the Everglades (Fuller et al. 2008) and reintroduction of wolves (*Canis lupus*) to Yellowstone National Park highlight the potential for science to inform both public debate and policy deliberations about legislation such as the ESA, NEPA, and the Antiquities Act (which allows for presidential designation of national monuments).

**14. Within and outside the United States, what are the ecological and economic effects of programs implemented under the Conservation Title of the Farm Bill?** The Farm Bill is reauthorized periodically by Congress, most recently as the Food, Conservation, and Energy Act of 2008. The bill has comprehensive effects on domestic agriculture. Programs that benefit from the bill include the Conservation Reserve Program, Grasslands Reserve Program, Wildlife Habitat Incentives Program, and Environmental Quality Incentives Program (reviewed in Haufler 2005).

**15. How do shifts in agricultural subsidies, commodity prices, and markets affect the location and rate of conversion of natural ecosystems to agricultural uses?** Choices by individual farmers and agricultural firms about where and how to farm are shaped by their economic environment. Subsidies, commodity prices, and market dynamics shape choices about the location and extent of land conversion for agriculture (e.g., Geist and Lambin 2002). Policies such as trade agreements, crop subsidies, and foreign assistance programs affect ecosystems outside and within the United States. Understanding the dynamics between ecological and economic systems informs decisionmaking, especially given volatility in global commodity markets and growing demand for biofuels.

**16. What are the ecological, social, and economic costs and benefits of different mechanisms of conservation financing?** Diverse mechanisms for financing conservation (e.g., tax incentives, licenses and other user fees, bond funds, carbon markets, governmental oil and gas royalties) may have considerably different ecological, social, and economic effects. Different mechanisms may be effective for conservation on public versus private lands or waters. Furthermore, different mechanisms may be feasible or preferable to different governments, nongovernmental organizations, and private entities.

**17. How do different systems of natural resource governance affect capacity for adaptive management and maintenance of ecosystem resilience?** Governance systems differ in structure, procedure, focus, and scope. Their characteristics (e.g., centralized versus participatory, sector specific versus holistic, local versus national) can have substantial effects on ecological, economic, and social outcomes. These differences also shape the ability of society to adaptively manage ecosystems and provide for ecosystem resilience in response to ecological and social change (Dietz et al. 2003).

**18. How do different types of cross-jurisdictional governance systems affect ecosystems?** Contemporary ecosystem management, especially at large spatial extents, frequently entails governance across traditional statutory, project, taxonomic, and political boundaries (USFWS 2009). For example, the Department of the Interior is establishing 21 regional Landscape Conservation Cooperatives among federal and state agencies, tribes, nongovernmental organizations, universities, and stakeholders. The cooperatives are intended to address phenomena such as fragmentation, genetic isolation, and water availability (*www.fws.gov/science/SHC/lcc.html*). Approaches to managing public and private lands will continue to evolve, as will the use of easements and other arrangements for conservation.

**19. What are reliable and scientifically defensible metrics for quantifying the benefits that humans receive from ecosystems and trade-offs among those benefits?** It has proven difficult to relate ecosystem status and trends to the supply of social benefits. Economic metrics are conceptually well established, but empirical data on benefits, especially nonmarket benefits, are limited because little primary research has been conducted on many land-cover types. Moreover, disparate valuation methods have been used to value context-dependent ecosystem services (Navrud and Ready 2007), thereby limiting the transferability of value estimates. Economic valuation is based on society's current preferences, which inevitably are on the basis of imperfect information. Improved understanding of ecosystem function, broader metrics, more valuation research, and new mechanisms for assessing trade-offs may better inform decisions about management of ecosystems.

**20. How do the economic costs and benefits associated with provision of ecosystem services vary spatially, temporally, and among social groups?** Existing data, analyses, and policies do not fully account for the fact that those who pay for the provision of services and those who receive services may diverge in space, time, social class, gender, and ethnicity (Fisher et al. 2008). An understanding of spatial, temporal, and social heterogeneity will increase the probability of successfully managing for efficient and equitable provision of ecosystem services, especially through development of markets and other payments for ecosystem services schemes.

**21. What are reliable scientific metrics for detecting chronic, long-term changes in ecosystems?** Effective monitoring programs detect ecosystem change at an early stage, permit statistical inference, and suggest mechanisms that may cause such changes. However, methods to detect gradual as opposed to sudden ecosystem changes are poorly developed. Moreover, long-term commitments to monitoring and adaptive management currently are difficult to secure and fund. Environmental history and social science research complement natural science in the understanding of gradual changes in ecosystems by addressing the construction of scientific knowledge and risk perceptions and uncertainties over time (e.g., Rosenberg et al. 2005).

**22. How does the configuration of land cover and land use affect the response of ecosystems to climate change?** Patterns of land cover and land use affect ecosystems at all levels, from connectivity among populations of a given species to webs of interactions within a community to fire dynamics across extensive areas. The locations of traditional protected areas are fixed, but the potential locations of different land-cover types and land uses are likely to change as climate changes. Because species interact with the environment at different spatial and temporal scales, understanding responses of populations, species, and processes to the pattern of land cover and land use will improve management of ecosystems (Opdam and Wascher 2004).

**23. How will changes in land use and climate affect the severity of infrequent, spatially extensive disturbance events?** Organisms have adapted to rare but recurring disturbance events such as stand-replacing fires, intense storms and floods, or outbreaks of certain insects and diseases. Land use alters the context in which these events occur and, in concert with climate change, may alter the frequency and ecological and economic severity of such events (Raffa et al. 2008). For example, it is unclear how trees will be affected by interactions among changes in climate and spatially extensive disturbances such as fire, insects, and pathogens (Anderson et al. 2004). Societal decisions about allocation of resources in responding to disturbances are informed by an understanding of the likely severity and frequency of those events.

**24. What attributes of ecosystems facilitate prediction of impending transitions among alternative states?** Not all ecological transitions in aquatic or terrestrial systems are reversible. Prediction of transition points or thresholds may be feasible (Scheffer et al. 2009). Detection of such signals might enable management interventions to prevent undesirable shifts in ecosystem states, or to minimize the duration of undesirable states. Evidence of pending transitions also may present opportunities for societal and policy dialogue about what future system states are ecologically possible or desirable, and the inputs that would be required to achieve and maintain those states.

**25. At what threshold values of abiotic or biotic attributes do ecosystems change abruptly in response to species extirpations or species introductions?** Changes in species composition affect ecosystems at multiple levels, from mutualisms or predator-prey relations to disturbance regimes. For example, the invasion of nonnative annual grasses has changed fire dynamics across the western United States (Knick et al. 2005). Few methods exist to detect impending threshold events. Knowledge of thresholds at which changes in ecosystems are irreversible would help prioritize responses to declines or introductions of species by management agencies.

**26. How will ecosystems be affected by the changes in species composition that are likely to result from changes in land use and climate?** As genetics; rates of birth, death, and dispersal; and distributions of species change, so do ecological functions and the composition of assemblages. Criteria for defining functional assemblages, and thus for quantifying resilience, have not been formalized. Because composition and relative abundance of species affect ecosystem resilience and the benefits humans receive from ecosystems, changes in species composition will affect decisions about land use and investments in climate-adaptation initiatives.

**27. What are the ecological characteristics of populations and species most likely to persist in the face of changes in land use and climate?** Many research and management efforts have attempted to categorize populations and species on the basis of their potential for adapting to projected changes in climate and human activity (e.g., Midgley et al. 2002), but methods are not standardized and often are not quantitative or repeatable. Spatially extensive or rapid landscape changes are of particular relevance to policy and management.

**28. What factors affect the ability of native species to move through and persist within human-dominated landscapes?** Rapid fragmentation of once-continuous land cover has necessitated a shift in focus to include the conservation of connectivity of species' habitats in space and through time (Cabeza and Moilanen 2001). Movement is affected by configurations of land cover and land use, resource availability, and barriers to dispersal. Individual states as well as cross-jurisdictional groups such as the Western Governors'

Association have begun to examine potential mechanisms for increasing the probability of species movements and persistence over decades to centuries.

**29. How will changes in land use and climate affect ecologically and economically important mutualistic relationships among species?** Land use can fragment formerly continuous native land cover, whereas climate change may affect the phenology and geographic distribution of species. The combined effects of changes in dispersal and phenology may disrupt mutualisms from pollination to the tending of butterflies by ants. Actions to minimize disruption of mutualistic relationships may be linked to implementation of the Farm Bill incentives programs, and projections of changes in mutualistic relationships will inform management of agricultural landscapes more broadly.

**30. How will changes in land use and climate affect the prevalence and rates of transmission of diseases among nondomesticated animals?** Disease reflects interactions among a susceptible host, a virulent pathogen, and environmental conditions that support the pathogen. Therefore, any environmental change—whether in climate or human migration and transport—that increases host susceptibility to a pathogen, or that results in an environment of higher quality for the pathogen, will increase the incidence of disease (Boxall et al. 2009), which may complicate management of human health across jurisdictions (Parkes et al. 2005). Diseases may be transmitted among nondomesticated animals, from wild animals to livestock and to humans, or from livestock to wild animals. A greater understanding of disease dynamics may affect policies ranging from quarantines to releases from hatcheries or other captive breeding facilities.

**31. How will changes in land use and climate affect factors that facilitate the spread of nonnative species?** Changes in land use and climate will affect modes and rates of introduction of nonnative species, which may complicate efforts to achieve ecological and agricultural targets. Among the many factors likely to increase rates of pathogen transmission and colonization by nonnative species are increases in air travel and increases in sea traffic in Arctic regions (facilitated by melting of sea ice). The introduction and spread of nonnative species may require developing and implementing new strategies for screening imports, assessing the potential for ballast water and hull fouling on ships to introduce species, detection, rapid response, and restoration.

**32. What are the attributes of species that will require ongoing human intervention to persist outside captivity?** About 1% of species listed under the ESA have met recovery standards and been delisted. A number of others meet goals for recovery but have not been delisted because stabilizing their status will require continuing management intervention and because assurances are lacking that such interventions will be continued after delisting (Scott et al. 2010). It may be possible to categorize species according to major threats to their persistence and the ability of different management actions to achieve societal goals such as preventing their extirpation, recreational harvest, and nonconsumptive use.

**33. How does domestic propagation of species affect the supply of, demand for, and persistence of these species in the wild?** Species are propagated for consumption (e.g., fish hatcheries), companionship (e.g., pet birds), and conservation (*in situ* breeding). Domestic propagation of certain species also can affect persistence of nontarget species. Breeding of animals and plants could reduce the demand for wild-caught individuals and increase the demand for and social legitimacy of ownership of certain species.

**34. How will changes in the Arctic's climate affect ecosystems in the Arctic and elsewhere in the United States?** Shifts in climate in the Arctic are expected to be more rapid and more substantial than in other regions, and they probably will affect the climate of those other regions. For example, many of North America's shorebirds and waterfowl breed in the Arctic. Projected changes in the quantity and quality of their breeding habitat are likely to change their abundances and distributions throughout continental flyways. At the same time, foraging opportunities for species that depend on sea ice are projected to decline (Julius and West 2008).

**35. How will changing levels of human activity in the Arctic that are enabled by climate change affect Arctic ecosystems?** Climate change has already resulted in the relocation of native villages along the Arctic coast and will enable expansion of human activities, such as transportation (van Loon 2007) and development of energy sources, in terrestrial and marine ecosystems in the Arctic. Unintended movement of nonnative species also is likely to increase.

**36. What ecological and economic changes will result from ocean acidification?** The pH of the surface waters of Earth's oceans has decreased by about 0.1 units since the pre-Industrial era and is expected to decrease by another 0.3 to 0.5 units by 2100 (Hendriks et al. 2010). Probabilities of persistence of shell-forming and calcifying species (e.g., shellfish, corals), and the economies of communities or industries that rely on communities of such species, may decline as a result. Potential effects of interactions among acidification and other stressors are largely unknown (Hendriks et al. 2010). Ocean acidification is of sufficient relevance to decisionmaking that a Senate subcommittee convened a hearing on the issue in April 2010.

**37. How will coastal ecosystems and human communities be affected by sea-level rise, storm surge, erosion, the intrusion of saltwater, and changes in the amount and variability of precipitation?** Ecosystem type, vegetation status, and human activity in coastal areas affect the extent to which waves will be attenuated and production of fishes and other resources sustained as climate changes. The scope of coastal changes will affect economic and social factors, such as industrial development, agriculture, and residential property values. The magnitude of long-term costs and benefits will depend on near-term decisions about spending to reinforce coastal areas and adaptation to environmental change (Turner et al. 2007).

**38. How do alternative ways of managing fisheries affect marine ecosystems and coastal human communities?** Approaches to managing commercial and recreational fisheries include restrictions on participation in the fishery; limits on fishing gear, locations, and seasons; limits on per-trip and seasonal landings; catch shares and other forms of privatized fishing rights; and specific reporting requirements (e.g., Costello et al. 2008). Ongoing policy debates highlight the potential for further research on ecological and social effects of different fisheries management strategies to inform specific policies.

**39. Within and outside of marine protected areas, how do the abundances and distributions of species with different life histories respond to establishment of those areas?** Considerable uncertainty remains regarding the effects of marine protected areas (MPAs) on the ecology of adjacent waters and on species that are highly mobile or migratory. Also, MPAs in temperate ecosystems generally are less well understood than those in tropical coral reef ecosystems. Improved understanding of the ecological effects of MPAs may increase their potential use concurrent with other strategies for managing marine ecosystems.

**40. How will changes in land use and climate affect the effectiveness of terrestrial and marine protected areas?** The effective sizes and isolation of protected areas are affected by surrounding human use (Radeloff et al. 2010) and potentially by climate change within and outside the protected area. Potential management responses include the designation of new protected areas, facilitation of the connectivity of populations or ecological processes among protected areas, and active manipulation of ecosystem components (Halpin 1997). Although species composition and structure in protected areas may change, those areas still may serve as refugia for native animals and plants.

## Themes, caveats, and insights

After compiling the 40 questions, workshop participants recognized that the questions highlight several consistent themes. Many questions address social and economic aspects of conservation policies. The questions emphasize governance systems, a reflection that ecosystem-level conservation and management efforts inevitably cross jurisdictional boundaries. Several questions focus on the market and nonmarket benefits that humans receive from ecosystems. Ecological and economic trade-offs among different methods of producing energy, timber, biomass, biofuel, and other agricultural products also are underscored. Questions often center on potential effects of climate change in the context of existing stressors, especially changes in land use.

The 40 questions reinforce the fact that partitioning the influence of multiple direct and indirect drivers of ecosystem responses can be extraordinarily difficult, perhaps even more so in aquatic than in terrestrial systems. The potential exists both for sudden shifts in ecological state (Scheffer et al. 2009) and for shifting baselines (i.e., temporal changes in perception of environmental status; Saenz-Arroyo et al. 2005). A subset of questions addresses species-level characteristics that may be associated with potential for resilience, adaptation, and persistence. Arctic and marine ecosystems are singled out given the magnitude of expected climate and land-use change in these areas (Brigham-Grette 2009).

Many issues that affect the ability of science to serve policy do not translate neatly into research questions. For example, computational infrastructure, education, and communications are fundamental to achieving many objectives for conservation and management of natural resources. It is possible to craft research questions about the comparative efficacy of educational methods or the merits of different metadata standards, but it may be more important to increase public understanding of scientific issues and create opportunities for clear and transparent dialogue about trade-offs.

We are not the first to propose priorities for research in conservation and resource management. Our work differed substantively from previous exercises in two ways. First, we explicitly aimed to identify questions that, if addressed or answered, would provide the scientific basis for the development of effective policies and management strategies for species, communities, and ecosystem processes in the United States. Second, we employed a participatory process that allowed input from hundreds of individuals and emphasized the perspectives of those who make decisions or advise decisionmakers as opposed to those of researchers, whose input characterized earlier efforts.

The questions identified by this process also differ from those generated by previous exercises. In the late 1980s, for example, a team of conservation biologists called for improvements in understanding of how biological systems work, particularly in terms of interspecific interactions at multiple scales and the perturbation they can accommodate; qualitative and quantitative effects of disturbance; patterns in the global distribution of species; the effects of fragmentation, biotic homogenization, and introduced species; reproduction and propagation of selected species; integration of biological communities with different proportions of intensive human use; and restoration (Soulé and Kohm 1989). Some of these themes endure in our 40 questions. Yet our process also highlighted novel themes and more practical issues such as the development of energy sources, alternative agricultural practices, social and economic trade-offs of different policies and management actions, toxicants, ecological thresholds, and social equity. Participants emphasized the need to conduct research in all types of terrestrial and aquatic ecosystems, to pursue simultaneous research in social and natural sciences, and to explore trade-offs among alternative policies or interventions.

It is likely that at least some relevant research, funded by public and private sponsors, is being conducted on all of the questions. The sense of the group of participants was that research on the questions is not being funded adequately, and that answers are not emerging rapidly enough to inform policy during the next 10 years. The group also felt that many academic researchers are unaware that answers to these questions are a high priority for policymakers.

The fundamental principles of ecosystem management and conservation science, such as the importance of size and connectivity of natural areas and the dynamic nature of ecosystems, have not changed over several decades (Groom et al. 2005). Rather there is increased recognition that human behavior and policy determine management success (Mascia et al. 2003). Accordingly, research in the social sciences and collaboration among disciplines has considerable potential to inform decisionmaking (Fox et al. 2006). Some novel stressors are emerging (e.g., new types of contaminants) for which ecological effects and policy options largely are unknown. Moreover, the extent to which species, economies, and human populations are affected by phenomena well outside their immediate geographic and temporal domains is unprecedented in the history of human society. Advances in computing power and in technologies such as geographic information systems and satellite remote sensing allow enduring questions (e.g., drivers of species distributions or configuration of land cover) to be addressed in new ways that may yield more information and can better inform policy.

It is not the intent of the authors or participants in the workshop to constrain discussion of research needs to these 40 questions, to prioritize them on the basis of our own perspectives, nor to prescribe ways to answer them. Additionally, the breadth of the topic area and of the interests of various decisionmakers means that different questions will resonate more with some decisionmakers than others. For example, different sets of decisionmakers have primary jurisdiction for areas such as energy, agriculture, and marine environments. We hope the issues raised will be considered by resource management organizations when deciding which information gaps to fill, by public and private funders when soliciting funding proposals, and by public and private investors as a preliminary screen for supporting research proposals. Mechanisms for addressing different questions will vary as a function of topic area and funder. Both opportunistic case studies and studies stratified by, for example, geography, ecosystem type, and demographic covariates might provide answers relevant to policy. In terms of feasibility, reliable scientific inference, and policy application, different questions are best addressed at different spatial and temporal extents and resolutions. The ideal scale of study also varies as a function of the policymaker or organization that wishes to inform its decisions with scientific information.

Use of scientific research to inform decisionmaking is affected by dynamic social and political processes that affect the feasibility and ease of communication among researchers and users of research (van Kerkhoff and Lebel 2006). When these two groups work together to define goals and agendas, the ability of research to inform decisions increases without compromising the authority of decisionmakers (van Kerkhoff and Lebel 2006). Iterative shared learning, including joint fact finding, can create knowledge that is scientifically credible, has public legitimacy (i.e., perceived as unbiased in conduct and attentive to diverse interests or values; Cash et al. 2003), and is relevant to management and policy (Karl et al. 2007). The questions presented here are the product of an inclusive and iterative effort that engaged individuals with different levels of expertise, experience, and power.

Practical methods for robust, scientifically informed planning and adaptive management exist (e.g., Margules and Pressey 2000, Holling 2001, Margoluis et al. 2009). To date, however, society at large has not committed to translating scientific understanding into practice and implementing management actions at scales that are relevant both ecologically and to policy (Hall and Fleishman 2010). History provides numerous precedents for transforming crisis into opportunity if the crisis can function as an incentive to action. The Marshall Plan, for example, revitalized economies, diplomacy, and societal confidence in Western Europe following World War II. If changes in land use and climate catalyze greater engagement among researchers and decisionmakers, phenomena with the potential to negatively affect ecological and human systems may lead to similar successes in the conservation and sustainable management of natural resources.

## Next steps

The process described here engaged nearly 400 hundred perspectives in developing research questions. We are now launching an effort to obtain the input of a considerably greater number of individuals who are more easily accessed by surveys. We are using the list of 40 questions as a basis for quantification of priorities by the public and by policymakers in governmental and nongovernmental organizations, charitable foundations, and academia. Priorities will be quantified by applying best-worst scaling analyses to the survey respondents' rankings of subsets of the 40 questions (Louviere and Woodworth 1983, Flynn et al. 2007). This approach recently was employed in a Canadian survey of research priorities in the social sciences and humanities (Rudd 2010). The latter experience suggests that we will collect several thousand completed surveys from the three groups of respondents. We will examine how rankings differ within or among sectors and whether all sectors perceive certain questions to be of great relevance to conservation policy. Ideally, we will be able to identify and stimulate research of uniformly high relevance across sectors.

## Acknowledgments
This work was supported by Kresge Foundation grant 239855 to the University of California, Santa Barbara. Thanks to World Wildlife Fund–US for hosting the workshop. We thank all individuals who contributed questions and three anonymous reviewers for comments that improved the manuscript. Affiliations of authors are provided for ease of identification only. No content in this manuscript implies endorsement by the US government.

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