May 2014

Science, Education and Outreach Roadmap for Natural Resources

Prepared by

Association of Public and Land-grant Universities

Board on Natural Resources

Board on Oceans, Atmosphere, and Climate

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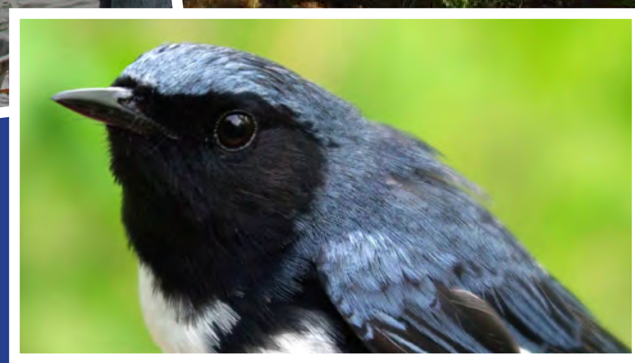


In November of 2010, the Agricultural Experiment Station Committee on Organization and Policy (ESCOP) published the *Science Roadmap for Food and Agriculture* (Association of Public and Land-grant Universities [APLU] 2010), which identified research priorities for agriculture for the next decade. Though the definition of agriculture[1] in the report includes natural resources, the focus of the report was primarily agriculture, with natural resources largely treated as an input into agriculture. Because of the lack of emphasis on natural resources in the report, several individuals in the natural resources academic community reacted to the report with disappointment, feeling that another story needed to be told, one with a more natural resources-centric perspective.

While there have been many high-level reports and strategic plans written about the topics covered by this report, most have tended to break natural resources into sub-disciplines representing particular resources: atmospheric, coastal, fisheries, forests, marine, rangelands, water, wildlife and others. Although universities frequently segregate these fields through disciplines, the resources themselves are all interrelated and need to be dealt with as a whole. With that in mind, the APLU Board on Natural Resources (BNR) and Board on Oceans, Atmosphere, and Climate (BOAC) jointly created the Science, Education, and Outreach Roadmap for Natural Resources (hereafter *NR Roadmap*).

The BNR represents over 500 university scientists in the fields of ecology, fish and wildlife, forestry, minerals and water resources. The BOAC represents over 250 university scientists in the fields of atmospheric, marine, and coastal sciences.

1 See Appendix A for definitions of commonly used terms.

The goals of the *NR Roadmap* are to:

- Chart a path for natural resources research, education, and outreach direction for public universities for the next 5-10 years;
- Identify major challenges, knowledge gaps and priorities;
- Provide guidance for policy makers in strategic planning and investment;
- Support natural resources agencies, professional societies, and non-governmental organizations in advocating for the use of sound science in natural resources decision-making; and
- Facilitate the development of interdisciplinary research, education and outreach teams focused on natural resources challenges.

Conceptual Framework

Historians often tie the success of the nation's land-grant universities to their tripartite mission of education, research, and outreach. Originally created to provide a practical and liberal arts education to average citizens, land-grant universities expanded their mission to include research and outreach with the passage of the Hatch and Smith-Lever Acts. This roadmap attempts to honor the tripartite mission by including education and outreach goals along with research goals.

The NR Roadmap is set in the context of the changing nature of funding opportunities and research needs. Calls for more interdisciplinary or transdisciplinary research are now routine among federal agencies funding research. Also routine are calls to include education and outreach goals during research development, not as an afterthought. Although the timeframe for implementation of the NR Roadmap is the next decade, we acknowledge that many of the resources we deal with have ecological and evolutionary processes with broader temporal and spatial scales.

This roadmap is framed around the following societal needs to:

- Optimize renewable resource productivity while maintaining environmental quality;
- Conserve and manage natural landscapes while addressing increasing human demands for natural resources;
- Protect, conserve and restore watersheds for biodiversity, water resources, and pollution reduction;
- Enhance water security globally;
- Understand the impacts of climate change on environmental processes;
- Develop a comprehensive strategy for managing natural resources to adapt to climate changes;
- Create a sustainable, profitable, and environmentally responsible agriculture industry;

- Identify new and alternative renewable energy resources and improve the efficiency of existing renewable resources;
- Minimize impacts of increasing energy demands on natural resources;
- Include natural resources in the K-12 education system and improve the scientific literacy of the nation's citizens;
- Promote natural resource stewardship; and
- Communicate scientific information to the general public in efficient and effective ways.

The NR Roadmap Process

Following the release of the ESCOP *Science Roadmap for Agriculture* (APLU 2010) in November of 2010, the BNR executive committee began discussing creation of a natural resources roadmap. On behalf of the BNR, Hal Salwasser, former dean of the College of Forestry at Oregon State University, obtained a grant from USDA's National Institute of Food and Agriculture to conduct a Delphi survey and write the *NR Roadmap* based on the results of the survey. The Delphi process utilizes experts in facilitated rounds of questioning that lead to synthesis and general consensus. Given that Dr. Travis Park of Cornell University had helped ESCOP conduct a Delphi survey to gather information for their roadmap, the BNR executive committee chose to contract with him for the *NR Roadmap*. The BNR also reached out to APLU's BOAC to gain participation from marine, atmospheric, and climate scientists as well as Sea Grant outreach experts.

The BNR and BOAC nominated 118 thought leaders by discipline or area of expertise to participate in the Delphi survey. Experts came from the following fields: atmospheric sciences, climate sciences, economics, energy sciences, fisheries, forestry, marine sciences, rangelands, recreation, water resources, and wildlife. All regions of the United States were represented. Of the 118 individuals nominated, 33 chose not to participate, so the survey results are based on the responses of 78 experts.

Participants completed five rounds of Delphi surveys focused on the grand challenges in natural resources. Given that the BNR and BOAC had not produced any previous roadmaps, the starting question for the study was:

> Preservation, conservation, and use of our natural resources, broadly defined, face many grand challenges in the next five to 10 years. These grand challenges are those which are difficult to solve, yet do have solutions, or at least milestones that mark progress toward solutions. These grand challenges also carry significant social, environmental, and economic impact. Grand challenges involve and stretch the limits of our collective research, extension, and teaching abilities and capacities.

> For example, a grand challenge in technology might be "to make solar energy economical," or one in global health might be "to create effective single dose vaccines that can be used soon after birth." What are the grand challenges in the research and teaching in and about natural resources over the next 10 years?

The first round of questions began on 19 March 2012 and the last round finished on 12 September 2012.

The first survey round resulted in 576 responses, which were reduced to 95 items through an inductive analysis of the responses by Dr. Park's team. In rounds two and three, participants were asked to rate their level of agreement that each item should be considered a grand challenge for natural resources. Based on those responses, the team narrowed the challenge items to 38 for round four. In that round, participants were asked to choose "yes" or "no" as to whether the item should be considered a grand challenge. If they chose "yes," participants were asked to group the grand challenge into eight general areas of natural resources issues (climate, land use, energy, water, education, sustainability, agriculture and food, or population). Round four resulted in 18 grand challenge items among the eight areas. The NR Roadmap Advisory Panel, composed of members from both the BNR and BOAC executive committees, reduced that to six categories by combining the three areas of sustainability, land use, and population into a single sustainability area. All three dealt with the impact of humans on natural resources as a direct result of using the natural resources or as an indirect result of degradation of natural resources through pursuit of fulfilling other needs, such as food or energy needs.

The final grand challenge areas identified after the Delphi surveys and the NR Roadmap Advisory Panel's decision to create a single sustainability area were climate change, sustainability, education, energy, water, and agriculture. The challenge statement that emerged on agriculture was "Develop a sustainable, profitable, and environmentally responsible agriculture industry." Given that ESCOP had produced an entire roadmap dedicated to the science priorities in agriculture, several of which aim to address the above challenge, the NR Roadmap Advisory Panel chose to reference the ESCOP *Science Roadmap for Agriculture* (APLU 2010) where appropriate rather than writing a separate chapter on the subject. This does not lessen the importance of the agriculture challenge area, but instead points out that the expertise for solving the problems of agriculture as they pertain to natural resources lies largely with those who conduct agricultural science, education, and outreach. Additionally, the NR Roadmap Advisory Panel crosswalked the priorities of both the ESCOP Roadmap (APLU 2010) and the NR Roadmap to look for areas of commonality in solving any of the six grand challenges identified in the NR Roadmap.

The NR Roadmap Advisory Panel invited scientists from each of the BNR and BOAC sections to serve as science leaders for each of the grand challenges; 35 scientists wrote the six sections in this roadmap. The Advisory Panel also nominated peer-reviewers for each section and each section received a minimum of two peer reviews. Finally, the Advisory Panel invited six thought leaders to provide

comprehensive reviews of the entire document. Science leaders and reviewers are identified in Appendix B.

The NR Roadmap is divided into five sections, each describing a grand challenge area in natural resources. Each section follows the same format:

- Framing the Issue — Provides background for the grand challenge, discussing historical, political, social, and/or economic context as needed.
- Gap Analysis — Examines current capacity and science gaps and identifies specific education and outreach needs for the challenge.
- Research Needs and Priorities — Identifies needs to conduct the necessary research and prioritizes research areas in order to solve the grand challenge.
- Expected Outcomes — A short summation of outcomes under two scenarios – status quo versus following the roadmap's recommendations.

The Six Grand Challenges

Grand Challenge 1: Sustainability

We need to conserve and manage natural landscapes and maintain environmental quality while optimizing renewable resource productivity to meet increasing human demands for natural resources, particularly with respect to increasing water, food, and energy demands.

The sustainability of natural resources must be evaluated not only by environmental quality standards, but also in terms of present and future social and economic expectations. Often, sustainable may be used synonymously to represent minimized inputs and idealized environmental quality. This vision of sustainability is often at odds with the reality of economics, a growing population with an increasing standard for quality of life, and the necessity to adapt to climate extremes. It is only with a mind towards the future that scientists can begin to analyze today's resource use patterns and start to compare alternative strategies to meet tomorrow's increasing natural resource demands.

Focal areas for this research are:

- Coupled Human-Natural Systems — Natural resource analyses must account for interrelated human and natural resource systems by improving the knowledge base of interactive processes between ecosystems and growing human populations. There is also the need to understand the influences of social and economic practices and policies on natural resources.

- Soils and Freshwater — Research on adaptive and effective soil and water management strategies and the role global climate change and demographic changes will play on crucial water and soil resources.
- Forestlands — Refine sustainable forest management and harvesting operations practices and technologies.
- Rangelands — Advance knowledge of how rangeland ecosystems, socioeconomics, climate, and specific management practices change and interrelate over time.
- Marine and Coastal Ecosystems — We need to understand: (1) the status and trends of resource abundance and distribution through more accurate, timely assessments; (2) interspecies and habitat-species relationships to support forecasting of resource stability and sustainability; (3) human-use patterns that influence resource stability and sustainability; (4) resiliency and adaptation to a changing climate; and (5) the interactions between coastal and marine operations/use and the environment. We also need to advance the environmental sustainability of ocean energy technologies and develop sustainable fishing practices and technologies.

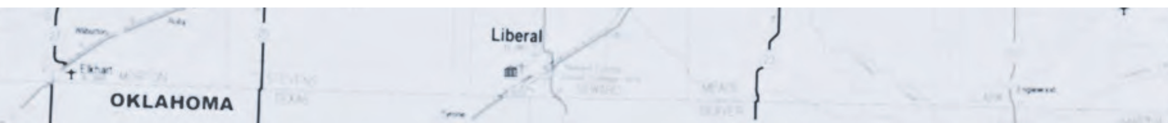
Grand Challenge 2: Water

We must restore, protect and conserve watersheds for biodiversity, water resources, pollution reduction and water security.

Water issues are becoming increasingly complex and require multi-disciplinary science to find cross-cutting solutions. Most of our existing knowledge of human or natural disturbance impacts on watersheds considers only two variables at a time. Given the complexity of watersheds and the demands placed on watersheds, along with a changing climate, we must expand our understanding of multiple stressors and plan our mitigation of those stressors accordingly. Furthermore, as we improve our understanding of the mechanics of our watersheds and the risks facing them, additional research into the impact of energy, transportation, agricultural, and urban policies on water security, quantity, and quality will need to occur simultaneously. This will entail integrated work with the social sciences and require outreach and education components to translate research into workable solutions.

Our areas of scientific focus should be:

- Improving understanding of mechanistic linkages between land uses, extractive consumption of water resources, and watershed resistance and resilience to better inform policy.
- Improving understanding of risks and impacts to water supplies from extractive uses, carbon sequestration technologies, and extractive technologies.
- Improving technology to process and allocate water in a manner that ensures sustainable, high quality water for human uses and maintenance of ecosystem services.



- Developing understanding of how existing and future policies and land uses impact water security, quantity, and quality over regional and national scales.
- Assessing how the intersection of social (or human) and natural (or environmental) systems impact water security, quantity and quality.

Grand Challenge 3: Climate Change

We need to understand the impacts of climate change on our environment, including such aspects as disease transmission, air quality, water supply, ecosystems, fire, species survival, and pest risk. Further, we must develop a comprehensive strategy for managing natural resources to adapt to climate changes.

Ecosystems are critical components of cultural, social and economic systems as they interact with water and climate to produce critically important natural resources, biodiversity, and an array of services upon which humans depend. Climate change threatens disruption of these systems on a massive scale, but our understanding of these complex systems and their reaction to rapid, multiple changes brought on by climate change is limited. Like water science, the difficult questions for natural resources and climate change lie in the complexity of the systems and the likely changes. While our knowledge of individual species reactions to individual stressors is good, our knowledge of an entire ecosystem response to the full suite of climate change variables is meager and will not be useful to natural resource managers or policy makers as it currently stands.

To remedy this situation, much greater research on the following will be necessary:

- Observational and Experimental Approaches — Many of the greatest challenges in understanding the effects of climate change on natural resources involve interactions between multiple climate variables, natural processes, and society. Ecosystem responses to climate change are contingent upon a large number of location, history, and stochastic variables.
- Simulations and Modeling — Computer models, whether statistical, dynamical, or mixed, provide useful tools for testing our understanding of the behavior of natural and human systems. If such models have been validated, they can serve as valuable planning and management tools.
- Management, Risk and Uncertainty — Risk evaluation and management of natural resources in the context of climate change requires real-time monitoring data, comprehensive exploration of the consequence of management choices, and models for testing management hypotheses. There is especially poor cross-disciplinary knowledge of the uncertainties associated with climate change and climate change impacts, leading inevitably to poor or biased understanding of uncertainty by natural resource managers and other stakeholders.

Grand Challenge 4: Agriculture

We must develop a sustainable, profitable, and environmentally responsible agriculture industry.

As mentioned before, the Delphi survey named agriculture as one of the six grand challenges of natural resources and we have chosen in this roadmap to reference the ESCOP *Science Roadmap for Agriculture* (APLU 2010) rather than writing a chapter specifically on creating sustainable agriculture. However, we would be remiss if we did not highlight the importance of developing a sustainable agricultural industry to the sustainability of our natural resources. Furthermore, we must also point out that agriculture cannot exist without the natural resources base upon which it exists, namely clean and abundant water, healthy soils, pollinators, genetic biodiversity, and a stable climate.

In lieu of a chapter, we provide a visual overview, in the form of a crosswalk (Appendix 3), of commonalities and differences between the NR Roadmap's and the ESCOP Roadmap's priorities.

Grand Challenge 5: Energy

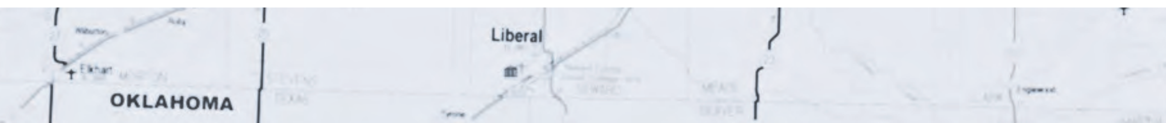
We must identify new and alternative renewable energy sources and improve the efficiency of existing renewable resource-based energy to meet increasing energy demands while reducing the ecological footprint of energy production and consumption.

Between 1980 and 2000, U.S. energy usage grew 21 percent. Though the past decade has seen some plateauing of energy consumption in the U.S., energy consumption is expected to rise again once the economy fully recovers. Even now, the U.S. is increasing exports of natural gas. To support this current and growing consumption, the U.S. expends a great deal of capital to produce or purchase energy sources, often at a cost to natural resources.

While the environmental effects of traditional, carbon-based energy are fairly well-known, most renewable energy sources are still quite new. Renewable energy research during the coming decades will need to balance various needs including environmental stress, public perception and acceptability, regional differences, economics, technical feasibility, geopolitics, and fluctuations in the supply, demand, and price of non-renewable energy forms.

Areas of scientific focus should be to:

- Improve understanding of costs and benefits of energy development and use and public perceptions related to energy.
- Minimize impacts of increasing energy demands on natural resources.
- Maintain available energy and increase efficiency to reduce ecological footprint.



- Provide educational opportunities to students, teachers, and consumers on the social, political, and environmental challenges related to energy production and use.

Grand Challenge 6: Education

We must maintain and strengthen natural resources education at our educational institutions at all levels in order to have the informed citizenry, civic leaders, and practicing professionals needed to sustain the natural resources of the United States.

Issues pertaining to sustainability of natural resources are the focus of local, regional, and national discussion. In a democracy such as ours, the development of natural resources policy involves interactions among professional managers, the public and elected officials. Public acceptance of natural resources plans and their effectiveness for achieving sustainable management depends upon the integration of scientific information and societal values.

However, much of the American public has little understanding of the process by which scientific knowledge is gained. That is, most people neither understand the framing and testing of hypotheses, nor the difference between hypothesis testing and construction of theory explaining a body of natural phenomena. Hence, it is not surprising that citizens—and frequently their leaders—misunderstand and often misconstrue scientific issues in discussions regarding the science and management of natural resources. Only by advances in popular understanding of scientific process, combined with more effective science communication, can discussion of natural resources issues be elevated. This goal may be achieved by the following:

- Include natural resources in K-12 education by incorporation into Science, Technology, Engineering and Math (STEM) curriculum and activities.
- Strengthen natural resources curricula at the higher education level.
- Improve the scientific literacy of the Nation's citizens.
- Communicate scientific information to the general public in efficient and effective ways.
- Promote natural resource stewardship.
- Promote diversity in the natural resources professions.

Conclusion

It is hoped that the *NR Roadmap* will serve as a point of reference for discussions about these crucial resources. Furthermore, the recommendations proposed in this roadmap should justify increased funding and collaboration for research, education and outreach in the natural resources.

References

Association of Public and Land-grant Universities, Experiment Station Committee on Organization and Policy—Science and Technology Committee. 2010. *A Science Roadmap for Food and Agriculture.* Association of Public and Land-grant Universities, Washington DC.

Grand Challenge 1: Sustainability

We need to conserve and manage natural landscapes and maintain environmental quality while optimizing renewable resource productivity to meet increasing human demands for natural resources, particularly with respect to increasing water, food, and energy demands.

Framing the Issue

Survival of human civilization is dependent on "life supporting" goods and services that are provided by healthy coupled human and natural resource systems, or social-ecological systems. Further, quality of life and connection to the natural world are positively affected by accessibility to intact natural resource areas and opportunities to experience the diversity of services that these areas offer to all facets of society at all times. Destruction or degradation of ecosystems threatens human well-being and the survival of civilization as we currently know it.

Human society has developed within the context of coupled human and natural systems, in which the natural systems are self-sustaining and support human activities so long as those activities do not deteriorate the system or extract system components in a manner that compromises the system's functional integrity (Figure 1). These coupled systems and their interactions are regulated by selected principles: (1) the functionality of natural systems varies along a condition continuum from intact to deteriorated, with each system component providing positive or negative input(s) (tradeoffs may exist with respect to inputs for any particular disturbance or management activity) to human well-being; (2) human decisions may affect ecosystems positively via recovery, restoration and reclamation, or negatively via degradation; and (3) real or perceived well-being of humans should have a direct input in decision making (policy) supporting adaptive and sustainable management of natural systems (Willig and Scheiner 2011). From this perspective, the positive inputs from ecosystems represent various provisions, regulations, support, or cultural services that are collectively considered to be ecosystem goods or services.

The linkages between the social and ecological systems are expressed through the delivery and utilization of ecosystem

goods and services (Figure 1). The biophysical condition represents the abiotic and biotic state of the ecosystem elements, while natural capital represents the stock of all ecosystem elements that lead to biophysical function.

Human condition represents the well-being of people, social capital is the capacity for innovation and adaptation, and economic capital represents built infrastructure and financial stocks that can generate financial dividends. The vertical arrows in Figure 2 represent the processes that affect capital and condition within the biophysical and socioeconomic subsystems over time. For example, biophysical processes lead to soil genesis, plant growth and reproduction, plant community shifts, and conversion of plant to animal biomass; while social and economic processes, such as demographic, cultural, and policy-based factors, influence the level of benefit derived from ecosystem services. Interactions between the biophysical and socioeconomic systems occur through the delivery and utilization of extractable ecosystem goods and the in situ provision of ecosystem services. The utilization of ecosystem goods and services can lead to external negative or positive effects. For example, natural capital and biophysical condition are diminished if ecosystem goods are extracted at rates greater than the capacity of the ecosystem to produce them. By contrast, sustainably-geared social policies can lead to changes in human behavior and investments in ecosystem conservation that enhance natural capital and biophysical condition. However, socially-imposed restrictions on ecosystem function that are the result of actions by poorly informed decision-makers can also lead to long-term deterioration of ecosystems and subsequent catastrophic events. A prime example has been widespread restrictions on the use of fire as a management tool, as well as the suppression of wildfires, that lead to unmanageable build-up of fuels. The result has been large, difficult-to-control wildfires that threaten lives, property, and reflect changes

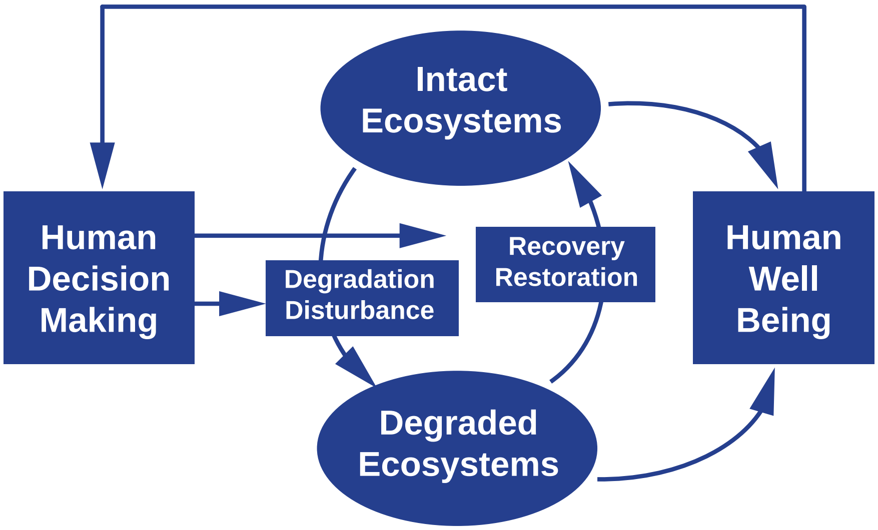


Figure 1. This simplified but overarching conceptual model (Willig and Scheiner 2011) defines key linkages between natural and human systems that together constitute a dynamic socioecological system.

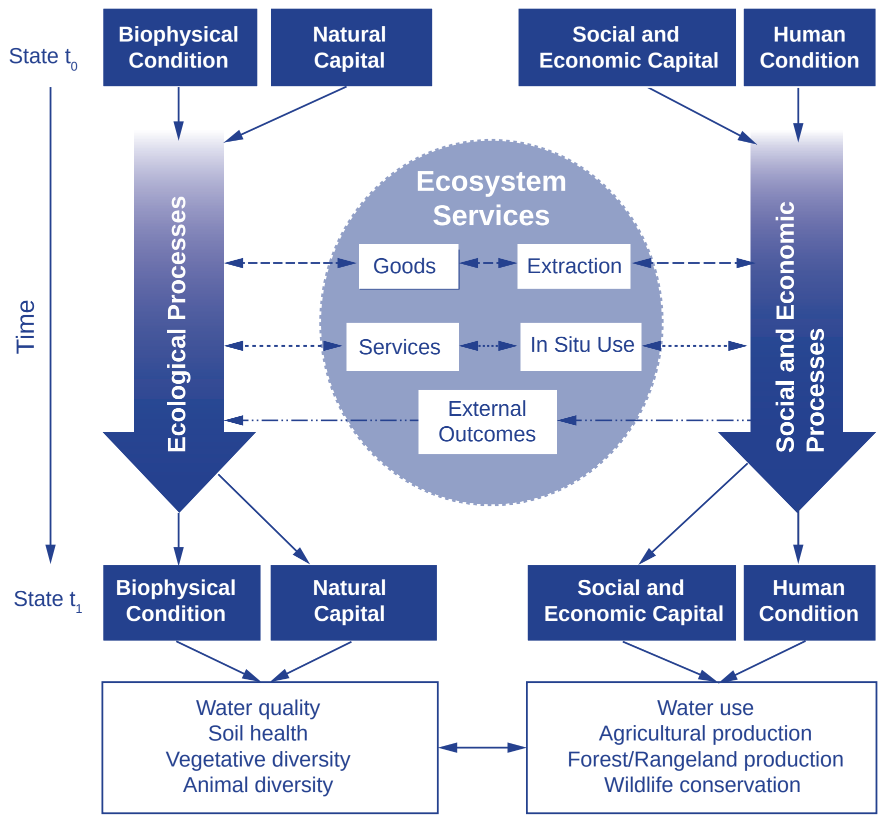


Figure 2. The integrated social, economic and ecological conceptual (ISEEC) framework for identifying ecosystem service linkages between biophysical and socioeconomic components of social-ecological systems (adapted from Fox et al. 2009).

in ecosystem function (away from historically fire-dependent ecosystems).

As human populations grow, pressure on natural resources increases as illustrated in the linkages in Figures 1 and 2 because each person requires space to live, shelter for survival, and infrastructure to meet daily needs. The result is increased dependence on extraction and deterioration of natural resources. Equally and maybe more importantly, per capita consumption is increasing and therefore the environmental impact of each human being is also increasing. The combination of a growing and more affluent population foretells serious natural resource challenges.

Incentives to sustain natural resources for the long term are often overshadowed by human desire for short-term gain and profit maximization (economic capital depicted in Figure 2). Climate regulation, water retention and filtration, healthy streams, intact forests and open rangelands provide habitat for many wild species. They exemplify natural capital and ecosystem services that have mostly unquantified economic value. By contrast, electricity generated from pollution-emitting power plants, corn produced in drained wetlands, and housing developments on open grasslands or timbered mountainsides have easily identified market values, but the associated negative impacts on the natural resources that they affect are generally externalized. If we continue "business as usual," current and future generations will increasingly experience the burden of ecosystems that have been degraded by economically-driven human activities. In turn, this would result in an ever-larger proportion of the human population with inadequate access to the natural resources that they need and ever-greater disparity in the quality of life between the rich and the poor, which represents a significant environmental justice issue.

To avoid this outcome, the highest research priorities should focus on the means to restore and maintain the health of existing and deteriorated social-ecological systems. Moreover, this restoration and maintenance must be accomplished in the face of rising global demand for basic human necessities (food, water, energy and shelter) under the uncertainty of ecosystem-wide effects of climate change and in a market economy that currently has a limited capacity to identify monetary value for ecosystem services that can be obtained only from properly functioning natural resource systems.

Natural Resource Stressors

Climate Change — Rapid changes in climatic conditions threaten to destabilize and possibly collapse existing social-ecological systems. For example, between 1980 and 2008 climate change reduced global maize and wheat yields (Lobell et al. 2011), elevating commodity prices and thus increasing pressure

to expand agricultural production into areas previously dominated by perennial plant cover that served as valuable wildlife habitat. Grasslands are vanishing in the upper Midwest faster than at any time since the 1920s and 1930s due to increasing commodity prices and farmers' desires to capture resulting profits (Wright and Wimberly 2013). These and multiple other examples identified in subsequent sections dealing with climate change and with water illustrate the complex and daunting task of sustaining or improving our natural resources under the influence of an increasingly variable climate.

Agriculture — Humans depend heavily on agricultural production for their survival. In turn, agriculture is heavily dependent on natural resources, especially soil, water and pollinators. In order to meet growing demand, current food production will need to be intensified and/or expanded. Such land use change often leads to degradation of soil and water resources both on-site and off-site, and destruction of currently intact natural resource systems. The need for a sustainable form of agriculture is paramount from multiple natural resource perspectives. For a more thorough discussion of the fundamental necessity to develop sustainable agricultural techniques and methods, refer to A Science Roadmap for Food and Agriculture prepared by the APLU and ESCOP, and see especially Grand Challenge 1 ("We must enhance the sustainability, competitiveness, and profitability of U.S. food and agricultural systems.") and Grand Challenge 6 ("We must heighten environmental stewardship through the development of sustainable management practices.") (APLU 2010).

Natural Resource Systems

Forestlands – The growth in industries that use forest biomass will increase utilization of forestlands not previously used due to relatively poor timber quality, low market prices (Janowiak and Webster 2010) and limited accessibility. However, these forested areas also contribute to carbon sequestration and, therefore, mitigate climate change (Vose et al. 2012), and may support high biodiversity. This change in utilization and increased environmental burden applies to increasingly large urban forests as well as traditional timberlands. It is imperative that all forests are managed not only for wood production but also to protect other ecosystem services and values, which may require the development of new valuation models. In developing these models there is also an opportunity to improve the values of the resource base in both rural and urban settings. For example, large acreages of hardwood forests have suffered from decades of high-grading in which the larger, more commercially valuable trees and species were removed, providing a market opportunity for the remaining less desirable species. An emerging market for "lower quality" wood products from urban and traditional forests could encourage a renewal of the forest ecosystem with a more balanced approach that protects species that are desirable for landscape, commercial, wildlife, and other purposes. In addition, enhancing the sustainability of forest ecosystem services and systems will require studies to consider the entire supply chain of forest products from stump to end use as well as focus on the effects of the harvest intensity and consequences such as the introduction of no-native trees and other invasive species on ecosystem services and on other environmental impacts. Life cycle assessment modeling will help identify the economic and ecosystem value of this natural resource (Wolfslehner et al. 2013). However, assumptions and inputs into these models will need to be specific in order to accurately represent local contexts and needs and develop new markets.

Rangelands – Rangelands encompass many natural resources and ecosystem services but are often discounted due to their relatively low potential for food and timber production. They are among the most widely distributed and diverse landforms in the world and include grasslands, shrublands, and savannas. Due to their extensiveness, rangelands not only support the livelihoods of over one third of the world's population (Reynolds et al. 2007), but they provide many critical ecosystems services, including water catchment and filtration, carbon sequestration, and the provision of wildlife habitat, all of which affect human well-being. Maintenance and restoration of rangelands ecosystems in a changing world are critical for the future welfare of burgeoning human populations. In the U.S., federal subsidies for some commodity crops have led to the conversion of marginally productive grasslands to croplands and subsequently to non-native pastures. Such land conversion negatively impacts the health of native rangelands as well as those species, especially birds, which depend on native grassland habitats. Another growing issue is the increasing utilization of rangelands for energy production, including the development of additional oil and gas resources as well as wind and solar energy (Kreuter et al. 2012). Such developments have both biophysical and socio-economic consequences for rangelands. A research, education, and outreach framework is needed in which rangelands are viewed as dynamic and integrated social-ecological systems, and in which the human dimensions of these systems are addressed concomitantly with and to the same degree as the their biophysical characteristics (Figure 2).

Wildlife — Changes in the composition of ecological communities through extirpations, invasions and altered abundances, which may be exacerbated through climate change, human use and altered disturbance regimes such as fire suppression, have resulted in an increasing need to understand the relationships between biodiversity and ecosystem processes. Results from biodiversity-ecosystem function studies have found that increases in diversity are associated with increase in resource capture efficiency, biomass production, organic matter decomposition and nutrient cycling. However, research that has focused on biodiversity has often been associated with economically important wildlife species while studies of the broader effects of wildlife species on ecosystem processes have been less common. As with agricultural and forest- and rangeland-related uses of natural resources, wildlife research needs to focus not only on management tied to the direct economic value of wildlife but also on the effects of other non-commercial species and suites of species on the health of ecosystems. An example of this is the removal of wolves leading to the increase of elk and the associated decrease in aspen and willows and subsequently also beavers in the Yellowstone National Park, which ultimately resulted in substantial changes in hydrology within the ecosystem (Ripple and Beschta 2012).

Marine and Coastal Ecosystems — Healthy marine and coastal environments are in decline, largely due to over-harvesting, pollution, climate change, reduced fresh water inflow, and land use change. Dramatic shifts in species composition have been observed for commercially and regionally important species (Scheffer and Carpenter 2003) as well as the intrusion of non-native and invasive species with significant consequences (Occhipinti-Ambrogi 2007). Understanding the influence of land use on marine and coastal habitats continues to emerge as a vital component of sustaining marine and coastal resources. Traditional uses, such as transport, fishing, and tourism now sit alongside more recent uses such as aquaculture, and tidal, current and wind energy production. These emerging uses are continuing to expand and it is becoming increasingly challenging to effectively coordinate sometimes competing uses through current management approaches. On 19 July 2010, President Obama signed an executive order establishing a National Policy for the Stewardship of the Ocean, Our Coasts, and the Great Lakes (Executive Order No. 13547, 2010). The national policy

identifies coastal and marine spatial planning as one of nine priority implementation objectives and outlines a framework for effective marine planning that addresses conservation, economic activity, user conflict, and sustainable use of the ocean, our coasts, and the Great Lakes.

Gap Analysis

The sustainability of natural resources must be evaluated by environmental quality standards as well as by present and future social and economic expectations. Heretofore, *sustainable* has been used to represent minimized inputs and idealized environmental quality. This vision of sustainability is often at odds with the reality of economics, a growing population with an increasing standard for quality of life, and the necessity to adapt to climate changes. It is only with a mind towards the future that scientists can begin to analyze today's resource use patterns and compare alternative strategies to meet tomorrow's increasing natural resource demands. For example, life cycle analyses used to evaluate the sustainability of a given system, compared to traditional research approaches, provide a more comprehensive opportunity to understand resource requirements of that system; similar approaches could be used to examine externalized costs that are not considered in the final prices of goods or services. A useful assessment of future decrease in economic profit, ability to rely on a resource, or standard of living will not be possible until the full value of externalities and resource systems is acknowledged and included in evaluations of social-ecological systems.

The means to generate or recognize incentives are limited by poor understanding of feasible ecosystem services trade-offs. Furthermore, mitigation of adversities will not be possible without understanding the factors that affect the values, goals, and decisions of stakeholders (public) and production groups (private). Research to better understand resource sustainability must consider both technologies and practices that improve or increase production as well as technologies and practices that protect or improve environmental quality.

There is a rising need for infrastructure planning to be coupled with resource location and production capability analysis. As human populations grow in size and density and expand geographically, it will not be feasible to continue converting natural (frequently less suitable) areas to resource production areas; nor will it be feasible from an energy balance stand-point to produce and process consumables at great distances from the populations needing these products. The development of decentralized means to accommodate food and energy demands is needed, as is public education on the benefits of available local resources.

An important knowledge gap in the understanding and implementation of sustainable systems involves the power of local practitioners to integrate recommendations based on scientific knowledge, or the barriers that prevent them from doing so. Further, the impacts of current policy on adoption of science-based resource management recommendations is not fully known, nor are the unintended impacts of such policies. The long-term success of such recommendations, especially between public and private use sectors, is also not fully known.

Interdisciplinary research must effectively address complex systems critical to the future management of sustainable natural resources. Should innovative methods to preserve and recycle critical resources, such as water, be insufficient to support future demands, implementation of adaptation strategies to certain priority resources may be necessary, perhaps even transferring the resource product or services produced from one area to another. The development of policies and market mechanisms to support such adaptation may also be needed.

Research on the responses of natural resource systems to different environmental stresses or management strategies has generated voluminous data, but these data are rarely amalgamated. There is a great need for the synthesis of these extensive data sets to better understand system responses to such stresses and strategies and, therefore, to better predict their positive or negative impacts on natural resources in the future. Also, the need for resolution of these interpretive or predictive functions at the local level has highlighted an inadequacy in both spatial and temporal analytical tools or methods in data capture. The National Center for Ecological Analysis and Synthesis exemplifies a strategy to meet this current data management inadequacy.

Resource priorities such as maintenance of soil and ecosystem resiliency, stream and aquifer water protection, public lands conservation, and natural landscapes for diverse demographics must be balanced against the need to develop novel agricultural systems that support ecological processes and that are capable of meeting the increasing demands for food, water, and energy of a growing human population. Policies, socio-economic challenges, shifting demographics, and public versus private stakeholder decision-making processes and behaviors are all important elements for understanding and optimizing the potential future use of natural resources in an environmentally responsible manner. There is a critical societal need to promote and adopt adaptive management practices while researchers and lawmakers collaborate to devise scientifically rigorous policies that will facilitate effective sustenance of natural resources. Only with the adoption of social-ecological frameworks for developing solutions to natural resources challenges can managers proceed with greater confidence in the sustainability of their actions.

Research Needs and Priorities

Coupled Human-Natural Systems

Natural resource analyses must account for interrelated human and natural resource systems by addressing interactive processes between ecosystems and growing human populations. Understanding the influences of social and economic practices and policies on natural resources is critical.

- Seek to more thoroughly understand and apply the concept of socioecology; human and natural systems are linked and should be studied as one broad human-natural system.
- Improve environmental and social justice for all social classes.
- Apply life cycle analysis to major materials and natural

resources management and production scenarios.

- Recognize and account for external costs not internalized in prices.
- Improve agricultural, forest and fisheries production through more efficient use of land, water, energy, and chemicals to meet the 9 Billion Challenge (United Nations 2013).
- Simultaneously increase the generation of renewable energy while reducing the impacts of infrastructure and land use change (e.g., wind farms, wells, pipelines) on fisheries and wildlife.
- Evaluate how food production, freshwater availability, and natural landscapes can coexist in a sustainable manner while facing the demands of a growing human population.
- Evaluate how different policy and economic scenarios might alter the future availability, utility, and resilience of natural resources.

Soils and Freshwater Resources — Adaptive and effective soil and water management strategies are necessary. Global climate and demographic change will further stress crucial water and soil resources.

- Quantify the benefits of technological innovation. Precision technologies (e.g., micro-irrigation) can enhance the sustainability of how humans use water and soil.
- Determine the capacity of soil and water reserves to meet current and future demands for agricultural and forest products.
- Evaluate the effectiveness of policies and incentives that promote soil and water conservation.
- Increase the spatial and temporal precision of climate simulations in order to improve the capability of climate-dependent natural resource models to predict outcomes under future climate scenarios (e.g., water availability; forest, rangeland, and crop response to drought persistence; and soil erosion).
- Predict and evaluate how a growing and urbanizing human populace with an overall increase in standard of living will affect how soils are managed and how water is allocated.
- Apply systems-level analytics to understand the complex feedbacks between humans, soil, and water and to identify key leverage points for policy makers in order to optimize the efficiency of public and private conservation expenditures.

Forestlands — Refined sustainable forest management practices and technologies will be required to meet the growing needs of an expanding and more diverse society.

- Create quantifiable measures of the cumulative effects of improved forest management, including harvesting and transportation practices, and products on integrated soil, water, ecosystem services and biodiversity protection needs.
- Research and identify forest management practices that support amelioration of climate change.
- Develop realistic economic assessments of the long-term

effect of current utilization rates on the resource and ecosystem productivity with the goal of determining the utilization rates needed to maintain forest health and reduce negative environmental effects, while meeting society's needs.

- Identify reasonable scale and utilization rates of resources to reduce negative environmental effects, e.g., limits for biomass removals to retain soil nutrients and organic matter and the effectiveness of intensive forestry for cellulose-based products in offsetting the need for tree harvests on ecologically or aesthetically sensitive sites.
- Identify forest management options for sustainable and economically viable use of non-forest timber products.
- Fully analyze the impacts of proposed large scale extraction projects, such as hydraulic fracking, on overall forest health and landscapes.

Rangelands — There is a fundamental need to advance knowledge of how rangeland ecosystems, socioeconomics, climate, and specific management practices change and interrelate over time.

- Emphasize and promote an integrated systems approach for research and outreach to improve policy formulation that supports the long-term sustainable management of dynamic rangeland ecosystems, including pastures and hayfields. Expand spatial and temporal scales of research to provide accurate measurements of the heterogeneous biophysical factors as well as response lags to management practices that influence rangeland productivity and the ecosystem services they provide.
- Promote transdisciplinary research to address cross-cutting social and biophysical factors that influence the dynamics of rangelands and tradeoffs resulting from changing demands for potentially competing ecosystem services.
- Develop protocols, document and assess contributions of science-based and local land management decisions to short- and long-term outcomes of conservation programs.

Biological Diversity — While the diversity of native flora and fauna —both aquatic and terrestrial—and ecological processes are integral to all of the mentioned systems, improved understanding of responses to and adaptation to climate change and land use change is a pressing need.

- Assess watershed and regional landscape connectivity factors for major groups of species, e.g., residential and migratory birds and mammals, with large area requirements, and pollinators.
- Monitor key wildlife populations and develop techniques for keeping them within the sustainable capacities of their habitats.
- Quantify native and invasive species responses to habitat changes imposed by climate and land use change and develop options that improve native species adaptation as well as invasive species containment or mitigation.
- Identify local and regional strategies for conservation of threatened and endangered species in light of likely climate and land change scenarios.
- Monitor the arrival and encroachment rate of invasive flora, insects, and diseases, and the resulting effects on biodiversity at the landscape level.

Marine and Coastal Ecosystems — To improve sustainability of marine and coastal ecosystems we must understand: (1) the status and trends of resource abundance and distribution through more accurate, timely assessments; (2) interspecies and habitat-species relationships to support forecasting of resource stability and sustainability; and (3) human-use patterns that influence resource stability and sustainability.

- Assess the coupled impacts of resource use and extraction (e.g., fisheries, ocean mining, tourism, energy) and systemic change.
- Monitor living resources at multiple trophic levels using both fishery-independent and fishery-dependent data

collected at appropriate levels of species resolution to understand and better identify physical, biological, and social thresholds and sustainability shifts.

- Promote marine spatial planning by developing and validating ecosystem and species interaction models.
- Develop approaches and scenarios to understand and integrate the specific and cumulative impacts of various natural resource policies on living resources and human communities.
- Conduct process studies and develop models to assess impact and recovery responses to natural and anthropogenic induced declines (e.g., linking effects of hypoxic zones to land use practices) in natural, biological or physical coastal and marine resources.
- Develop means to measure the impact of invasive species, aquaculture development, disease and pathogens, ocean warming and acidification, severe weather and coastal flooding/erosion on marine organisms and ecosystem function.
- Model release, dispersion, cycling, and cumulative ecological impacts of contaminants (e.g., from oil spills and releases, air emissions, and non-point sources of pollution).

Expected Outcomes

Status Quo — Disconnected silo-type research approaches may not only be economically inefficient but may also hinder a broader understanding of natural resource system dynamics and factors that influence the sustainability of such systems. Especially problematic is the lack of knowledge about feedback effects resulting from human economic activities on biophysical functions and processes that produce the ecosystem goods and services upon which human well-being is predicated. Moreover, an over-emphasis on reductionist science and the lack of focus on integrated systems-thinking approaches to problem solving with respect to the management of natural resources contradict the goal of sustainability, whereby future generations have the same right and ability to benefit from natural resources as current generations. It also inhibits the capacity of natural resources managers to adapt to changing biophysical and socioeconomic conditions; such adaptation requires a more integrative and holistic approach to the evaluation of the conditions and trends of natural resources.

New Directions

Future investments for research, education, and outreach relating to the provision and use of natural resources must promote systems-thinking approaches to developing new knowledge and novel solutions to natural resource challenges. Such approaches must incorporate rigorous scientific methodology with integrative modeling and adaptive management approaches to problem solving. Moreover, increasing emphasis needs to be placed on multidisciplinary research, education, planning, and outreach endeavors, all supported by the development of a comprehensive knowledge network for sustainability science. As the biophysical and social scientists increasingly interact in such integrative solution-oriented approaches, a wider range of knowledge bases as well as data acquisition and analytical tools need to be appreciated and utilized. These include scientific as well as local knowledge sets, and both quantitative and qualitative research methods. With such multifaceted approaches there is a greater potential that complex and dynamic natural resources systems can not only be better understood but also that natural resources managers will develop a greater capacity to adapt to changing biophysical and socioeconomic conditions. This is critical for the sustainable use of natural resources under changing conditions in an increasingly populated world.

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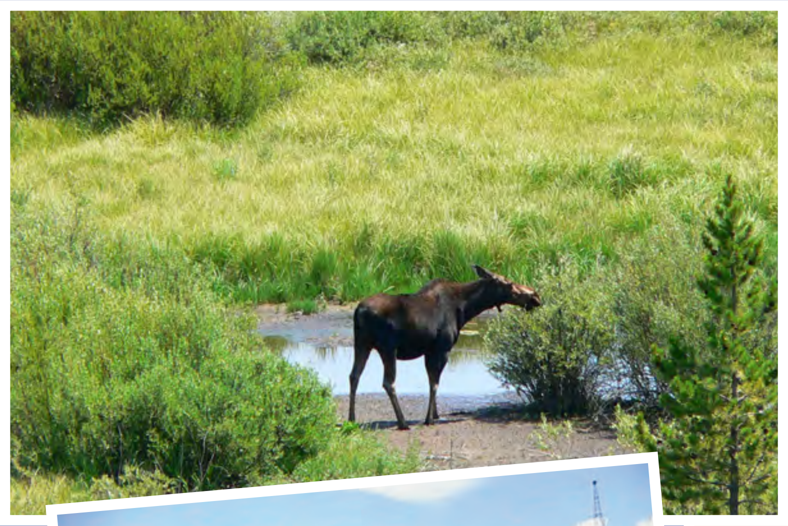
Grand Challenge 2: Water

We must restore, protect and conserve watersheds for biodiversity, water resources, pollution reduction and water security.

Framing the Issue

Humans, animals, plants, and terrestrial ecosystems depend on a consistent supply of freshwater. Indeed, most major civilizations have been formed near the sources of clean and abundant freshwater that are critical for drinking, raising agricultural crops, supporting industry, and transporting goods (Naiman et al. 1995). Although 71 percent of the earth's surface is covered by water, only about 2.5 percent of the earth's water is freshwater, primarily composed of groundwater and glaciers. Surface waters such as wetlands, lakes, and rivers comprise only 0.3 percent of total global water resources, which are constantly being cycled from rainfall to the oceans (Oki and Kanae 2006). Efficient and balanced use of clean freshwater supplies is critically important (Russi et al. 2013).

Scientists, managers, and policy makers have made great strides in improving water quality and equitable access to water in the U.S. The 1969 fire on the Cuyahoga River, Ohio was a major event that led to the passage of the Clean Water Act (CWA—originally the Federal Water Pollution Control Act of 1972). The CWA and subsequent updates and guidance have provided a solid framework for regulating direct discharge of pollutants into U.S. waters and have resulted in a reduction in certain types of water pollution. For example, the CWA led to the development of Best Management Practices (BMPs) for forestry and agriculture, which have helped to reduce sediment, nutrient, and pesticide discharges to waterways. The CWA also led to the development of the Total Maximum Daily Load program, which has helped managers to prioritize pollutant reductions based on localized watershed conditions, although this effort has been hampered by inadequate understanding of water quality thresholds and contaminant movements (Keisman and Shenk 2013).



Furthermore, an increased understanding of the importance of wetlands led to the 1985 Farm Bill "Swampbuster" Provision, which makes agricultural producers ineligible for certain farm programs if they convert wetlands to farmland. Wetland and stream mitigation policies and technologies have led to further protection and enhancement of water resources. For example, scientific breakthroughs including genetic alteration of plants have resulted in reduced water requirements for some crops (Paoletti and Pimentel 1996). Improvements in irrigation technology have led to the conservation of water in arid and semi-arid environments. Watershed modeling has provided information on attributes that contribute to a high quality and high functioning watershed. In spite of significant progress, we still have polluted waterways in agricultural, rural and urban areas, limited water availability in arid regions, water use conflicts even in humid regions, rivers with highly modified water flows and habitat connectivity, and deteriorated watersheds. A complex regulatory system that cannot always accommodate whole ecosystem services or all potential water users, the failure of our economic systems to properly account for externalities, and rigid institutional structures all contribute to these problems. Effectively addressing these challenges will require enhanced technology, policy, and management approaches.

There are potentially large economic and human welfare costs of failing to conserve water and sustain water quality. Recent unexpected droughts and floods in regions not previously thought vulnerable (e.g., drought in Georgia, Alabama, and Florida) demonstrate the need to plan for the unexpected. They further demonstrate the need to form more nimble water management institutions and adapt water law to allow more flexibility in times of stress.

Water also has cultural and recreational benefits to our society.

We rely on clean fresh water for spiritual and cultural activities. In some areas, recreational fishing, boating and swimming are the primary sources of income in regional economies. All of these uses depend on healthy ecosystems and healthy watersheds.

Researchers and managers increasingly recognize watersheds and aquifers as the proper scale for action when addressing nonpoint source pollution problems. Watersheds and aquifers form useful identifiable areas for management of water and other natural resources. Well-functioning watersheds are more resilient to external pollution loads, and their protection, restoration, and conservation at all scales (e.g., from headwater streams and wetlands to estuaries, bays, and oceans) are vitally important for maintaining biodiversity, water resources, and pollution reduction. High quality, functional watersheds are characterized by:

1. Naturally vegetated riparian zones and wetlands that assimilate nutrients, shade the water, reduce sedimentation, sequester carbon, and provide habitat for fish and wildlife;
2. Working, well maintained forests and grasslands that promote infiltration, resulting in cleaner water and reduced incidence of flooding;
3. Connected aquatic and terrestrial habitats, allowing for animal movement, plant dispersal, and recolonization of disturbed habitats and thus maintaining ecosystem function and biodiversity;
4. Dynamic flow regimes that support multiple water quality processes and aquatic physical regimes, including temperature dynamics, biogeochemical cycling, and geomorphological processes (woody debris, sediment deposition, floodplain connectivity), across spatial and temporal scales important to proper ecosystem functioning; and
5. Built-in natural redundancy—if one water source should fail or experience disturbance (e.g., wildfire), another is available for ecosystem services (and to provide source populations for plant and animal recolonization).

Watersheds can be resilient and accommodate a variety of land use changes and impacts. However, there can be tipping points at which cumulative water quality impacts move aquatic and wetland ecosystems to new quasi-equilibrium states associated with greatly diminished ecosystem services. A prominent example is the recurrent algal bloom and zone of hypoxia off the mouth of the Mississippi each summer due to excess nitrogen fertilizer leaching into the Mississippi tributaries. In some cases, watersheds require minimum flows and peak flow events to sustain aquatic biodiversity. Management of withdrawals and storage systems do not always take these concepts into consideration.

Future economic and environmental sustainability, human health, and population growth are all tied to and limited by the supply of water and the ecosystem services provided by healthy watersheds. Hullar (1996) grouped water issues into three key areas: (1) physical and hydrologic challenges, (2) biological problems, and (3) policies and institutions.

More recently, Kiang and others (2011) stress the impact of land use change, climate change and variability, and markets, policies, and regulations on watershed health and resilience. Water issues are becoming increasingly complex and require multi-disciplinary science to find cross-cutting solutions. There are a number of emerging factors that impact a watershed's ability to deliver clean and plentiful water supplies, including: (1) climate change and its potential effects on biodiversity, water availability, and water quality; (2) groundwater overdraft for urban and suburban water supplies and cropland irrigation, leading to depleted water tables and drying aquifers; (3) changing land use such as increased urbanization, which result in more impervious surfaces and leads to increased incidences of flooding and pollutant inputs; (4) contaminants, such as endocrine disruptors, or activities such as hydrofracking or mining and their impacts on aquatic life and human health; (5) deposition of atmospheric pollutants and impacts on surface water quality; (6) shifts in agricultural commodities or production methods, which may lead to increased erosion and sedimentation from conventional tillage or overgrazing, increased inputs of nitrogen, phosphorous, and carbon from fertilizer and livestock feed, and decreased stream flows due to surface diversions for irrigation; (7) estuarine eutrophication due to leaching of high levels of nitrate from fertilized farm fields; (8) emergence of legacy contaminant issues and the influence on water quality; and (9) overall increased demand on the water supply at regional domestic and international scales.

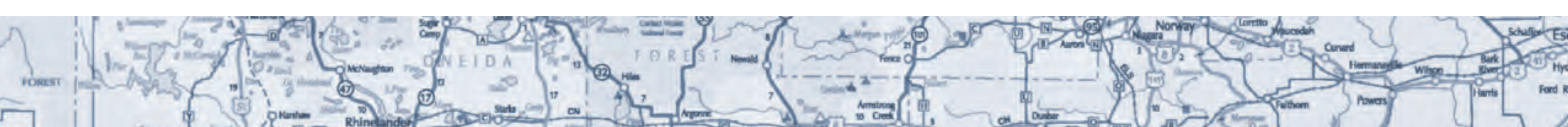
Watershed function (health and resilience) and water security (quantity, quality, and variability) are inter-related, and they must be sustained at local, regional, national, and global scales. For example, local communities are often more attuned and responsive to watershed conditions and thus are critical in developing rapid responses to perturbations. Regional-scale assessments and management includes potential conflicts across political boundaries (e.g., state, county), but usually at scales that are consistent with locally developed solutions.

National-scale policies and actions are important for multi-jurisdictional issues, but can involve more complex trade-offs and equity issues. Globally, watersheds encompass transboundary issues that have the potential to create international disputes and conflicts (Michel and Pandya 2009).

Lessons learned from studying watershed function and management within the U.S. are transferable to other parts of the world. In particular: (1) industrial and municipal wastewater and drinking water treatment technologies for improving water quality; (2) implementation of policies, laws, and rules for governance to promote fair water allocation and access; (3) political and technical interstate and interbasin transfer of water; and (4) redundancy of backup systems and conservation strategies.

Water Research Gaps

While the Clean Water Act has significantly decreased point sources of pollution, non-point sources of pollution such as sediment, excess nutrients, solar insolation (causing high summer water temperatures), and urban runoff continue to plague many of the nation's waterways. Research has significantly advanced our understanding of the importance of aquatic physical regimes, including temperature, sediment, wood debris input, and flow, for maintaining functioning flowing water ecosystems from headwaters to estuaries. Our understanding of the watershed processes that contribute to functioning non-flowing water systems, from small ephemerally flooded wetlands to the Great Lakes, has also improved. This understanding has yet to be fully implemented in a policy framework—we monitor and regulate systems using maximum daily loads and maximum or minimum threshold values rather than maintaining spatially explicit, regime-based water quality standards that may be more relevant for maintaining watershed function.



Successfully conserving watersheds for biodiversity and water quality requires holistic, interdisciplinary research. This research can be paired with policy and social-science studies to develop science-based solutions to on-the-ground problems. To foster public support and understanding of policy changes, research needs to be accompanied by outreach and education focused on policy outcomes that translate to improvements in human quality of life and biodiversity.

The impacts of natural and human disturbances, including silviculture, agriculture, and urbanization on freshwater and coastal marine habitats are generally well understood, but in a piecemeal fashion. While we understand that water quality stressors are inter-related, our knowledge of system responses to pollutants is usually based on a series of bivariate relationships (i.e., one response variable and one stressor). Watershed urbanization imposes broad simultaneous changes to many aspects of stream function, and prioritizing stressors is difficult (Wenger et al. 2009). Further stressors include nonnative species introductions, interbasin transfers, and habitat and species homogenization. We generally lack a full understanding of how these changes in habitat translate to changes in watershed biodiversity and ecosystem functioning (e.g., Jackson and Pringle 2010). A better understanding of linkages could inform policy aimed at setting meaningful water quality thresholds, the maximum human footprint levels in a watershed, or regime-based standards for water quality and quantity that are necessary to maintain ecosystem function and biological diversity from headwater streams to estuaries (e.g., Poole et al. 2004, Ice et al. 2004). To be effective, regulatory thresholds and/or landscape planning must be spatially explicit to protect areas of watersheds or landscapes that are more vulnerable than others or more essential for ecosystem functioning and water quality (e.g., areas of groundwater recharge, riparian areas, wetlands, or floodplain habitats) (Wickham and Flather 2013).

Despite our broad understanding of the impacts of human activity on water quality and quantity, watershed planners face a variety of unknowns, including changing economic conditions for crop production (e.g., corn production for ethanol markets), the impact of new extractive technologies (e.g., hydrofracking), and issues for which there is little guidance, such as minimizing and mitigating introductions of nonnative species. In addition, the energy-water nexus continues to dominate many aspects of water quality and quantity as energy extraction can sometimes both use and contaminate water (e.g., through damming, acid mine drainage, mine tailings, hydrofracking solutions), while cheaper energy increases options for water supply (e.g., desalination).

Further complicating planning is a lack of technology to process and distribute water in a manner that ensures consistent and high quality supply to both human users and the ecosystem services expected from freshwater habitats. In particular, we lack sufficient techniques for removing pharmaceutical waste from wastewater, which may impact to an unknown extent the integrity of biological systems, animal behavior (both domestic and wildlife), and human health. It may be more effective to consider watershed mitigation activities that address water quality and aquatic ecosystem function holistically rather than through ad-hoc implementation of simple and individual water properties and attributes (e.g., temperature, nutrient loads). In addition, the importance of understanding watershed physical regimes (water quantity and stream flow, thermal regimes, and groundwater recharge) necessitates the advent and advancement of technology that allows us to monitor and manage water in real-time.

Finally, we must understand the policies—including mitigation requirements, watershed management, and water allocation—that best contribute to sustaining aquatic ecosystem services in the face of human land use activities, natural disturbance, and climate change. Resistance, the ability of an ecosystem to maintain function when disturbed or undergoing environmental change, and resilience, the ability of an ecosystem to rapidly return to a pre-disturbance state, are increasingly important research topics. This importance increases given the increased impact on society from natural disasters, including drought, hurricanes, and wildfire. Intact systems with a full complement of native fauna appear more resistant to the impacts of disaster, and redundancy in water supplies and key habitat features allows for increased resilience in human and biological communities should important primary water supplies or habitats become temporarily unavailable. Policies must facilitate spatially explicit management, and focus on resistance and resiliency that are most relevant in our most disaster-prone areas (e.g., coastal habitats, areas prone to drought, wildfires and areas of high-seismic activity).

Ultimately, to sustain watershed functioning and water security at a range of geographic scales, we need to understand which human factors impact water and energy security, water quantity, and water quality at the local, regional, national, and global levels. Human factors include impacts of existing energy policy (biofuels, hydrofracking, drilling, atmospheric deposition from coal fired power plants, pipelines, mineral extraction), forest management policy (streamside management zones, and other BMPs), agriculture policy (water subsidies and other agriculture policies and practices that lead to unsustainable water use), residential and urban development (land-use and city planning), and transportation (urban sprawl, mass transit, and highway development). Policies appropriate for each factor across the range of scales are required to ensure a balance of water supply with demand, and resilience of supply in the face of unexpected disaster, disturbance and ongoing climate change. In summary, we need to understand which policies lead to a watershed-specific 'tipping point' from fully functioning to impaired.

Research Needs and Priorities

In the United States, a number of water quality challenges, particularly related to point sources of pollution, have been effectively addressed. The water problems we face now are more complex and multi-dimensional. Developing solutions will require inter-disciplinary approaches involving the social and natural sciences. This integration of physical, biological, and social sciences can help to create linkages between the science and management that allow for adaptive approaches to both. Prioritizing challenges and research needs will help lead to the development of more efficient and effective environmental policies. Gold et al. (2013) and APLU (2010) outline a set of research needs for water in agriculture. Here we expand this scope beyond agriculture to propose five research themes and associated objectives for moving water quantity and quality management forward.

Theme I: Improve understanding of mechanistic linkages between land uses, extractive consumption of water resources, and watershed resistance and resilience to better inform policy.

- Quantify loads and impacts of nutrients in watersheds. Identify methods to reduce loads while maintaining healthy economies.
- Identify meaningful water quality thresholds related to biological and human health.

- Determine the undeveloped footprints needed in watersheds to buffer hydrologic and water quality changes and sustain biodiversity, water quality, or water quantity.
- Identify the land use variables (indicators) that impact watershed biodiversity and associated thresholds (tipping points) beyond which watersheds are impacted or degraded.
- Define components of natural regimes (flow, temperature, natural vegetation) required to maintain ecosystem services, and develop regime-based standards for water quality and quantity that are necessary to maintain ecosystem function and biological diversity, from headwater streams to estuaries.
- Improve understanding of sub-surface flow and groundwater and surface water interactions, which can be crucial for biological communities and provide mechanisms for resilience to drought, climate warming, and disturbance.
- Improve understanding of groundwater recharge and contaminant fate and transport in both ground and surface waters.
- Define achievable restoration targets for forested, urban, agricultural, aquatic and wetland systems.

Theme 2: Improve understanding of risks and impacts to water supplies from extractive uses, carbon sequestration technologies, and extractive technologies.

Quantify current agriculture use and overdraft.

- Quantify the impacts of increased irrigation due to drought and changing climate in agricultural areas and define sustainable use limits.
- Improve understanding of the presence of introduced chemicals and resulting byproducts resulting from hydrofracking.
- Improve understanding of the presence of introduced chemicals and resulting byproducts resulting from carbon injection in deep water wells.

Theme 3: Improve technology to process and distribute water in a manner that ensures sustainable, high quality water for human uses and maintenance of ecosystem services.

- Develop techniques and processes for removing pharmaceuticals from wastewater.
- Develop technology that allows us to monitor and manage water systems in real-time.
- Identify spatially explicit landscape and groundwater features that provide mechanisms of resistance and resilience to natural and man-caused hazards, particularly in our most disaster-prone areas (e.g., coastal habitats, areas prone to wildfire and areas of high-seismic activity).
- Increase precision of groundwater data and modeling to better manage lands that recharge aquifers to increase aquifer yield and prevent groundwater quality deterioration from agricultural and other sources.
- Apply geospatial approaches such as modeling and remote sensing technologies to better model water quality and quantify future water supply and demand at regional and national scales.
- Use satellite and advanced information technologies to predict potential water conflict at all scales (inter- and intra-basin) and inform policy and management.

Theme 4: Develop understanding of how existing and future policies and land uses impact water security, quantity, and quality over regional and national scales.

- Engage communities early, and in meaningful ways, in decision and policy making processes at the watershed level, giving them a voice and ensuring that the results are implementable and effective.

- Identify water impacts resulting from existing energy policy (e.g., production of biofuels, hydrofracking, oil drilling, atmospheric deposition from coal fired power plants, pipelines, mineral extraction, carbon injection, acid mine drainage, valley fill from mountaintop removal mining) and potential solutions.
- Identify regional and national water impacts resulting from existing forest, rangeland, and agriculture policies and subsidies (e.g., water allocation laws, existing national cropping and grazing patterns resulting from farm bill incentives relative to local supplies and resiliency) and potential solutions.
- Define water impacts resulting from existing regional and national residential and urban development patterns and identify potential alternatives and solutions.
- Examine water impacts resulting from existing transportation patterns and policies (e.g., impervious surface, sprawl, habitat loss, introduction of metals and salts into aquatic ecosystems), and analyze effects of potential solutions (e.g., mass transit, high speed rail, cluster development, etc.).
- Analyze inter- and intra-basin policy alternatives required to ensure a balance of water supply with demand and resilience of supply in the face of unexpected disaster and ongoing climate change.
- Analyze the importance of scale for watershed management and BMPs implementation to maximize cost effectiveness and ecological benefits and environmental services.
- Assess the optimal places to focus future production of timber, bioenergy crops, commodity crops, fruits and vegetables, and livestock grazing within sustainable water use limits.
- Assess the regional and national future water pricing, policy, conservation, and management programs needed to balance national water demand with sustainable supply.

Theme 5: Assess how the intersection of social (or human) and natural (or evironmental) systems impact water security, quantity and quality.

- Increase use of hydro-economics to understand and predict how new technologies and policies will ultimately affect the condition of the targeted water resource systems.
- Increase economic understanding of management alternatives for wetland and aquatic systems.
- Enhance use of benefit/cost analysis and policies to increase understanding of public opinion (and determinants of) concerning economic-environmental trade-offs in watersheds.
- Increase social science research that identifies decision-making processes that are necessary for watershed solutions.
- Increase understanding of how educational, incentive, or regulatory tools change the behavior of the individual and institutional users of water resources.
- Develop a holistic understanding of our water resources in a systems context.

Expected Outcomes

Water is a key component of our ecosystems and our economy. While significant progress has been made in protecting and restoring our watersheds, there is a need to continue and even accelerate our efforts. Additional research, education, and outreach efforts are needed to better understand the challenges we face in protecting, restoring, and conserving our watersheds and aquifers.

Implementation of the *NR Roadmap* will create the knowledge necessary to inform policy decisions that can result in more

resilient watersheds with improved watershed quality, security, and water supply. More resilient watersheds can better adapt to climate change, land use change, population growth, and other processes. These watersheds will be able to provide economic services while also providing ecosystem and environmental benefits. This will increase our ability to produce food, fiber, and abundant and safe drinking water with decreased watershed stress related to water pollution and overuse of water supplies.

Specifically, implementation of the *NR Roadmap* will assist us in sustaining watershed functioning and water security at a range of scales by proactively implementing BMPs and conservation alternatives, management strategies, watershed planning, and comprehensive conservation policies, all in balance with societal needs. It will allow us to identify opportunities for improved water management, provide baselines for evaluating trends in water supply and water quality, identify threats to water supply in a spatially explicit manner, and provide broad geographic context for assessing the consequences of not addressing threats.

Implementation of the *NR Roadmap* will help inform policy from the local to the global level. It will give communities the information they need to ensure that land use in watersheds will be sustainable. As a result, communities will be better able to recover from disturbance and interruption of clean water supply from natural disasters. The science in this roadmap will inform policies related to energy, forestry, agriculture, land use, and transportation in ways that will improve water demand management and sustain water quality and supply.

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Grand Challenge 3: Climate Change

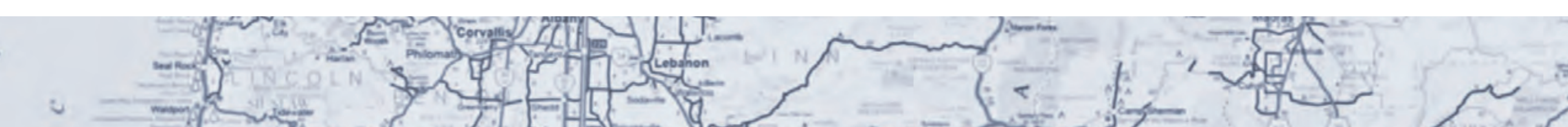
We need to understand the impacts of climate change on our environment, including such aspects as disease transmission, air quality, water supply, ecosystems, fire, species survival, and pest risk. Further, we must develop a comprehensive strategy for managing natural resources to adapt to climate changes.

Framing the Issue

Natural and managed ecosystems are presently undergoing changes in many respects at rates and magnitudes that mankind has never previously witnessed. The key drivers of these changes are traceable to human civilization, and climate change is one such driver. Climate change involve atmospheric composition, temperature statistics, rainfall statistics, sea level rise, the frequency and severity of extreme events, and many other characteristics of the climate system.

The Earth's climate is always changing, and ecosystem changes are known to have taken place during the past 10,000 years even while the climate was relatively stable. Present-day climate change, including but not limited to change caused by our alteration of greenhouse gas concentrations, is almost certain to move the Earth's global mean temperature beyond the limits of the past 10,000 years (Marcott et al. 2013), is likely to move it beyond the nominal 2°C (above preindustrial temperatures) limit of the past few hundred thousand years (Masson-Delmotte et al. 2013), and in some circumstances may cause global temperatures to exceed the bounds of the past few million years (Dowsett et al. 2010). The wide range of future possibilities, in not only temperature change but also sea level rise and altered storminess, make quantifying the future impacts of climate change difficult.

Much of the challenge of understanding the interaction between climate change and ecosystems is that present-day climate change is relatively small and within the bounds of recent variability, while most projections foresee much larger future changes. At the local level, changes in weather patterns over the past few decades are sometimes as much or more a product of natural variability as climate change. This makes it all the more challenging to distinguish effects caused by climate change from effects caused by other



external or internal drivers. Also, climate change responses will likely not be linear, meaning that as the climate changes beyond its recent geological envelope, many new and unforeseen ecosystem responses are likely to emerge.

As a society, we must seriously explore the potential impacts of climate change on ecosystem structure and function. Ecosystems are critical components of cultural, social, and economic systems. Ecosystems produce an array of critical services that support our society, including but not limited to regulation of water quantity and quality, carbon sequestration, provision of renewable natural resources, harboring biodiversity, supporting wildlife and fisheries, and providing recreation opportunities.

At the same time that we must understand how climate will impact ecosystem structure and function, we will also benefit by understanding how ecosystems themselves have the potential to mitigate or exacerbate climate change through natural responses and manag=ement choices. For example, because ecosystems store large quantities of carbon in soils and biomass, many ecosystems such as forests have the potential to feedback positively or negatively on atmospheric CO_2. Whether such feedbacks are positive or negative will depend both on forest management and interactions with other human influences on the environment such as atmospheric nitrogen deposition (Templer et al. 2012). The permafrost underlying the Arctic tundra has stored carbon reserves on the same order of magnitude as the total human release of CO_2 to the atmosphere to date. The melting of the tundra is therefore one of the largest single threats to rapidly increase the global atmospheric CO_2 concentration (Schaefer et al. 2011).

Climate change affects agriculture directly because crops are sensitive to temperature and precipitation and to extreme weather events such as intense rain events, flooding, frost, heat waves, and drought. Climate change also affects agriculture indirectly by changing the natural resource

base it is built upon, such as water available for irrigation. Regional climate warming has already caused snowpack in western mountain ranges to melt more rapidly, causing diminished dry-season streamflows and reduced water availability for irrigation. Agriculture is perhaps the economic sector in the United States most vulnerable to climate change; agriculture is the largest water user in the United States and accounts for 80-90% of consumptive water use in the western United States (U.S. Department of Agriculture [USDA] 2012).

Climate change affects the emergence and re-emergence of diseases of humans, livestock and other animals, as well as plants, and can be viewed under the national and global concept of One Health (2014)) and phenology for plants and animals, the central focus of the USA National Phenology Network (USA-NPN 2014). Changes in distribution and abundance of vectors such as mosquitoes and ticks and both native and exotic vertebrate host species change risk profiles for pathogen transmission and subsequent diseases of humans, livestock and wildlife (Tabachnick 2010). Likewise, invasive species and their negative impact on recreation and economics is well recognized, costing for example, the Great Lakes Region ~$200 million dollars per year (Rothlisberger et al. 2012). Increasing globalization of trade is enhancing the mobility of potentially invasive species, and climate change can make them more suited to a local climate than the native species (Drake et al. 2007, Litchman 2010, Strain 2012). New waterborne diseases and outbreaks (WBDOs) are spreading in a similar way. For example, Hong et al. (2006) have documented the presence of a subtropical neurotoxin-producing cyanobacterium (*Cylindrospermopsis raciborskii*) in Muskegon Lake, Michigan (USA). Climate-driven anomalies associated with global climate variability patterns (Linthicum et al. 2010) are also responsible for epidemic and epizootic events of both infectious and vector-borne pathogens including diarrheal diseases, cholera, bluetongue, Rift Valley fever, dengue, and malaria. Assessing risks and developing strategies to focus interdisciplinary research and to mitigate these complex systems against global health threats require adaptation in scientific and policy considerations at all levels (Caceres 2012).

Understanding the magnitude and direction of the direct and indirect effects of climate change on ecosystems, combined with the effect of ecosystem changes on climate, are among the most important questions facing ecologists and natural resource scientists and managers in the 21st century.

Current Capacity and Science Gaps

Our knowledge about responses of ecosystems to climate change lies along two continua: from single components of climate change to the complete suite of climate change effects, and from the response of individual organisms or characteristics to the response of entire ecosystems, including human components (Figure 3).

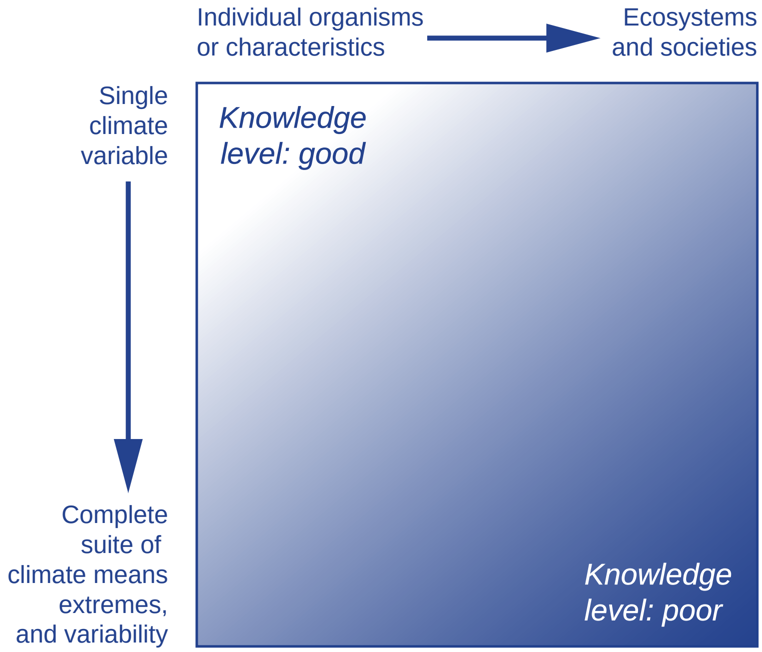


Figure 3. Level of knowledge concerning climate change impacts along climate and environmental complexity continua.

In general, our understanding of the response of individual organisms or characteristics to a single component of climate change is relatively good, because questions of this sort are amenable to experimentation and often a wide variety of observations are available. Although studies are emerging that account for effects over many generations of rapidly growing microorganisms (Lohbeck et al. 2012), it still remains a challenge to adequately approach appropriately long timescales for larger organisms (months, years and longer), as well as timescales relevant for evolution (Vose et al. 2012).

Our knowledge is much more scarce when considering entire biomes. We have a general sense of the effects of climate change on ecosystems from the behavior of individual species. Increases in CO_2 concentration generally lead to increases in water use efficiency, and often but not always enhance net primary production and carbon storage (Andreu-Hayles et al. 2011, Keenan et al. 2013). Increases in temperature lead to phenological responses in freshwater (Berger et al. 2010), marine (Winder et al. 2012), and terrestrial environments (Cleland et al. 2012). Increased ocean acidification due to increased CO_2 loading is hypothesized to cause negative effects on calcifying organisms (Lohbeck et al. 2012), and food web transfer between trophic levels (Rossoll et al. 2012) and may be partially responsible for the rapid expansion of the oxygen minimum zones in the oceans (e.g., Gilly et al. 2013). Terrestrial ecosystems respond to increased precipitation by increasing net primary production and carbon storage (Sala et al. 1988, Knapp and Smith 2001). However, ecosystems are more than a collection of independently acting species, and our understanding of how species interactions will be impacted by climate change is rudimentary (see, e.g., discussion in Thingstad et al. 2008). These interactions will be critical determinants of future changes in ecosystem structure and function, and thus direct and indirect effects on cultural, social, and economic systems.

Scale issues remain a problem for most ecosystems studies. While some plankton ecosystems have been successfully manipulated in large-scale water enclosures, known as mesocosms (e.g., Riebesell et al. 2010), larger or more complex systems are more difficult to treat holistically. For example, in forest systems, climate change effects research has focused on individual trees, usually seedlings or small individuals. Research on stands is rare due to the difficulty of manipulating most climate-change factors at large scales, and studies on interactive effects (involving multiple climate factors) are almost non-existent (Vose et al. 2012). Most ecosystems are tightly linked to human systems through the services they provide, yet funding for human dimensions research as it pertains to natural resource management, such as ecosystem services, natural resource policy, and environmental education, is even more limited than the biophysical research on these systems. Ecosystem perturbations driven by climate change will have direct impacts on natural resources and thus on jobs, economic growth, health, and well-being. While it is relatively straightforward to predict how changing temperature and precipitation will alter water quantity (Sun et al. 2011), it is much harder to determine how natural resource productivity will be sustained as water quality and quantity change within and across biomes. The United Nations Conference on Sustainable Development (2012) and the United Nations Development Program (Kjørven 2012) have both recently noted many emerging research topics that are essential to the management and sustainability of the natural resource base on our planet.

As scientists attempt to fill gaps by expanding our knowledge of individual effects, it is also possible to work from the observed effects of a changing climate. The response of ecosystems to past or ongoing climate change is often the first and best empirical data we have to predict future responses. However, natural resource changes are complex and are also strongly affected by increasing human populations searching for better standards of living, increased energy demands, housing, and food. Changing habitats will be a major factor in determining how climate change impacts the earth. Because future climate change will not necessarily match past climate change, it is necessary to develop a mechanistic knowledge of the particular aspects of climate change that are likely to have the greatest impacts. For example, the rapid increase in Oxygen Minimum Zones (OMZ) in the world oceans (e.g., Gilly et al. 2013) is thought to be related to climate change through changes in weather patterns in turn altering ocean currents. Many ecosystem changes, such as earlier growing season starts, earlier migration arrivals, and species distributions shifting upward in elevation and pole-ward, are explainable as a direct consequence of changing temperatures. However, the more complex interactions must be studied in the context of entire ecosystems to be understood, because present models fail to explain these mechanisms. In fact, whereas many ecosystem-scale models have been developed that can explain observed changes (i.e., hindcast), few if any biological ecosystem models forecast complex interactions with any accuracy (see examples from marine ecosystem models tested on an ecosystem-scale in mesocosms [Thingstad and Cuevas 2010]).

To predict future ecosystem changes, it is further necessary to predict future changes in climate. At present, such predictions are rudimentary and uncertain. Challenges in estimating future emissions, and the strength of climate feedbacks, mean that estimates of global temperatures in the year 2100 vary by several degrees Celsius. Scale issues are important here as well: at the local level, some aspects of climate change seem relatively certain such as temperature changes, while other aspects are much more poorly known. For example, just about everywhere in the United States there are some climate models that project an increase in summertime precipitation and others that project a decrease (Scheff and Frierson 2012).

Uncertainties in future climatic conditions are but one source of uncertainty. Universities and their federal, state, non-profit and private partners have a wealth of scientific expertise on how to quantify population, metapopulation and community dynamics and the relationship of fish and wildlife to habitats (e.g., Brodie et al. 2013, Parn et al. 2011, Schwartz 2012, Weber and Brown 2013). For many decades, scientists have been studying and modeling factors that impact species' persistence and then implementing necessary conservation and management actions (e.g., Langwig et al. 2012, Peron and Koons 2012). The great challenge and gap, albeit a gap that is closing with modern technologies and improved statistical knowledge, is to quantify and understand the uncertainty and variability in population, metapopulation and community dynamics, habitat ecology, and climate change and to then incorporate that uncertainty and variability into management actions. We also need to bridge gaps among the physical, biological, and social sciences by encouraging interdisciplinary teams that will link climate change models to habitat models to models of population and community dynamics (e.g., Gieder et al. 2014). As such integrated models become accurate, we will need to translate their predictions into actionable knowledge for natural resource managers and policymakers.

Much research has focused on the potential environmental and economic impacts of climate changes. How these impacts are distributed spatially and across socioeconomic groups are not well understood. Are low-income households more vulnerable to climate change? How will climate-related changes impact the economical basis for rural versus urban communities, and thus demography and infrastructure? In addition, we have limited information about the extent to which climate change impacts can be reduced through adaptive management. But this information is critical to determine the benefits and costs of proactively managing climate change risks. In some cases, it may be best to prevent emerging threats, while in other cases it may be best to simply deal with the consequences as they occur.

Ultimately, these combinations of uncertainty mean that the challenge of natural resource management in a changing climate is fundamentally an exercise in risk management. Understanding the potential impact of climate change and the benefits and costs of proactively managing climate change risks is the ultimate challenge for economic research on climate change. These challenges include:

- What are the potential economic impacts of climate change at local, state, regional, national, and global levels, and on individuals, businesses, and public institutions?
- What are distributional impacts of climate change? In other words, how does climate change affect populations in different regions and income groups?
- What are the opportunity costs of proactive adaptive management?
- How do uncertainty and irreversibility affect the benefits and costs of climate change risk management?

Society has historically not done a very good job with risk management. Policymakers tend to advocate the elimination of risk, even though elimination of risk may be cost-prohibitive or technologically impractical. For example, many government organizations (e.g., the Great Lakes Restoration Initiative) and non-government organizations are calling for a "zero tolerance level" of aquatic invasive species and water-borne disease outbreaks through early detection surveillance, rapid response capability, and development of ballast water technology. Traditional sampling practices of netting, trapping, or time series analysis will not accomplish these goals.

Research Needs and Priorities

Much could be written about promising approaches for reducing the various knowledge gaps discussed in the previous section. Here we highlight some overarching research themes that apply across many subdisciplines and offer the greatest potential for practical knowledge gains.

Observational and Experimental Approaches

Many of the greatest challenges in understanding the effects of climate change on natural resources involve interactions between multiple climate variables, natural processes, and society. Ecosystem responses to climate change are contingent upon

a large number of location, history, and stochastic variables. Among the highest-priority research challenges are to:

- Identify signals of climate change that inform short-, intermediate-, and long-term predictions, forecasting, and early warning involving whole-system structure and function;
- Define effects of predicted climate change on nature-human interactions;
- Define interactions and effects of climate and habitat changes on population, meta-population, and community dynamics and change at ecosystem boundaries, along habitat gradients, and within ocean current systems, at local to regional scales;
- Develop early warning systems (e.g., real-time analyses) that utilize confluences of modeling technologies in predicting changes and are informative to governments, agencies, and the public at large;
- Prioritize resources for research in different geographical areas on the basis of level of present understanding, the speed of environmental change, and the potential for far-reaching impacts.
- Develop practical technologies for measuring, analyzing, and assessing environmental responses to climate change, especially on full ecosystem levels to separate single species vulnerability from system resilience; and
- Support long-term ecosystem research that offers unique opportunities to study responses to recent climate change as well as capturing ecosystem response to stochastic events along the way.

Simulations and Modeling

Computer models, whether statistical, dynamical, or mixed, provide useful tools for testing our understanding of the behavior of natural and human systems. If such models have been validated, they can serve as valuable planning and management tools utilizing long-term data sets (e.g., Dodds et al. 2012, Hunt and Nuttle 2007). Key needs are to:

- Develop mechanistic ecosystem models with predictive power comparable to statistical models, suitable for ecosystem management planning under uncertain or novel climatic futures;
- Improve climate-based models for areas where we presently are expecting the most rapid global impacts, such as for the melting tundra where present models predict a third of the global soil carbon may be released as CO_2 within decades (e.g., Dorrepaal et al. 2009);
- Improve climate-based models for key insects, diseases, disease vector dynamics, and potential human, animal and plant health impacts;
- Improve methods for quantifying carbon pools and fluxes suitable for use by resource managers and incorporation into ongoing inventory programs such as

those for fisheries, forestry, and agriculture;

- Improve models for predicting changing hydrologic regime impacts on natural and managed ecosystems – e.g., range or forest health and yield under warmer scenarios with increased evapotranspiration; and
- Coordinate climate and ecosystem researchers and data for improved modeling of weather variability and extreme cyclical events (wildfire, insect and disease, cyclonic storms, etc.) and their alteration by predicted or forecast climate change.

Management, Risk and Uncertainty

Risk evaluation and management of natural resources in the context of climate change requires real-time monitoring data, comprehensive exploration of the consequence of management choices, and models for testing management hypotheses. Cross-disciplinary knowledge of the uncertainties associated with climate change and climate change impacts is especially poor, leading inevitably to poor or biased understanding of uncertainty by natural resource managers and other stakeholders. Among the highest-priority challenges are to:

- Determine the uncertainties in estimates of ongoing and future local and regional climate change that arise from potential errors in climate change drivers, model simulations, and natural variability;
- Identify and estimate location-specific climate drivers and their uncertainties under a range of future scenarios;
- Define the impacts of uncertainty and irreversibility associated with climate change and their impacts on management strategies and public policies for mitigating climate change impacts;
- Develop improved communication language and education from the scientists/researcher to the decision maker/politician/land manager, and public at-large; and
- Define best-practice tools and processes for quantifying and assessing risk (vulnerability, susceptibility, and probability) under typical natural resource management scenarios and for better managing under uncertain future conditions.

Expected Outcomes

Climate change impacts are complex, that is, they cut cross traditional population, community, and ecosystem boundaries, and they are often not fully understood unless the cumulative impacts can be quantified across large spatial and long temporal scales. Research efforts to address cumulative impacts of climate change, and to quantify and understand uncertainty related to the impacts, will enable us to effectively use our limited resources to prioritize mitigation strategies and manage climate change risks at a scale that will lead to the best outcome. Research, teaching, and outreach are the key components to preparing for, mitigating, and adapting to future climate changes. Better coupling of teaching (kindergarten through graduate school) and outreach

(to professionals, policymakers, and the general public) functions to research efforts are central to achieving meaningful societal outcomes. These coupling functions must operate multi-directionally, allowing for crosstalk and feedback among functions that will enhance the efficiency and effectiveness of the research, education and outreach enterprises.

Presently, natural resource management agencies are addressing climate change impacts and threats with the existing laws and regulations, including the Endangered Species Act, National Environmental Policy Act, Clean Water Act, and Clean Air Act. Industries, municipalities, land trusts, NGOs, and private citizens are also adapting in many instances with the knowledge and resources available to them. University research, teaching and outreach programs will lead to the development and implementation of improved adaptation measures, public policy and management tools for the natural resources systems that we rely upon for economic goods and services. Adopting these policies and measures will lead to more effective mitigation actions and will better prepare us for climate change risks.

Specifically, the expected outcomes from adopting recommendations in the *NR Roadmap* include:

- Improved outreach education and communication of climate change effects and adaptation strategies;
- Improved adaptation strategies for all stakeholders;
- Additional management and evaluation tools for natural resource managers;
- Improved mitigation and conflict resolution for resource managers;
- Improved allocation of resources to manage risks associated with climate change and variation;
- Rational, scientifically informed public policy for addressing climate change issues;
- Discovery of new paradigms supporting real-time management; and
- Discovery of new technologies for monitoring, evaluating, adapting and managing resources, risk, and mitigation.

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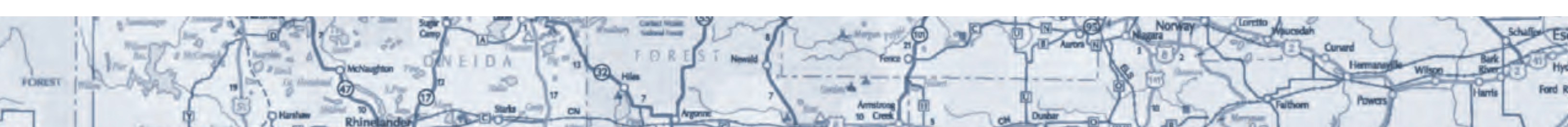

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Grand Challenge 4: Agriculture

We must develop a sustainable, profitable, and environmentally responsible agriculture industry.

Framing the Issue

The Delphi survey named agriculture as one of the six grand challenges of natural resources. We have chosen in the *NR Roadmap* to reference the ESCOP *Science Roadmap for Agriculture* (APLU 2010) rather than writing a chapter specifically on creating sustainable agriculture. However, we would be remiss if we did not highlight the importance of developing a sustainable agricultural industry to the sustainability of our natural resources. Furthermore, we must also point out that agriculture cannot exist without the natural resources base upon which it exists, namely clean and abundant water, healthy soils, pollinators, genetic biodiversity, and a stable climate.

To demonstrate the degree of overlap between the natural resources and agriculture, we have examined the goals under the challenges in both roadmaps and looked for commonalities. We present the areas of overlap in Appendix C.

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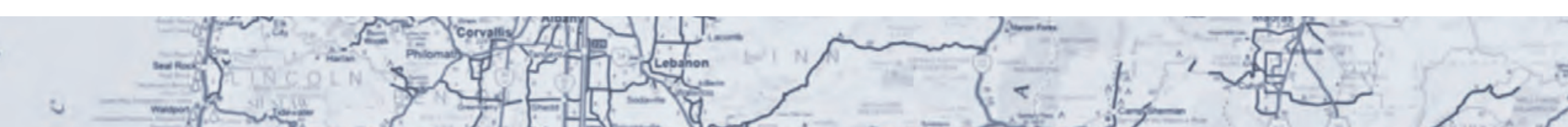


Grand Challenge 5: Energy

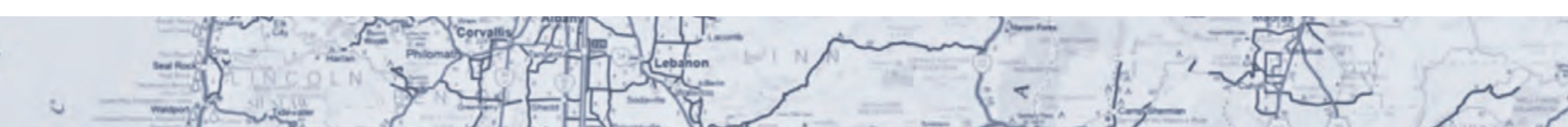
We must identify new and alternative renewable energy sources and improve the efficiency of existing renewable resource-based energy to meet increasing energy demands while reducing the ecological footprint of energy production and consumption.

Framing the Issue

Throughout history, all civilizations have depended on some type of energy, but modern society consumes vast quantities of energy. Energy consumption is a primary base upon which the U.S. economy rests. From transportation to food production and consumption to climate-controlled buildings to manufacturing to delivery of tap water to households, Americans could not live in the manner they are accustomed if not for large energy production, availability, and consumption.

Between 1980 and 2000, U.S. energy usage grew 21%. Though the past decade has seen some plateauing of energy consumption in the U.S., energy consumption is expected to rise again as the economy cycles back into a strong growth period. Even now, the U.S. is increasing exports of natural gas. To support this current and growing consumption, the U.S. expends a great deal of capital and resources to produce or purchase energy sources.

Energy production and transformation, no matter the source, creates stresses on the environment. This chapter examines those impacts and ask what gaps in knowledge exist and where we need to focus our research. This is meant to be a high-level, broad overview of the intersection of energy and natural resources. By necessity, most topics are covered briefly. Furthermore, the chapter is not intended to be all inclusive, but to focus particularly on new and developing energy sources. That said, some traditional energy sources are raising new questions related to natural resources. In particular, hydrofracking has raised a variety of new natural resources issues. This chapter does not address research related to energy efficiency although there have been remarkable gains in this area over the past 20 years. Continued improvements in energy efficiency



represent a key opportunity for meeting energy demands of the world's growing human population.

When considering the impact of energy production and use on natural resources, it is useful to divide the sources of energy into non-renewable and renewable. Non-renewable energy sources include traditional sources such as coal, petroleum, natural gas, and nuclear. Renewable energy sources include hydropower, wind, solar, geothermal, marine, and biomass/bioenergy.

The impacts on natural resources and society from the extraction, production, and use of non-renewable energy are fairly well-known. Nuclear energy risks potential releases of radiation and the concomitant dangers of those releases as well as release of excess heat into the atmosphere and water bodies. Coal production raises concerns about mining and its effects on local ecosystems, particularly water contamination, soil erosion, and loss of biodiversity. Historically, its associated air pollution has been costly to the environment, particularly in the form of acid rain down-wind from coal burning facilities. Oil production and delivery comes with concerns about oil spills, water contamination, habitat disturbance, air pollution, and noise. Natural gas production and delivery brings concerns about air pollution, land and habitat fragmentation, and water contamination. Hydrofracking may add to this list of concerns for natural gas production, so additional research will be needed in that area. The biggest challenge for these traditional carbon-based energy sources, however, has been the growing knowledge and evidence of their impact on climate change. Concern about climate change has led the coal-related industries to research carbon sequestration as a tool to reduce their carbon emissions. Because this technology is still under development, additional research on impacts of natural resources of carbon sequestration from coal will be needed.

Renewable energy research during the coming decades will need to balance various needs including environmental stress, public perceptions and acceptability, regional differences, economics, technical feasibility, geopolitics, and fluctuations in the supply, demand, and price of nonrenewable energy. In sum, the environmental impacts of carbon-base energy extraction are highly complex and require multi-disciplinary input. Similarly, the varied factors associated with renewable energy development require broad and multi-disciplinary consideration. There is no single-best or one-size-fits-all answer.

Gap Analysis

Energy production is a stressor with respect to natural resources. Exploration and development of coal, petroleum, and natural gas can disturb the environment at, above, and below the earth's surface. The direct economic costs of development, e.g., environmental permitting, infrastructure development, labor, and equipment, are quantifiable. The externalities, such as negative impacts associated with contaminated ground and surface water, noise and air pollution, temporary and permanent changes to the landscape, biodiversity, and impacts to natural resources are more difficult to valuate. These often require environmental economics, life cycle analysis, social science and human dimensions studies.

There is a great national interest in developing means of renewable energy. Hydroelectric power is perhaps the most mature of these areas. Deriving its energy from the combination of gravity and water, hydroelectric power has a long history and produces a great deal of electricity, particularly in the Pacific Northwest. There are very few new opportunities to expand hydroelectric power in the U.S. However, operating hydropower dams as a system, there is potential to increase the overall capacity (i.e., meeting peak loads) of the hydropower system. Furthermore, many small and large dams are being removed for environmental reasons as their operation licenses expire (Poff and Hart 2002, Gowan et al. 2006). The rivers that can be cost effectively dammed have been harnessed. The capital cost of hydroelectric power, along with the environmental costs (particularly to riverine fish and other aquatic resources) is increasingly difficult to justify in the U.S. This notion is evidenced by the lack of new and removal of some existing hydroelectric structures. In areas where hydroelectric power will be maintained, substantial challenges and knowledge gaps remain with respect to fish passage (both upstream and downstream) and effects on aquatic resources from hydrology and hydroperiods that differ from natural flows (Renöfält et al. 2009). Two related energy sources may largely replace new dams. Pump storage facilities are viable environmentally. These require a major capital outlay and consume large amounts of land. These systems work by using two reservoirs, one elevated with respect to the other. At night, when electric power demand and rates are low, water is pumped to the

upward reservoir. During the day, when electric power demand is peaking—and most costly—water is released from the upper reservoir to generate power. Given the advances in real time metering, use of pump storage facilities may increase. Secondly, in-stream turbines that can be used in both riverine and tidal situations are showing potential (Khan et al. 2009).

Wind power is also a proven technology that is expanding dramatically worldwide, and is the most rapidly growing renewable energy source in the U.S. Most studies of impacts of wind developments on wildlife have been short-term in nature and longer term studies will be needed to better elucidate patterns and develop models predicting habitat fragmentation and other disturbance effects (Arnett et al. 2007). Wind energy causes both direct and indirect impacts on ecosystems and wildlife species. Wind energy developments affect the visual landscape as wind towers and wind farms are visible for many miles. Other direct effects include mortality of birds and bats that are struck by turbines or by collisions with other structures associated with wind development (i.e., towers, fences, transmission lines) (Arnett et al. 2007, Smallwood and Thelander 2008). Indirect effects of wind energy are less well understood and likely pose greater impacts on wildlife populations than the direct effects (Arnett et al. 2007). Disturbance of wildlife and avoidance of areas in proximity to turbines may represent the greatest impact on wildlife (Arnett et al. 2007, Pearce-Higgins 2009, Sovacool 2009). Loss and fragmentation of habitat due to construction, increased human access and the footprint of the facilities can be significant issues in some habitats. Thus, there are knowledge gaps with respect to wind farm siting, turbine design and long-term operations. Some studies suggest that bat mortality frequently occurs during periods of low wind and energy production suggesting that curtailment experiments might be possible to reduce impacts (Arnett et al. 2007). Research on alerting and deterring mechanisms such as visual or auditory approaches may also help reduce conflicts (Arnett et al. 2007).

Several sources of marine renewable energy are under development or consideration, and the potential resources are substantial (Bedard et al. 2010, Boehlert and Gill 2010). These include extraction of energy from waves, tides, ocean currents, temperature gradients, and salinity gradients. Offshore wind is an important resource that is included here because the technology and potential environmental effects differ from those in terrestrial installations, but the full realm of offshore wind impacts are not well understood. In general, research on environmental effects of marine renewable energy in Europe has moved forward more rapidly than that in North America (see, for example European Marine Energy Centre [EMEC] 2005, Maunsell and METOC PLC 2007), but this summary will focus on North American.

Marine renewable energy sources are not without environmental and social effects (Pelc and Fujita 2002, Boehlert and Gill 2010, Henkel et al. 2013). Early development of

tidal energy, for example, used the barrage, basically a dam across a tidal area that allowed water in on incoming tides but held it on outgoing tides and used the trapped water height differential to generate electricity. Much like traditional dams, these are in disfavor due to their environmental effects, and in-stream turbines have taken their place. More recent development of new marine technologies (e.g., wave, tidal, ocean current, offshore wind, ocean thermal energy conversion) is accelerating, but examination of environmental effects is just beginning; the potential impacts on natural resources represent an important part of these undertakings. The level of interest in these impacts is shown by a report on possible environmental effects documented in response to an act of Congress (Department of Energy [DOE] 2009). Review papers (e.g., Boehlert and Gill 2010) and reports of workshops (Boehlert et al. 2008, Polagye et al. 2011, Bureau of Ocean and Energy Management [BOEM] 2011, Boehlert et al. 2013) generally show that we are in an early stage of our understanding, and that research is needed to identify the stressors that may have serious impacts and rule out those that will not; several common threads of potential impacts to natural resources cross the various technologies (Table 1).

Some effects of developing marine renewable energy in marine systems have been cited as positive or beneficial. Many of these effects have to do with structural changes to the marine environment associated with anchors or drifting structures. In the case of wave energy development, the majority of installations will take place on relatively featureless sand or mud-sand bottoms. Placement of anchors, in many cases large concrete and steel structures, will have an "artificial reef" effect, changing bottom type and consequently the communities of organisms that are found there. Some have cited this change as a beneficial increase in biodiversity in these systems (Inger et al. 2009, Witt et al. 2012). Langhamer and Wilhelmsson (2009) noted an increase in fish and crab abundance near anchors for a wave energy development, and by engineering the foundations with holes, noted a five-fold increase in the abundance of commercially important crab species compared to nearby areas. Similarly, floating devices or structures in the water column can aggregate organisms through the "FAD" or fish aggregation device effect (Addis et al., 2006). Larger-scale installations of marine renewable energy devices may also act as de facto marine reserves due to potential exclusion of fishing within deployment areas (DOE 2009).

Biomass fuels, derived from plant materials and animal wastes, can provide a significant portion of the nation's renewable energy (Energy Information Administration [EIA] 2008). While many definitions of "biomass" are available, in

Table 1: A summary of marine renewable energy sources and examples of knowledge gaps regarding possible environmental effects, with references for further reading.

Technology	Examples of Environmental Knowledge Gaps	Reference
Wave Energy	Marine mammal and endangered fish interactions; alterations to benthic ecosystems; impacts on near-shore sand transport; electromagnetic effects; acoustic effects	Boehlert et al. 2008, DOE 2009, Boehlert et al. 2013
Tidal Energy	Acoustic effects, electromagnetic effects, benthic changes; fish and marine mammal impacts	DOE 2009, Polagye et al. 2011
Offshore Wind	Seabird interactions; lights; acoustics; cetacean impacts with in-water structures	Arnett et al. 2007, BOEM 2011, Boehlert et al. 2013
Ocean Current Energy	Entanglement, pelagic organism aggregation and community effects, electromagnetic effects, acoustic effects	DOE 2009
Ocean Thermal Energy Conversion	Thermal discharge effects, noise, entrainment and impingement	DOE 2009

the case of bio-energy it basically encompasses the parts of plants that are generally indigestible (non-food) and from which no other value added products such as lumber and engineered panel products can be derived. Biomass from the unused stems and leaves of plants, bark, needles, roots, shells, etc. can be burned directly, pelletized, or converted to liquid fuels. Additionally, biomass can be converted to synthesis gas (syngas) in a gasifier and subsequently the syngas can be burned, transported, or compressed and stored. Clean low-value wood, such as that from thinning southern pines is also a candidate for bio-energy production. The Gulfsouth and Southeast region of the U.S. is a strong candidate for biomass-related research as it has warm temperatures and ample rainfall for biomass production. The availability of marginal land is a key to large scale biomass production. If biomass is to achieve widescale acceptance as an energy source, it must be competitive for land use; that is, its cultivation must be more financially attractive than the crop with the next highest value. Prime farmland, developed real estate, and lakefront recreational areas for example are worth more per acre for those uses than they would be if deployed for biomass production. At present, biomass is typically a coproduct from agriculture and forestry sources. That is, corn, soybeans, paper, lumber, etc. are the primary products and burning or baling of forest and agriculture residues is performed as a means of achieving the maximum possible rates of use. Forestry-based biomass – whether as bark, leaves, branches, etc., or as clean woody fiber, is one of the most important sources. Forest-based biomass is readily available throughout the year. This seasonal availability is advantageous as compared to agriculture-based biomass sources, which generally have fixed and limited annual growing and harvesting seasons. While corn-based ethanol is a bio-fuel, it is not biomass derived. Biomass energy can be generated from plant materials and animals wastes in a number of ways including anaerobic digestion, gasification, direct combustion, co-firing (with coal or natural gas), and combined heat and power generation. There have been substantial advances over the past two decades in making biomass generation more efficient and cleaner and this will continue to be a critical research need into the future (Tilman et al. 2009). Comparatively low ash content is another benefit of forest-based biomass. Clean woody fiber, that is debarked wood, has one of the lowest ash contents of all bio-based plant materials (<0.5% on a dry basis). Bark, leaves, and needles from trees as well as plant-based stems, stalks, husks, shells, etc., commonly have ash contents above 1%. Due to its ready availability, transportation infrastructure, and existing conversion facilities such as gassifiers, burners, and boilers, as well as nearby markets, basic wood energy is well developed.

Ash content minimization is one of the key factors related to energy from biomass. Levels on the order of 1% ash cause major tool wear, poison catalysts, create enormous spent ash and boiler slag disposal problems, etc. In general, wood as a biomass source for other energy technologies such as liquid fuels, briquettes, pellets, lead other biomass types in commercialization. Other key issues are continuity of supply and transportation distance as forest residues are bulky and given their often high moisture content are expensive to move. Further reference is available from the Journal of Forestry, special issue related to biomass use and feedstock issues (Society of American Foresters 2011).

New technologies for bio-fuel production are rapidly emerging and represent a significant focus for research and development (Abbasi and Abbasi 2010). These emerging technologies include microalgae (Chisti 2007), fuel cells

for converting sugars directly to electricity (Chaudhuri and Lovley 2003), and development of engineered yeast for increased ethanol yields (Alper et al. 2006) among others. In some cases, fuel production may be coupled with water treatment plants because oil can be extracted from microbes that digest sludge.

Biomass energy has environmental risks that need to be mitigated and addressed in energy policy (National Research Council [NRC] 2011). Sources of biomass can be harvested at unsustainable rates and their production and extraction can damage ecosystems. There are many historical examples in which forests have been wholly denuded in support of heat energy production. Production of energy from biomass may also consume large amounts of water and produce harmful air pollution or net greenhouse gas emissions (Table 2). Three areas warrant special mention because of their potential impacts on natural resources.

Production agriculture dedicated to biomass production may have substantial ramifications for natural resources depending on the crops produced and the production systems used and may increase net greenhouse gas emissions (NRC 2011). The use of non-agricultural lands or conversion of conservation easements (i.e., Conservation Reserve Program lands) for biofuel production may impact biodiversity (Bies 2006, Fargione et al. 2009, Rupp et al. 2012), wildlife habitats, water quality and soil productivity (Wu 2000, NRC 2011, Rupp et al. 2012). Research is needed to evaluate and mitigate these impacts.

Biomass fuels derived from forest resources may also pose substantial environmental issues (NRC 2011). Much of these fuels are likely to come from non-industrial private forestlands (U.S. Forest Service [USFS] 2001) that are primarily regulated at the state level, resulting in substantial variation in permissible practices across jurisdictions. Two primary issues are supply dependability and environmental sustainability (NRC 2011). Environmental sustainability is maintained by state-specific BMPs, third-party forest certification, or by forest management plans. These approaches seek to minimize short-term impacts and avoid long-term deterioration of key indicators of sustainability—water quality, soil productivity, wildlife habitat, and biodiversity. Forest biofuels that rely on removal of timber residues such as branches, bark and tree

Table 2: A summary of possible negative environmental effects from biomass energy production, with references for further reading.

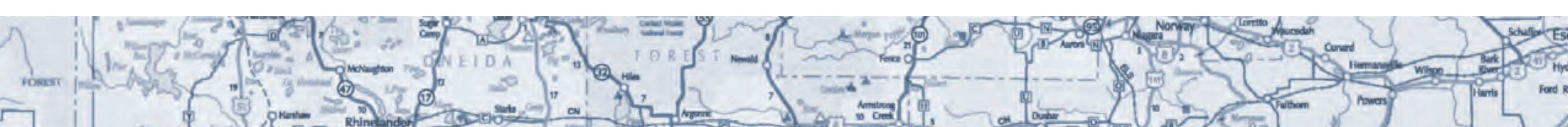
Possible Environmental Effects	Reference
Air quality and net carbon emissions	Bain 2003, Tilman 2009, NRC 2011
Biodiversity	Bies 2006; Fargione et al. 2009, 2011; Webster et al. 2010; NRC 2011
Wildlife habitat loss and degradation	Abbasi and Abbasi 2000, Wu 2000; Rowe et al. 2009, Tilman 2009, NRC 2011
Nutrient removal and loss	Pimentel et al. 1983, National Academy of Sciences [NAS] 2003, Eisenbies et al. 2009, NRC 2011
Soil erosion and run-off	Abbasi and Abbasi 2010
Water quality and use	Pimentel et al. 2004, Schilling 2009, Murphy and Allen 2011, NRC 2011

tops that are commonly left on the ground are likely to decrease ground-level habitat for wildlife and arthropods (Webster et al. 2010, Rupp et al. 2012) and reduce site productivity (Eisenbies et al. 2009) and water quality (Schilling 2009). Forest biofuel production that removes logs and snags may reduce biodiversity (NRC 2011, Rupp et al. 2012). However, converting woody material into products and biofuels and subsequently intentionally managing and replanting the forest is more favorable for carbon tracking and sequestration than letting the forest decay. For additional information about this complex issue, the reader is referred to the Journal of Forestry special issue (Society of American Foresters 2011).

Biofuels produced from microalgae and cyanobacteria offer high biomass productivity and can be grown in cultivation ponds, bioreactors or on non-arable lands using waste and saline water (NRC 2012). Algal biofuels are among the least well-developed renewable energies and substantial research and development is needed in the areas of strain selection, use of wastewater and recycling of harvested water and recycling of nutrients (NRC 2012). Use and production of algal biofuels may cause significant environmental impacts. Water quantity and quality are critical concerns in several aspects of algal biofuel production, including amounts of water added to or purged to maintain appropriate water chemistry, and water level maintenance and evaporative loss of open systems especially in arid regions most suitable for cultivation, and wastewater pollution of aquatic systems (Murphy and Allen 2011). Supply and recycling of key nutrients affect net energy production and may pose substantial environmental costs depending on the source and production system used (Cai et al. 2011). Conversion of land (primarily grasslands and rangelands) for algal biofuel production impacts terrestrial (Fargione et al. 2011) and aquatic ecosystems (NRC 2011) and results in land-use changes with ramifications for natural-resource based communities (Darzins et al. 2010). Finally, whether algae would be burned, extracted for oil, fermented into alcohol, or other, its high water content is problematic. The water must be removed, an energy intensive process, for any type of fuel development.

Finally, substantial research is needed to quantify policy options associated with biomass energy production. These analyses should examine trade-offs between economic benefits and environmental costs at appropriate scales over the life cycle of the fuels (NRC 2011) and develop uniform indicators for monitoring environmental effects of biofuels (van Dam et al. 2008). Landscape planning approaches that integrate bioenergy into agriculture and forest management are likely to lead to development of biofuel industries that result in net environmental benefits.

Solar energy production is rapidly increasing in the U.S. primarily in the form of solar photovoltaic and solar thermal systems. Solar systems adapted to the built environment (i.e., roof-top solar panels) are assumed to have minimal impact on natural resources (Katzner et al. 2013).



The primary environmental issue associated with industrial-scale solar systems is the large collection areas required for deploying the systems for energy capture and electricity generation (NRC 2010) and the resulting ecological and environmental impacts. The principal region to deploy solar energy systems in the U.S. is in the desert Southwest and a typical system may cover more than a square mile of land resulting in wildlife habitat loss and degradation. Roads and transmission lines associated with these developments cause additional habitat loss and fragmentation. Furthermore, arid areas where solar systems are most likely to be deployed commonly have high biodiversity and endemism (Katzner et al. 2013). The external costs of solar energy production, such as those associated with mining and refining the raw materials to make the photovoltaics are not well documented.

Distributed versus centralized power systems is an area of current research. Smaller, distributed generation systems place different demands on the electrical grid. Distributed systems are often less efficient than centralized generation facilities however, less transmission infrastructure is required. Ultimately, if technologies such as solar panels and residential hydrogen turbines are perfected, then every household could be its own generation point. Similarly, there are active discussions related to electric cars wherein they could be plugged in and recharged at night (when overall grid demand is low), driven to work, then plugged in such that the battery discharges in part to the grid (when overall grid demand is high), then driven home. These possibilities are decades away at best, but they help exemplify the need for consideration of changes to the grid.

Geothermal energy is among the best developed renewable energy sources. Geothermal energy uses the earth's heat as an energy source and is developed in three general ways: geothermal springs and hot dry rock geothermal for electricity production, and ground-source heat pumps for direct heating and cooling of buildings and homes. Environmental impacts of geothermal energy production depends on the technology used to convert the heat to electricity and the type of cooling technology used. Geothermal energy production has the potential to impact both water quantity and quality. Because some water is lost to steam, geothermal plants require additional water to maintain underground reservoirs and prevent ground subsidence, and some cooling system technologies require substantial water inputs. Some plants use treated wastewater to maintain reservoir levels, but no cases of water contamination have been documented in the U.S. (National Renewable Energy Laboratory [NREL] 2012). Open-loop systems emit hydrogen sulfide, carbon dioxide, ammonia, methane, and boron, which may contribute to acid rain. Land use is another potential issue with geothermal energy production because plants have large footprints and are frequently located in remote, environmentally sensitive areas.

Regardless of energy or bioenergy type a variety of issues must be addressed. These include compliance with or influencing rules and regulations have been developed over time that apply directly to the energy sector and its relationship with natural resources. The environmental costs associated with any energy type need to be addressed. Air pollution, water pollution, noise, light pollution, land changes, and public perception all must be addressed constructively.

Research Needs and Priorities

Demand for energy in the U.S. and globally is expected to increase 56% by 2040 (EIA 2013). Increasing demand will necessitate increased production of alternative energy sources while at the same time concerns regarding greenhouse gas emissions and other environmental and land-use impacts are likely to lead to increased efficiencies in our current energy sources and changes in public preference among available sources of energy. Prioritizing research needs will help lead to the development of more efficient and effective environmental policies related to energy production and use. Here we propose research themes and objectives for identifying and reducing the impacts of energy development and use on natural resources and society. Some of these relate solely to natural resource issues; some of these can only be addressed with cooperation among natural resource professionals, policy makers, engineers, etc.

Improve understanding of costs and benefits of energy development and use and public perceptions related to energy.

- Conduct full life-cycle analyses of costs and benefits of different energy sources at local, regional and national scales.
- Quantify trade-offs among land/sea-use alternatives (i.e., fisheries, forestry, grazing) in areas that may be developed for energy production.
- Conduct economic analyses regarding present and forecasted future energy production costs compared to the projected costs of renewable energy types.
- Develop new and more efficient renewable energy supply systems.
- Identify and test new bioenergy systems especially from waste streams of existing land management activities.
- Identify and test new or more efficient feedstocks production and conversion systems for bioenergy.
- Develop marine renewable energy sources.
- Identify and develop markets for renewable energy. Many such markets are similar to existing markets but require process, transportation, or combustion modifications.
- Identify opportunities to improve redundancy and capacity in the electrical grid.
- Scale up from bench-top to pilot level conversion technologies, on the path toward commercialization.

Minimize impacts of increasing energy demands on natural resources.

- Develop uniform indicators, such as life cycle analysis scoring or reporting of environmental effects of energy development and use.
- Quantify biodiversity impacts of energy development and use (e.g., slash and coarse woody debris removal for biofuels; fish passage and hydrological changes at hydroelectric power facilities; land conversion for fuel production and facility siting).
- Quantify behavioral changes and mortality of organisms associated with energy development and use (e.g., bird and bat mortality at wind turbines; marine mammal and fish attraction or avoidance of tidal energy facilities; relationship of animal movements to electromagnetic field changes).
- Identify sources and quantify water and air pollution associated with energy production.

- Quantify water demand for steam production and cooling of geothermal, biofuels, solar and traditional energy sources (coal, natural gas, nuclear).
- Understand public's perceptions of alternative energy sources and barriers to adoption of energy conservation practices.

Maintain available energy and increase efficiency to reduce ecological footprint.

- Increase water-use efficiency in steam production and cooling systems to reduce water use.
- Increase efficiency and use of existing energy sources/infrastructure (e.g., hydrofracking for natural gas production).
- Increase fuel conversion efficiency for biofuels.

Education and Outreach Needs

Education and outreach will be required at all levels, not only through formal education programs but also informal ones, bringing in both lifelong learners as well as stakeholders who may not otherwise be identified (Henkel et al. 2013). This is nowhere more true than in considerations of natural resource and environmental effects of energy development. Conflicts between consumptive and non-consumptive users as well as the concerns of the general public can only be met through a better understanding by all parties.

- The National Renewable Energy Laboratory (U.S. Department of Energy) reports that renewable energy and energy efficiency research and development is only part of the new energy future equation. Educating students, teachers, and consumers is the other key to finding new renewable ways to power our homes, businesses, and transportation. Priority should be given to the following:

1. K-12 Science Programs to engage young minds in renewable energy and also provide teacher support. Educational programs that explain the social, political and environmental challenges associated with reliance on fossil fuels and the challenges and opportunities for transitioning to renewable sources are critical needs for K-12 science programs.
2. College and Post-Graduate programs to help develop a capable and diverse workforce for the future through mentored research internships and fellowships. Energy development and production in the U.S. and globally will require well-trained scientists from diverse STEM-related disciplines ranging from math and physics to geology and biology to agriculture and forestry. The need for graduate degrees is likely to increase in this sector, necessitating increased funding for internships and fellowships.
3. Broadening college-level requisite curriculum beyond natural-resource-specific content to include a greater emphasis on public policy making, life cycle analysis, economics, statistics, and multidisciplinary problem solving.
4. Renewable energy education and outreach programs through the university system throughout the U.S. Outreach and engagement programs, such as those in place nationally through Cooperative Extension at land-grant universities, can enable the public to better understand the sustainability, environmental impacts, and potential issues related to carbon sequestration and climate change associated with their energy choices and promote energy conservation practices.

Expected Outcomes

We now live in a world in which global economic growth—particularly the growing energy demand in developing countries—will contribute to a 50% increase in worldwide energy consumption by 2025. By 2050, the world will need to find an additional 20 terawatts of energy and the U.S. will be competing along with countries such as China and India to satisfy our growing energy needs. To meet the challenges of this new energy future, we will need new ways of thinking about and producing energy. Pursuit of alternative sources of renewable energy with considerations of efficiency, conservation, increased energy yields, and minimal impacts on the environment, can help the U.S. increase its national energy trade balance and security. This scenario has the potential to improve economic stability of the U.S. and improve national security.

Investment in continued and aggressive research, education and outreach programs will ensure a ready source of highly efficient energy sources that has minimal impact on the environment but helps to maintain a thriving and vibrant economy, and strong U.S.

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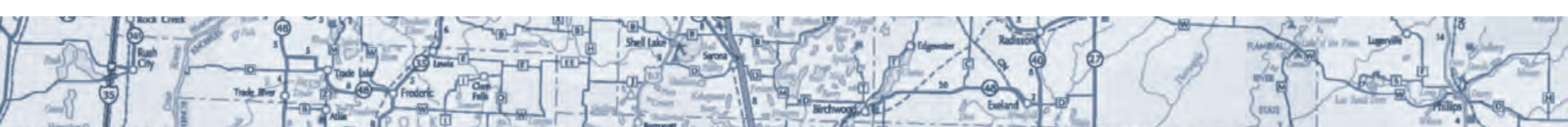

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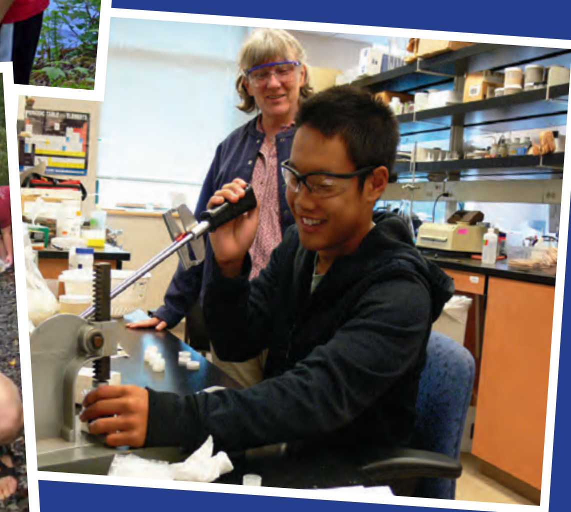
Grand Challenge 6: Education

We must maintain and strengthen natural resources education at all levels to have the informed and engaged citizenry, civic leaders, and practicing professionals needed to sustain the natural resources, ecosystems, and ecosystem services of the United States.

Framing the Issue

Broadly defined, natural resources include renewable resources (forests, fisheries, rangeland, water, and wildlife), non-renewable resources (such as minerals), ecosystems, and ecosystem services (such as groundwater recharge, assimilation of wastes, pollination and recreation). Issues pertaining to long-term sustainability of natural resources are the focus of local, regional, and national discussions. In a representative democracy such as ours, development of natural resources policy involves structured interactions among career professionals, the public, and elected officials. Public understanding and acceptance of natural resources policies and management plans and their effectiveness for achieving sustainability depend on integration of scientific information and societal values. Fruitful interaction among well-trained natural resources professionals, an informed citizenry, and civic leaders favors effective natural resources management. Effective natural resources education at the K-12 and university levels—burnished by life-long learning—will provide the informed citizenry and practicing professionals needed to sustain the natural resources of the U.S. Key supporting roles must be provided by informal education institutions such as museums and by youth organizations such as 4-H, scouting groups, and Boys and Girls Clubs (Bell et al. 2009).

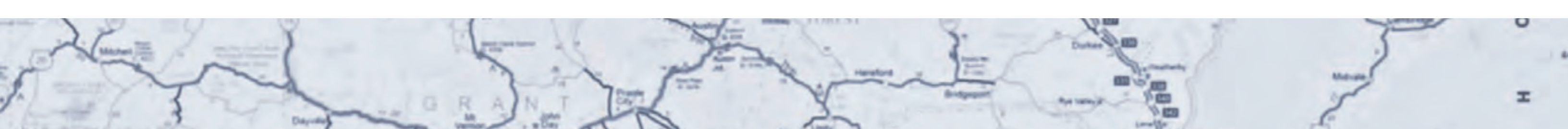
However, much of the American public has little understanding of the process by which scientific knowledge is gained. That is, most people do not understand framing/testing of hypotheses or the difference between hypothesis testing and construction of theory explaining a body of natural phenomena. Hence, it is not surprising that citizens—and frequently their leaders—misunderstand and often misconstrue scientific issues in discussions regarding the science and management



of natural resources. Only by advances in public understanding of the scientific process, combined with more effective science communication, can discussion of natural resources issues be elevated. We also need education regarding how representative government works; the roles of individuals, governments, and private-sector entities; and the process of translating scientific information into public policy and implementation regarding natural resources management. This chapter identifies knowledge gaps, research needs and priorities, and expected outcomes related to six natural resources goals: including natural resources in youth education by incorporation into STEM curriculum and activities; strengthening natural resources curricula at the higher education level; improving the scientific literacy of the Nation's citizens; communicating scientific information to the general public in efficient and effective ways; promoting the sustainability of natural resources; and promoting diversity in the natural resources profession.

Goal I: Include natural resources in youth education by incorporation into STEM curriculum and activities.

Natural resources-oriented professionals have long recognized the need to include instruction in natural resources within our educational system, including classroom-based and informal education. Although progress has been made, we must further embed natural resources and environmental education within K-12 curricula (Ramsey et al. 1992). Our citizenry, as it becomes more urbanized, is becoming detached from understanding and appreciating the social, ecological, and economic importance of our natural resources (Louv 2005). Our citizens and civic leaders must understand the multi-faceted importance of natural resources so that they may act responsibly regarding policy, legislative, and management actions. Hence,



we must educate regarding the fundamental values and importance of sustainable management of natural resources; we must start at the K-12 level, as it is then that cognitive skills are optimal for learning (North American Association for Environmental Education 2010). Attitude and value formation also occur during childhood and youth; hence, informative, positive experiences with nature and in natural resources-centered education will have greater probability of changing behaviors as adults.

The goal of youth education in natural resources is to realize the knowledge base and integrative abilities that underpin understanding of natural resources-related issues, as well as foster behaviors that promote sustainability of our natural resources. Fundamental concepts of natural resources science and management can be embedded within K-12 curricula, ensuring that national core competencies (in science, technology, engineering and mathematics, termed "STEM" requisites) are met (Hopkinson and James 2010). Much research has addressed approaches to improve natural resources and environmental education that lead to youth engagement and active behavioral change (e.g., Reilly et al. 2011). There are significant nation-wide natural resources and environmental education programs, such as Project Wet (http://projectwet.org/), Project WILD (http://www.projectwild.org/) and Project Learning Tree (https://plt.org). However, use of activities from these supplemental curricula is insufficient for a significant portion of the K-12 population to achieve the necessary knowledge, understanding, and problem-solving skills associated with the science and management of natural resource stewardship. There are notable efforts at the state level; for example, the environmental education program at the Wisconsin Center for Environmental Education (WCEE) in the College of Natural Resources at the University of Wisconsin-Stevens Point fosters, develops and evaluates environmental education in K-12 schools of Wisconsin. Some states have made notable attempts to develop Environmental Literacy Plans (ELP). Around 2010-2011, a national grassroots initiative aimed to pass legislation encouraging integration of environmental education into K-12 curricula; the proposed program was known as "No Child Left Inside." This legislation proposed federal funding for states to implement K-12 environment education through statewide educational standards voluntarily developed by a state's Department of Education in concert with its respective natural resource agencies and environmental educational entities. States with approved ELPs would be eligible for federal funding that would aid in fulfilling ELP objectives within state schools. Maryland and Rhode Island (http://rieea.org/resources/ri-environmental-literacy-plan/) are two of the few states that completed the process, although legislation died during deliberations. However, despite these notable programs, significant gaps remain in the preparation of our students, teachers, and institutions to understanding, comprehending, and engaging in meaningful behavioral changes regarding natural resources.

Gap Analysis

Impediments to achieving integrated natural resources education within K-12 curricula include the following:

- Natural resources education starts with those who establish certification criteria for K-12 and informal teaching and learning. There are programs evaluating embedding of natural resources (environmental sciences) within K-12 training that satisfy STEM standards (Hopkinson and James 2010). However, misunderstanding regarding natural resources education remains among research scientists, university faculty, federal and state leaders, school superintendents, principals, and teachers. Until an appropriate niche (Ramsey et al. 1992) is determined, implementing any definitive K-12 curriculum in natural resources will be impossible. Integration of natural resources topics into K-12 curricula will remain problematic until state or federal departments of education require that these topics be included in their curriculum standards, as in the case of Maryland and Rhode Island.
- Integration of natural resources content into pre-service teacher training at the university level will prove largely untenable if the status quo is maintained. These institutions are preparing education students to meet the current demands of curricula within K-12 schools; unless states mandate natural resources STEM in K-12 curricula, teacher preparation programs are not likely to include it in their courses of study. State departments of education determine what college-level courses are required or acceptable for teacher certification, and if these agencies do not accept natural resources science-based credit hours toward certification (as is the case, for example, in Mississippi), then the students will be less interested in taking these classes that do not apply toward their degree program.
- Active-learning curricula appropriate to a wide range of target populations should be developed and implemented, perhaps nationally. The Association of Fish and Wildlife Agencies' (2008) conservation education strategy, Stewardship Education: Best Management Planning Guide, is an excellent starting point. We need educational resources (e.g., hands-on, learner-centered curricula, as well as interactive online learning activities) that satisfy the requisites of STEM core competencies and include fundamental concepts of natural resources science. This goal can be accomplished by encouraging publishers to use concepts of natural resources to illustrate principles of science, technology and mathematics. Natural resources problems are a great way to approach the multidisciplinary, problem-solving approach that Common Core curricula promote.
- A keystone for any educational endeavor is to have in place a consistent and effective evaluative process to ensure that the curriculum is effective, learning is achieved, and the citizenry (child and parent/guardian) are increasingly more aware and responsive to issues pertaining to natural resources science and management. The National Center for Education Statistics (2012) biennial report, The Nation's Report Card: Science 2001, is a promising start, but lacks specific reference to natural resources. Natural resources education programs could be evaluated not only on a national, but also on a local level. Scientific literacy is considered to be contextual in nature, and local evaluation would capture more of such context than would a national evaluation. We need goals (Hungerford et al. 1980) to ensure that all levels of governance of education programs (federal, state, regional, and district) are consistent in application and program evaluation.
- Because much science is learned in out-of-school settings (Bell et al. 2009), we also must consider how to strengthen natural resources education in the informal education sector.

The successful integration of natural resources within K-12 and informal curricula will require cooperation among federal, state, and private conservation organizations. Key state and federal natural resources management agencies and many non-governmental organizations (e.g., Ducks Unlimited, National Turkey Federation, National Wildlife Federation, American Forests, Council for Environmental Education, and Project Wet Foundation) have youth education programs involving principles of management of wildlife and their habitats. A unified coalition of these entities supporting the goals, curricula, and evaluative mechanisms of the curricula, perhaps spearheaded by the Coalition of Natural Resource Societies, would be useful. Land-grant universities may play a key role in such coordination. We note that these types of informal science learning opportunities are often not available to or used by under-represented groups; hence, cultural, financial and transportation barriers to access need to be considered with respect to out-of-school settings.

- Play in nature, particularly during the critical period of middle childhood, appears to be especially important for developing capacities for creativity, problem-solving, and emotional and intellectual development (Kellert 2005). Research results indicate optimal learning opportunities at age-appropriate times and differentiate between indirect, vicarious, and direct experiences with nature, with the latter becoming less and less available to children. Hence, designers, developers, educators, political leaders, and citizens throughout society should make changes in our modern built environments to provide children with positive contact with nature.

Research Needs and Priorities

Research needs that must be met before we can effectively integrate natural resources science and management within youth education include the following:

- A solid definition or description of what is meant to be "literate" in natural resource science must be agreed upon. Once a definition has been selected, specified, and announced as an anchoring concept, the work of program development can go forward (Roberts 2007).
- Further research is needed to evaluate the most effective suite of experiential activities and pedagogical approaches that maximize understanding of natural resource science and management and address key components of STEM requisites. Classroom and laboratory time as well as informal learning opportunities are limited; thus, integrated programs must be developed and evaluated for effectiveness in knowledge retention, critical thinking, and application over the long-term.

- We need to understand the potential use of technology as a bridging tool for connecting youth to the outdoors. We need to develop a better understanding of the role of social science and use of social indicators in youth that lead to behavior change (Lerner 2005). Few studies exist to examine young people's views towards environmental and natural resources issues and what motivates them to take action. Youth perceive issues in different terms than adults, so it is important to know how those issues are understood by youth and gaps that may exist in those understandings.
- Non-Caucasian participation in natural resources fields is disproportionately low; we need to engage underrepresented populations in STEM, natural resources and sustainability curricula in our schools. Curricula must be developed that recognize differences in cultural values regarding natural resources. The effectiveness of these curricula in instilling an awareness and appreciation of natural resources must be evaluated over the long-term.
- We need evaluative mechanisms to assess effectiveness of K-12 natural resource curricula. Simply measuring student test scores temporally will not provide a true assessment of the effectiveness of curricula. Evaluative mechanisms must assess the degree to which concepts are retained over multiple years and used in multi-faceted, integrated critical thinking exercises.

- Specific topics needing empirical research include surveys in order to better understand youth concerns. Longitudinal studies are needed to address whether increased knowledge and awareness of natural resources issues leads to behavioral change. Longitudinal studies are needed to address promising strategies and practices for natural resources education that are accessible to school administrators, decision makers and educational funding bodies. Research is needed on how adult constructs such as "climate change" might be translated into actionable items for youth. Research is needed on how adult learning and attitudes about science impact the way youth perceive natural resources education. Promising practices in systems thinking and complexity education need to be further developed and analyzed.

Expected Outcomes

Under the status quo, natural resources education is uncoordinated, minimally integrated within current curricula, and minimally if at all integrated with state teacher certification requisites. Students' and teachers' concepts of ecological systems are often naïve. Schools and educators are insufficiently prepared to understand the critical connections between social indicators and youth learning, engagement, and behavior change with respect to natural resources issues. Insufficient evaluation strategies and tools limit understanding of how students best learn and engage

on natural resources issues. The full implications of how family and community dimensions affect youth perceptions, engagement, and behaviors in the context of natural resources education remain unclear.

Integrating fundamental concepts of natural resources science and management within K-12 science curricula is a long-term endeavor that will involve coordinated engagement and support by federal, state, local, and private entities. Implementation of the recommendations within the *NR Roadmap* will result in a coordinated effort promoting a fully integrated curriculum derived from empirically-based research findings and integrated within STEM requisites. Its effectiveness will be evaluated by long-term assessment of learning skills, knowledge retention, and behavior characteristic of an environmentally sensitive citizenry. Such responses are indeed possible, as demonstrated by past research (e.g., Ramsey 1993). Natural resources education standards with diversified learning strategies that incorporate service learning, age-appropriate and culturally relevant curricula, field experience, and community engagement in learning will set the stage for active learning and critical comprehension of natural resources issues. Students will be better prepared for natural resources careers, and underrepresented populations will have better access to these careers.

Goal II: Strengthen natural resources curricula at the higher education level.

Gap Analysis

The U.S. faces unprecedented challenges regarding sustainability of our natural resources and critical ecosystem processes, including issues posed by climate change, energy development, and impacts of introduced and invasive species. Managers must cope with these challenges with adaptive management (i.e., by monitoring system outcomes, learning about the system, and improving management over time; Walters 2002, Holling 2005) while sustainably meeting society's needs for natural resources. Further, the American public demands greater input into natural resources management decision-making. Against this background, the training of natural resources professionals must be multidisciplinary and rigorous, polishing the critical thinking, problem-solving, and communications skills needed for a career of adaptation to changing management circumstances.

Natural resources managers need a bachelor's degree for technical-level positions and a master's degree for professional and leadership positions. Enrollments in natural resources management-related fields, while varying over time, are at about the same level as in 1980 (Sharik 2013). However, the proportion of enrollments among natural resource fields has undergone dramatic shifts, with some of the more traditional disciplines such as forestry and wood science/forest products experiencing substantial declines, and other fields, particularly interdisciplinary programs, showing dramatic increases. The drivers for changes in natural resources curricular enrollments over time are complex, likely involving numerous demographic, economic, and social factors. Further, a generational shift is ongoing, with Baby Boomers retiring and insufficient numbers of younger natural resources management professionals following behind (McMullin 2005a, 2005b; Colker 2005). In certain natural resources management fields, e.g., marine resources management (U.S. Departments of Commerce and Education 2008), professionals with appropriately targeted advanced degrees are in short supply. At the same time, there is a surplus of students in some areas, such as environmental studies, conservation biology, and marine biology, with comparatively few practical skills needed by natural resources management agencies. Guiding students so that more of them obtain a set of marketable skills should be an outcome of higher education.

While U.S. curricula in natural resources science and management are among the best in the world, natural resources programs at our public universities are struggling to maintain faculty lines and face the prospect of continuing declines in public funding. The ability to maintain natural resources programs and curricular quality is at stake. Some public universities have dropped natural resources-related programs; e.g., Washington State University has dropped its undergraduate forestry program, but has maintained its natural resources program, while the University of Washington has moved its accredited undergraduate forestry program (B.S.) to the graduate level (M.F.). Faculty lines in traditional natural resources fields are being replaced to a great extent by faculty with more molecular and biophysical interests, in part because they can compete more efficiently for federal research grants. Changes in research funding opportunities and information needs of management agencies drive change at universities.

American employers want universities to produce graduates who can think critically and creatively and can communicate orally and in writing, according to results of a public opinion survey recently released by Northeastern University (Berrett 2013). A primary problem with higher education in natural resources and across the sciences, however, is the dated teaching focus on subject matter content. Recent pedagogical developments suggest that students do not need instructors to deliver information, but rather that students will benefit most from curricular focus on developing critical skills for information processing (finding, judging, and applying information in a creative and well-reasoned fashion; Barr and Tagg 1995). "Active learning" research has addressed general learning situations and specifically the sciences. In science teaching, this research has led to the development of case study teaching (Herreid 2007, Herreid et al. 2012), peer instruction (Crouch and Mazur 2001), SCALE-UP teaching (student-centered active learning environment with upside-down pedagogies; Beichner et al. 2006), and Scientific Teaching (Handelsman et al. 2004; Handelsman and Pfund 2007). All of these 'learning-centered' teaching approaches are well researched and documented, but relatively few science teachers are aware of them or they resist such changes to 'traditional' science teaching. Educators in natural resources fields need to focus their efforts on helping natural resource graduates develop critical 21st-century skills (Institute for the Future [IFTF]

2011). The basic problem is two-fold: (1) most natural resources and science instructors are either unaware of the research that shows improved learning outcomes when instruction is switched from 'instruction-centered' to 'learning-centered' teaching; and (2) the reward structure in the university is skewed toward research productivity, with little incentive for faculty to spend the time necessary to convert and to teach courses in the new modes of instruction (Hines et al. 2013). Good teaching takes significantly more time than average or poor teaching, and time spent on teaching is not adequately rewarded.

Research Needs and Priorities

Faced with unprecedented challenges regarding sustainability, energy development, climate change, introduced and invasive species, and other natural resources-related issues, support for applied research is needed more than ever. Competitive grants programs targeting critical needs that are administered by the U.S. Departments of Agriculture, Commerce, Interior, and other agencies will shape our nation's response to these challenges. Support for such programs must be maintained.

Institutions of higher education, public agencies, and private- sector employers need a better understanding of factors affecting undergraduate and graduate enrollments and career opportunities in natural resources-related fields, both now and over the long-term. Our ability to maintain a well-qualified workforce in natural resources-related fields will depend upon filling the educational pipeline while improving educational quality in order to produce managers prepared to adapt to the evolving and increasing demands upon our natural resources. University education will have to achieve student learning outcomes including not only the traditional base of technical knowledge, skills, and behaviors, but also inquiry, problem-solving, quantitative reasoning, critical thinking, and communication skills. While the pedagogy required to produce professionals ready to face modern natural resources management challenges is the subject of research and discussion (see, for example, CIDER 2014), greater attention must be paid to implementing the findings of such research in university education. The emergence of online courses and curricula at public and for-profit universities (e.g., Oregon State University, http://ecampus.oregonstate.edu/online-degrees/undergraduate/fw/) poses challenging questions regarding their effectiveness for natural resources fields.

Funding to improve education should be focused on: (1) helping faculty understand the crisis in graduates' poor preparation for the 21st century professional world; (2) helping existing faculty convert 'old' courses to meet new needs; (3) new faculty developing effective courses and curricula from the start of their careers; and (4) helping programs retool faculty and redesign curricula to effectively meet the challenges of the new century. The USDA Higher Education Challenge Grant program is a good model, as are the National Science Foundation grant programs that led to the development of the National Center for Case Study Teaching in Science, Scientific Teaching and the SCALE-UP model for physics education. Virginia Tech has adopted SCALE-UP for biology and natural resources education, and grants supporting classroom conversion were critical for its success. Most university classrooms are not designed to accommodate learning-centered teaching. Once faculty and academic programs are convinced that such is the teaching style of the future, there will be critical need for classroom conversion funding.

Expected Outcomes

Under the status quo, the pipeline feeding entry-level natural resources managers into the profession will not be filled with quality graduates, leaving certain key areas (e.g., human dimensions of natural resources decision-making, quantitative modeling of natural resources) short of qualified practitioners. Natural resources curricula and approaches to pedagogy will not advance in concert with the changing needs of the profession, leading to insufficient preparation of entry-level professionals. Entry-level professionals will lack certain key skills – such as quantitative, analytic, and "soft" (e.g., interpersonal, problem-solving, and communication) skills – valued by employers. With insufficient applied research, managers will lack the scientific information and analytic tools needed to sustainably meet the natural resources management challenges faced by American society in our changing world.

By following the *NR Roadmap*'s recommendations, the profession will have the information needed to effectively recruit diverse, highly talented, and motivated individuals to technical and leadership positions. Better information on workforce needs in various sub-disciplines will permit a more strategic approach to student recruitment. University curricula and pedagogy will embody the latest developments in the field of natural resources science and management, training well-qualified entry-level professionals prepared for a career of life-long learning and adaptation. Universities will have the educational infrastructure and faculty expertise to engage in active teaching and learning. The profession will have the scientific understanding and management skills needed to effectively address the growing range of natural resources-related issues facing the United States.

Goal III: Improve the scientific literacy of the Nation's citizens.

Gap Analysis

Scientific literacy is the knowledge and understanding of scientific concepts and processes for personal decision-making, participation in civic affairs, and economic activities (NAS 1996). A scientifically literate person has the capacity to understand experiments and reasoning as well as basic facts, to comprehend articles about science, and to engage in discussion about the validity of conclusions. At the national level, scientific literacy often is taken as the expectation that everyone should have a working knowledge of science and its role in society (Rutherford and Ahlgren 1991, American Association for the Advancement of Science [AAAS] 1993). Roberts (2007) describes broad "visions" of scientific literacy; vision I starts from a scientific perspective, and vision II situates itself from the perspective of the citizen. The scientific literacy of the American public is limited, however, in the context of public controversies over science and technology policy, for example regarding bioethics, genetic engineering, and climate change. Further, some segments of society tend to disregard scientific evidence when it challenges their established belief systems.

The formal development of scientific literacy, especially in our young citizens, is the domain of schools, with important contributions also from informal science education (Bell et al. 2009). However, too much of science teaching and learning – including that in natural resources-related subjects – is simple transmission of knowledge, a shortcoming at the course and curricular levels. There is a great need in both K-12 and higher education for active teaching and learning of science. Science should be presented as a process of building theory and models using evidence, checking it for internal consistency and coherence, and testing it empirically (NRC 2007). In our context, then, education must promote critical thinking skills, i.e., the ability to use this knowledge to assess specific issues and evaluate various management or societal options.

The media play an important role in informal and life-long education; that is, citizens receive much of their information on natural resources and other science-related issues from media outlets such as television, radio, newspapers, and the internet. With budget cuts at major newspapers and broadcast media outlets, however, there are fewer working science journalists than formerly (Brumfiel 2009). While blog-based science reporting fills the gap to some degree, its problems include bias, inaccuracy and confirmation. Because science writing often focuses on controversial topics, the public can conclude that disagreement within the scientific community is greater than it really is, as with issues such as climate change. Scientists tend to be very conservative when discussing the implications of their findings, especially with journalists. Science journalists find it difficult to communicate risk-related issues effectively (NRC 1996).

Research Needs and Priorities

A multi-pronged strategy is needed to improve the scientific literacy of our nation's citizens in general and natural resources-related fields in particular. Proponents of scientific literacy often focus on what a student has learned by the time they graduate from high school. All our young people need exposure to effective science education, including natural resources-related science, and science literacy has been an important part of the standards movement in education. Such standards, however, must go beyond requiring knowledge per se and include demonstrable understanding of the process through which new scientific knowledge is realized. While some inroads have been made (e.g., Minner et al. 2010), further pedagogy research is needed to determine how to more effectively include active inquiry into teaching and learning at both the K-12 and higher education levels. Educator professional development in K-12, informal, and higher education is critical. Most educators lack a background in effective science pedagogy. University educators need to develop instruments to measure scientific literacy.

The goal of science journalism is, in an unbiased manner, to translate detailed, technical, often jargon-laden information produced by scientists into a form that non-technical audiences can understand and appreciate. To maintain life-long learning in science, including natural resources-related issues, the nation needs to train more science journalists. We need to encourage the offering of science reporting specialization in journalism curricula. Science journalists may or may not have training in the scientific disciplines on which they report, although graduate-level training in science writing is a great way to enter the field. Science journalism programs, such as those at Massachusetts Institute of Technology, Boston University, the University of California at Santa Cruz, and other universities, generally comprise an intensive one-year program and an internship.

Expected Outcomes

Under the status quo, scientific literacy in natural resources will remain the domain of those trained in natural resources management. The general public and civic leaders will remain disengaged except on matters of controversy. Decisions on how to use our nation's natural resources often will be made on the basis of partial information and ideological viewpoints.

With the heightened investment in science education called for in the *NR Roadmap*, not only the technically trained, but also society and its leaders will understand natural resources science and management and decision-making within a representative democracy. Natural resources decision-making will prove less controversial, less contested in the nation's courts, and more defensible to broad segments of the public.

Goal IV: Communicate scientific information to the general public in efficient and effective ways.

The fundamental purposes of communicating scientific information about natural resources are to inform multiple audiences so that defensible, science-based decisions can be made. In a representative democratic society, the public, civil servants, and elected leaders need open and unbiased scientific information in order to make such decisions. However, traditional methods of communicating scientific information about natural resources have not been as effective as they could be. Flood protection is an example of this failure. While federal, state, and local agencies exert substantial efforts in flood management, flood damage remains high as property development continues in flood-prone locations (e.g., Morss et al. 2005); Hurricane Sandy's impact on coastal New Jersey in October 2012 is a recent example. Communicating the science of natural resources can be difficult because of the complex and often subtle and abstract aspects of many scientific issues. Scientists often communicate in jargon that requires specialized knowledge to understand. Even more confusing, scientists often use common words in very specific ways that may have little relevance to common usage; examples include such common words as "work," "heat," and "uncertainty."

Scientific understanding of natural resources is complex because all natural systems are inter-connected and cannot be understood in isolation. Additionally, many natural resource systems are valued not only for their economic potential, but also for less tangible values such as beauty. These often-conflicting values are addressed in policy, which is inherently political. Additionally, many scientific results, especially in the natural resources, are often politicized. Politicization of science often confuses the public and conflates science with policy, which makes it very difficult to communicate the underlying science.

Confirmation bias also makes effective communication difficult, particularly when dealing with complex and politicized information. In confirmation bias, information that confirms a currently held idea, stance, or opinion is selected, while information that counters it is ignored. Confirmation bias is common to almost all information-collecting and decision-making processes. In most cases, individuals are not aware of their confirmation bias (Mlodinow 2008). Confirmation bias is a basic misunderstanding of the "Scientific Method." The scientific method often is explained as a way to prove truth; it is rare that the method is taught as a method of inquiry that emphasizes the falsification of hypotheses, theories, or understanding. Misunderstanding of the scientific method leads individuals to select information that confirms rather than challenges established views. Good science communication requires overcoming confirmation bias.

Gap Analysis

Traditionally, the emphasis of scientific communications has focused on a "deficit of knowledge" model, which assumes that individuals just need information, and then the right decision would follow. This model is based on at least two tenuous assumptions, that knowledge of facts leads to understanding and that decisions are made only on the "facts."

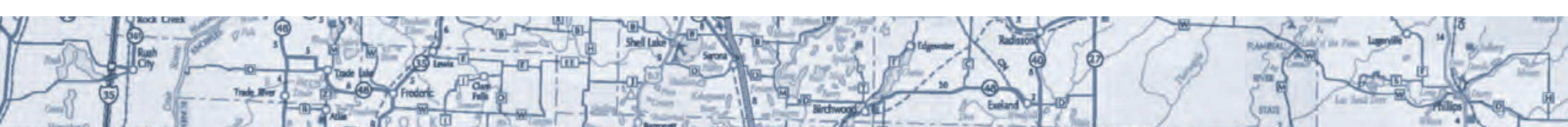
A better understanding on how individuals make decisions about natural resources is needed in order to increase the effectiveness of scientific communications. Such understanding will increase the effectiveness and efficiency of communicating scientific information because the fundamental goal of communication of scientific information is to support better decisions. Decision-making research has shown that most decisions are made primarily using intuition with facts selected after deciding to support the decision. Intuitive decisions are made on six foundations, which usually are not articulated, including care/harm, fairness/cheating, loyalty/betrayal, authority/subversion, sanctity/degradation, and liberty/oppression (Haidt 2012).

Professional journalists have largely shaped the communication of science to the public. However, as noted above, over the past 25 years there has been a slow erosion of science journalism (Brumfiel 2009). There are fewer magazines devoted to science for the general reader, and many large newspapers have discontinued daily or weekly science sections. As traditional print journalism has become less important in communicating scientific information, other communication platforms have developed rapidly. New media platforms, such as blogs, YouTube, and other evolving communication platforms, impact the communication of scientific information. The democratization of information may lead to more confirmation bias.

Research Needs and Priorities

Research is needed into how to communicate scientific information about natural resources in ways that support individual decision-making:

- The highest research priority is to understand the linkage between effective communication of scientific information and decision-making. Understanding this linkage will require teams of experts in communication, decision science, and natural resources scientists.
- Better methods of communicating uncertainty and probability to the public are the second priority. Scientists and the public usually do not share the same understanding of these terms. While to scientists these terms communicate deeper understanding, to the public these terms are interpreted as lack of understanding.
- Related to communication of uncertainty and probability is the development of methods to lessen the influence of confirmation bias in order to communicate natural resources scientific information effectively.
- Research is needed on how to communicate effectively and efficiently using new media platforms, particularly to integrate teams of scientists and experts in technological aspects of new media with communication experts.
- The reward structures within scientific agencies and universities need to be revised so that communicating scientific information to decision-makers is appropriately valued. A broader range of federal grants should require a comprehensive plan for communicating the results of natural resources research to decision makers. Grants should include a



significant component related to communicating research results to a non-scientific audience in understandable and useful terms. Experts in communication, extension/outreach, decision science, and other social scientists should be part of the proposal team from the beginning, and involved at a level that makes a real difference, not as an after-thought or "add-on." Extension specialists at land-grant universities can and do play a key role in communicating research findings to the public.

Expected Outcomes

A democratic society requires the exchange of sound and unbiased information. Under the status quo, with the rapid development of many new communication platforms, we can expect the communication of scientific information to become more fragmented. This fragmentation will lead to an increased tendency for confirmation bias in scientific communications. Many in decision-making roles will remain confused concerning the proper role of probability and scientific uncertainty in decision-making processes. The application of science in decision-making will thus tend to be overly optimistic or all but ignored.

Following *NR Roadmap* recommendations, there will be increased effectiveness in communicating scientific information to the public and decision-makers. With many new and developing communication platforms becoming available, fragmentation of scientific communication is becoming more common. Implementing the recommendations of the *NR Roadmap* will assist in effective and efficient communication of scientific information, supporting its proper role in decision making.

Goal V: Promote the sustainability of natural resources.

Gap Analysis

The landscape for natural resources management is rapidly changing, with unprecedented challenges arising. Human demand for finite natural resources is increasing with increasing human population, growing worldwide affluence, and increasing per-capita use of natural resources. Novel climate conditions are changing the productive potential of many ecosystems, in the face of decreasing availability of clean fresh water. Introduced species are changing farmland, forest, rangeland, and aquatic ecosystems.

Natural resources education long has relied on traditional management disciplines, integrating over a century of experience. However, sustaining natural resources in the face of unprecedented need through an unknown future will require different strategies and well-prepared leaders. It is our challenge to educate future leaders, managers, and decision-makers such that they are dynamic, critical thinkers who can recognize important changes that are occurring, describe key problems, assess needs, and develop and apply new tools in collaboration with experts from multiple disciplines. Professionals with such abilities should be educated in what public health sector academics label "integration and implementation science" (Bammer 2003, 2013).

Needs and Priorities

Educating tomorrow's leaders in natural resources stewardship will require cultural change in our institutions, as well as change in the curricular underpinnings for undergraduate and graduate students:

- Natural resources management must be integrated with the natural sciences. Approaches to solving complex issues in natural resources stewardship must necessarily engage knowledge about the cutting edge in science, including genetic engineering, atmospheric dynamics, biological control, fire physics, and many other disciplines, not as a separate set of courses, but as issues integrated into applied natural resources courses.
- Quantitative simulation models represent the best tool for predicting future conditions and assessing alternative stewardship strategies; these models must be improved by assimilating current data and monitoring to test and refine models. Working knowledge and ability to apply quantitative models will be critical for future leaders.
- While best stewardship practices potentially can be defined by natural resources science, it is application within the human context of social science and humanities that determines policy and practice.
- Communication and collaboration skills are needed to realize solutions to complex natural resources issues that involve engaging stakeholders. Stakeholders need to understand scientific information and uncertainties, and leaders need to be able to understand and engage groups with highly divergent values systems.
- A cross-APLU study might recommend alternative exploratory structures to enhance interdisciplinary engagement across university campuses and lead to more innovation in educating our future natural resources stewards.

Expected Outcomes

Under the status quo, higher education institutional structures often separate natural resources sciences (biology and social science) from the natural resources management disciplines, thereby separating "basic" from "applied" research and teaching. Faculty and students select the basic or applied scientific cultures on the basis of relatively arbitrary criteria and affinities, often leading to limited interaction across institutional barriers, with two or more institutional units for economics, ecology, watershed hydrology, and other critical areas. Reward structures for faculty tend to prioritize grants and publications in the basic disciplines, and outreach or management-relevant products in the applied disciplines.

Institutional structures and curricula with fewer barriers between scientific advances and natural resources management will provide us with current knowledge and flexible thinking needed for wisest stewardship. We envision public higher education institutions with new structures—perhaps including centers and institutes—that stimulate and reward interdisciplinary engagement by faculty and students. In addition to integrating natural resources sciences with management, these interdisciplinary structures will prove strong centers for research and education related to the skills necessary for tomorrow's leaders, including quantitative modeling, communication, and collaboration.

Goal VI: Promote diversity in the natural resources profession.

Gap Analysis

Recent Census Bureau data indicate that Agriculture and Natural Resources as a field ranks second only to Engineering in the lowest percentage of women potentially in the workforce, and at the very bottom in percentage of minorities (i.e., under-represented racial and ethnic groups) compared to 14 other major disciplines (Sharik 2013). Within Agriculture and Natural Resources, Forestry ranks at the bottom among 10 sub-disciplines. These findings are mirrored by the undergraduate student body in the U.S., where women and minorities in natural resource fields, although increasing, are only about two-thirds and one-third, respectively, of their numbers in the overall student population across all fields of study. Undergraduate enrollments in natural resources academic programs are currently at about the same level they were three decades ago, but the proportion of students among disciplines within natural resources has shifted dramatically to where enrollment in interdisciplinary programs eclipses those of the more traditional disciplinary programs such as forestry and fisheries and wildlife. Moreover, the percentages of women and minorities in these interdisciplinary programs are significantly higher than in the more traditional programs, especially in forestry. These findings have important implications for academic institutions and those who employ their graduates, and for how society views and values the natural resources professions. The under-representation of women and minorities in the natural resources professions creates special challenges for managing natural resources well into the future, and raises the question of what strategies should to be employed to bring their numbers more into alignment with those within society as a whole.

Research Needs and Priorities

We need to better understand the factors that lead to women and minorities choosing natural resources curricula and ensuing careers in numbers far below their proportion in the population, such that the natural resources professions are not representative of society as a whole. We also need to better understand factors contributing to the imbalance in enrollments of women and minorities among various natural resources disciplines, and how this imbalance stands to affect the availability of highly qualified professionals in the workforce. Research also is needed to determine those factors that contributed towards retaining these individuals to graduation (and thus employment) once enrolled in a college or university.

Expected Outcomes

Under the current trajectory, women and minorities will be more poorly represented in the natural resources professions than in most other professions, and our ability to make gains in the value that society places on these professions will be limited. Moreover, the availability of women and minorities in various natural resources disciplines will vary greatly and will not be well aligned with workforce needs.

Alternatively, by following *NR Roadmap* recommendations, we will gain enhanced understanding of the factors that cause women and minorities not to choose natural resources careers, and will be able to focus on these factors in order to increase their enrollment in natural resources degree programs and their numbers in the professional workforce. These efforts will also allow us to better understand differences among minority groups in their attractions to various natural resources careers and to better advise students on the greatest opportunities for employment.

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Appendix A: Glossary for Science, Education, and Outreach Roadmap for Natural Resources

Acidification — the process by which water bodies, such as rivers and lakes, and other natural features become affected by excess acid can also be described as acidification.

Adaptation — the act or process of adapting to new environmental, social or cultural conditions, or the state of being adapted (i.e., adaptation to climate change).

Adaptive management — a structured, iterative process of robust decision making in the face of uncertainty, with an aim to reducing uncertainty over time via system monitoring.

Agriculture — the cultivation of animals, plants, fungi, and other life forms for food, fiber, biofuel, drugs and other products used to sustain and enhance human life.

Best Management Practices (BMPs) — those practices determined to be the most efficient, practical, and cost-effective measures identified to guide a particular activity or to address a particular problem.

Biodiversity — the number, variety, and genetic variation of different organisms found within a specified geographic region.

Bioenergy — renewable energy made available from materials derived from biological sources.

Biomass — biological material derived from living, or recently living organisms.

Biome — a major ecological community of organisms adapted to a particular climatic or environmental condition in a large geographic area.

Carbon sequestration — is the process of capture and long-term storage of atmospheric carbon dioxide (CO_2).

Climate change — a significant and lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years.

Diversity — the inclusion of different types of people (as people of different races, cultures or sexual orientation) in a group or organization.

Ecosystem — a community of living organisms (plants, animals and microbes) in conjunction with the nonliving components of their environment (such as the atmosphere, water and mineral soil), interacting as a system.

Ecosystem function — the interactions between organisms and the physical environment via processes, such as nutrient cycling, energy flow, soil development, and water budgeting.

Ecosystem services — the important benefits for human beings or life systems that arise from healthily functioning ecosystems, such as the production of oxygen, soil genesis, water detoxification and pollination.

Ecosystem structure — attributes related to the physical state of an ecosystem; examples include species population density, species richness or evenness, and standing crop biomass.

Environmental justice — the fair treatment and meaningful involvement of all people regardless of race, color, sex, national origin, or income with respect to the development, implementation and enforcement of environmental laws, regulations, and policies.

Habitat — the area or environment where an organism or ecological community normally lives or occurs.

Hydrofracking or hydraulic fracturing — the use of pressurized solutions to cause fracturing around horizontal boreholes to increase the flow of natural gas or petroleum to an extraction well.

Invasive species — non-native species that adversely affect the habitats and bioregions they invade economically, environmentally, and/or ecologically.

Life cycle analysis or assessment — is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling).

Mesocosm — an experimental tool that brings ecologically relevant components of the natural environment under controlled conditions.

Metapopulation — a group of spatially separated populations of the same species which interact at some level through dispersal and gene flow.

Natural resources — naturally occurring materials or ecosystem components such as soil, water, forest, rangelands, marine, etc, that can be used by humans.

Net primary production — the rate at which all the plants in an ecosystem produce net chemical energy; it is equal to the difference between the rate at which the plants in an ecosystem produce chemical energy and the rate at which they use some of that energy during respiration.

Oxygen Minimum Zone (OMZ) — the zone in which oxygen saturation in seawater in the ocean is at its lowest.

Phenological responses — changes in timing of biological events or cycles (i.e., breeding, flowering, migration) as a result of environmental change.

Renewable energy — energy that comes from resources which are continually replenished on a human timescale such as sunlight, wind, rain, tides, waves and geothermal heat.

Resilience — the ability to recover from a perturbation, disaster or catastrophe.

Resistance — the ability of an ecosystem to maintain function when disturbed or undergoing environmental change.

Restoration — the practice of renewing and restoring degraded, damaged, or destroyed ecosystems and habitats in the environment by active human intervention and action.

Scientific literacy — the knowledge and understanding of scientific concepts and processes required for personal decision making, participation in civic and cultural affairs, and economic productivity.

Socioecology — the study of critical resources (natural, socioeconomic, and cultural) whose flow and use is regulated by a combination of ecological and social systems

Species — the largest group of organisms capable of interbreeding and producing fertile offspring.

Stewardship — the activity or job of protecting and being responsible for something.

Stressor — an activity, event, or other stimulus that causes stress on an organism, population or ecosystem.

Sustainability — the potential for long-term maintenance of well being, which has ecological, economic, political and cultural dimensions.

Scientific literacy — written, numerical, and digital literacy as they pertain to understanding science, its methodology, observations, and theories.

Total Maximum Daily Load (TMDL) — a value of the maximum amount of a pollutant that a body of water can receive while still meeting water quality standards.

Watershed — the area of land where all of the water that is under it or drains off of it goes into the same place.

Appendix B: Science, Education and Outreach Roadmap for Natural Resources Contributors

NR Roadmap Advisory Board

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Appendix C. Crosswalk for priority areas in the NR Roadmap with priorities identified in the ESCOP Science Roadmap for Agriculture

Research Needs and Priorities*

Couple Human-Natural Systems	Soils and Freshwater	Forestlands
Understand and apply more widely the concept of socioecology: human and natural systems are linked and should thus be studied as one broad human-natural system.	Emphasize technological innovation. Precision technologies (e.g., micro-irrigation) can enhance the sustainability of how humans use water and soil.	Integrate forest management practices with overall environmental sustainability and ecosystem services protection goals. Currently this is only guaranteed by using non-mandatory guidelines which require regular development and upgrades to meet more intensive resource use.
Increase environmental justice.	Determine the capacity of soil and water to meet current and future demands for agricultural and forest products.	Increase understanding of the integrated effects of forest management and harvesting practices on soil, water and biodiversity protection needs.
More thoroughly apply Life Cycle Analysis to major materials and natural resources.	Evaluate the effectiveness of policies and incentives that promote soil and water conservation.	Increase awareness towards reducing wood extraction from sensitive sites due to long term effects on reduced productivity.
Identify and account for external costs not internalized in prices.	Increase the spatial and temporal precision of climate simulations in order to improve outcomes prediction under future climate scenarios (e.g., water availability; forest, rangeland, and crop response to drought persistence; and soil erosion).	Develop realistic economic assessments of the long-term effect of current use rates on resource and ecosystem productivity.
Improve agricultural and fisheries production through more efficient use of land, water, energy, and chemicals.	Predict and evaluate how a growing and urbanizing human populace with an increasing standard of living will affect how soils are managed and how water is allocated.	Promote alternative practices that are less environmentally taxing.
Simultaneously increase the generation of renewable energy while reducing the impacts of infrastructure (e.g., wind farms, wells, pipelines) on fisheries and wildlife.	Apply systems-level analytics to understand feedbacks between humans, soil, and water and identify key leverage points for policy makers to optimize the efficiency of public and private conservation expenditures.	Promote understanding of the reasonable scale and utilization rates of resources to reduce negative environmental effects.
Evaluate how food production, freshwater availability, and natural landscapes can sustainably coexist while facing a growing human population.		Promote/manage forests for sustainable use of non-forest timber products.
Evaluate how different policy and economic scenarios might alter the future availability, utility, and resilience of natural resources.		

* Items in Green come from ESCOP *A Science Roadmap for Food and Agriculture* (APLU 2010); items in Blue come from the *NR Roadmap*; items in Purple are overlapping. Items in Orange indicate the original wording of overlapping agricultural priorities.

Research Needs and Priorities*

Rangelands	Marine and Coastal Ecosystems	Development of Sustainable Management Practices
Emphasize and promote an integrated systems approach to research and outreach to improve policy formulation that supports the long-term sustainable management of dynamic rangeland ecosystems.	Understand the status and trends of resource abundance and distribution through accurate, timely assessments.	Reduce the use of nonrenewable inputs in agricultural production.
Expand spatial and temporal scales of research to address heterogeneous biophysical factors and response lags to management practices that influence rangeland productivity and ecosystem services.	Understand interspecies and habitat-species relationships to support forecasting of resource stability and sustainability.	Assess the capacity of agricultural and other managed systems to deliver ecosystem service, including trade-offs and synergies among ecosystem services.
Promote trans-disciplinary research to address crosscutting social and biophysical factors that influence the dynamics of rangelands and tradeoffs resulting from changing demands for potentially competing ecosystem services.	Understand human-use patterns that influence resource stability and sustainability.	Enhance internal ecosystem services that support production outcomes that reduce chemical inputs.
Emphasize and promote integrative social science research that addresses science-based data interpretation and experience-based user knowledge.	Advance the environmental sustainability of ocean energy technologies.	Assess food animal production in relation to ecosystem services.
Document and assess contributions of management decisions to short- and long-term outcomes of conservation programs.	Develop sustainable fishing practices and technologies.	Develop innovative waste management technologies.
Develop protocols and programs that generate systematic and standardized evidence-based assessments of conservation investments in rangelands.	Understand resiliency and adaptation to a changing climate.	Pursue systems-oriented and science-based policy and regulation for agricultural and other managed systems.
Develop integrated research and outreach programs that bridge rangelands, pastures and hayfields.	Understand the interactions between coastal and marine operations/use and the environment.	

Water Challenge

Appendix C (cont'd.)

Research Needs and Priorities*

Improve understanding of mechanistic linkages between land uses, extractive consumption of water resources, and watershed resistance and resilience to better inform policy	Improve understanding of risks and impacts to water supplies from extractive uses, carbon sequestration technologies, and extractive technologies	Improve technology to process and allocate water that ensures sustainable, high quality water for human uses and maintenance of ecosystem services	Develop understanding of how existing and future policies and land uses impact water security, quantity, and quality over regional and national scales	Assess how the intersection of Social (or Human) and Natural (or Environmental) Systems impact water security, quantity and quality
Quantify nutrients loads and impacts on watersheds. Identify methods to reduce loads while maintaining healthy economies.	Quantify current agriculture use and overdraft.	Develop techniques and processes for removing pharmaceuticals from wastewater.	Engage communities early, and in meaningful ways, in decision and policy making processes at the watershed level, giving them a voice and ensuring that the results are implementable and effective	Increase use of hydro-economics to understand and predict how new technologies and policies will ultimately affect the condition of the targeted water resource systems.
Identify water quality thresholds related to biological and human health.	Quantify the impacts of increased irrigation due to drought and changing climate in agricultural areas and define sustainable use limits.	Develop technology that allows real-time monitoring and management of water systems.	Identify water impacts and potential solutions resulting from existing energy policy (i.e., production of biofuels, hydrofracking,etc.).	Increase economic understanding of management alternatives for wetland and aquatic systems.
Determine the undeveloped footprints needed in watersheds to sustain biodiversity, water quality, or water quantity.	Improve understanding of introduced chemicals and byproducts resulting from hydrofracking.	Identify spatially-explicit landscape and groundwater features that provide mechanisms of resistance and resilience to natural and man-caused hazards, particularly in disaster-prone areas (e.g., coastal habitats, areas of high-seismic activity, etc.).	Identify regional and national water impacts and potential solutions of existing agriculture policies and subsidies (i.e., water allocation laws, farm bill incentives, etc.).	Enhance use of benefit/cost analysis and policies to increase understanding of public opinion (and determinants of) concerning economic-environmental trade-offs in watersheds.
Identify land use variables (indicators) impacting watershed biodiversity and associated thresholds beyond which watersheds are impacted or degraded.	Improve understanding of the presence of introduced chemicals and byproducts resulting from carbon injection in deep water wells.	Increase precision of groundwater data and models to better manage lands that recharge aquifers and prevent groundwater quality degradation from agricultural and other sources.	Define water impacts resulting from regional and national residential and urban development patterns and identify potential alternatives and solutions.	Increase social science research that identifies decision-making processes that are necessary for watershed solutions.
Define components of natural regimes to maintain ecosystem services, and develop regime-based standards for water quality and quantity that maintain ecosystem function and biological diversity, from headwater streams to estuaries.		Apply geospatial approaches such as modeling and remote sensing technologies to better model water quality and quantify future water supply and demand at a regional and national scale.	Examine water impacts resulting from existing transportation patterns and policies (impervious surface, sprawl, habitat loss, etc.) and analyze effects of potential solutions (mass transit, high speed rail, cluster development, etc).	Increase understanding of how educational, incentive, or regulatory tools change the behavior of the individual and institutional users of water resources.
Improve understanding of subsurface flow and groundwater and surface water interactions crucial for biological communities and provide mechanisms for resilience to drought, climate warming, and disturbance.		Use satellite and advanced information technologies to predict potential water conflict at all scales and inform policy and management.	Analyze inter- and intra-basin policy alternatives required to balance water supply with demand and ensure resilience of supply in the face of disaster and climate change.	Develop a holistic understanding of our water resources in a systems context.
Define achievable restoration targets for urban and agricultural streams.			Analyze the importance of scale for watershed management and BMPs implementation to maximize cost effectiveness and ecological lift.	
			Assess the optimal places to focus future crop production and livestock grazing within sustainable water use limits.	
			Assess regional and national water pricing, policy, conservation, and management structures needed to balance water demand with sustainable supply	

Research Needs and Priorities*

Water use efficiency and productivity	Groundwater management and protection	Wastewater reuse and use of marginal water for agriculture	Agricultural water quality	Water institutions and policy
Develop crop and livestock systems requiring less water per unit of output.	Develop new management and institutional arrangements to sustain groundwater systems, including real-time data networks and decision support systems to optimize use of surface and groundwater.	Develop cropping systems and irrigation strategies using impaired and recycled water while protecting soil health and quality.	Develop new approaches to reduce nutrients, pathogens, pesticides, salt, and emerging contaminants in agricultural runoff and sediments.	Develop river basin-scale institutional and planning approaches that integrate land use, water, and environmental and urban interests for robust management solutions.
Develop systems with increased resilience to flooding, drought and interruptions in supply.	Develop watershed management systems that more effectively capture water during intense precipitation events and store it for use during droughts.	Address institutional barriers to the use of non-conventional waters.	Determine socioeconomic barriers to adoption of new water quality practices and develop innovative approaches to encourage and sustain adoption.	Investigate policy needs to sustain agricultural water supplies and increase institutional and administrative flexibility.
Develop institutional arrangements facilitating water sharing across sectors.		Assess public health issues related to pathogens and heavy metal contamination.	Develop methods for onsite treatment of tile drainage water.	
Develop water pricing and other market-based approaches.		Explore marginal water treatment technologies to reduce energy requirements for treatment.	Explore new methods to reduce water quality impacts from animal waste.	
		Investigate use of brackish water to supplement freshwater resources.		
		Consider new approaches to reduce costs for desalination.		
		Develop salt-tolerant crops.		

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Appendix C (cont'd.)

Research Needs and Priorities*

Observation and Experimental Approaches	Simulations and Modeling	Management, Risk, and Uncertainty	Climate Science	Crop, Livestock, Weed, and Pest Models	Improved Economic Assessments of Climate Change Impacts and Adaptation
Identify signals of climate change that inform short-, intermediate-, and long-term predictions, forecasting and early warning involving whole-system structure and function.	Develop mechanistic ecosystem models comparable to statistical models, suitable for ecosystem management planning under climatic futures.	Identify uncertainties of future climate parameters as a function of spatial scale, given uncertainties in mode accuracy, future anthropogenic forcing, natural variability, and attributable past changes.	Development of climate change scenarios relevant at local to regional scales and time horizons that include factors ranging from unique physical features not captured by climate models, such as lake influences, to regional projections of changes in land use, environmental policies, or economics.	Improve and evaluate existing models for use in climate change and weather variability studies; for addressing carbon, nitrogen, and water changes in response to climate; and for assessing resource needs and efficiencies.	Quantify costs and benefits of adaptation at the farm level and for specialty crops, livestock and grain crop production systems.
Define effects of predicted climate change on nature-human interactions.	Improve climate-based models for areas where we are expecting the most rapid global impacts (e.g., melting tundra).	Identify and estimate location-specific climate drivers and their uncertainties under a range of future scenarios.	Improve and develop physical and empirical downscaling techniques tailored to agriculturally relevant variables (e.g.,. leaf wetness, livestock heat stress, and drought and freeze risk).	Develop and test new crop models for perennial fruit crops, vegetables, and other "specialty" food crops, wood products; and biofuel crops.	Assess economic impacts and costs of adaptation for entire foods systems.
Define interactions and effects of climate and habitat changes to population, metapopulation, and community dynamics and change at ecosystem boundaries, along habitat gradients, and within ocean current systems, at local to regional scales.	Improve climate-based models for key insects, diseases, and disease vector dynamics, and potential human, animal and plant health impacts.	Define the impacts of uncertainty and irreversibility associated with climate change and impacts on management strategies and public policies for mitigating impacts.	Develop methods to spatially interpolate climate data.	Develop and test new livestock models focused on heat stress and greenhouse gas mitigation in livestock facilities.	Integrate economic with environmental and social impacts of climate change and adaptation (e.g., valuation of ecosystem services, impacts on farm structure, and rural livelihoods, social equity and justice, etc.).
Develop practical technologies for measuring, analyzing, and assessing environmental responses to climate change, especially on full ecosystem levels.	Improve methods for quantifying carbon pools and fluxes suitable for incorporation into ongoing inventory programs such as for fisheries, forestry, etc.	Develop improved communication language and education from the scientists/researcher to the decision maker/politician, and public at-large.	Develop sophisticated real-time weather-based systems for monitoring and forecasting stress periods, pest and weed pressure, and extreme events.	Develop and test new insect, pathogen and weed models to project future range shifts, population dynamics, and epidemiology.	
Develop real-time early warning systems that use confluences of modeling technologies in predicting changes and are informative to governments, agencies, and the public at large.	Improve models for predicting changing hydrologic regime impacts on natural and managed ecosystems (e.g,. forest health and yield under scenarios with increased evapotranspiration).	Define best-practice tools and processes for quantifying and assessing risk under typical natural resource management scenarios, and for better managing under future conditions.			
Prioritize resources for research to previously understudied areas where changes appear to be the most rapid and may have the largest global and economic impacts (e.g., high latitudes).	Coordinate climate and ecosystem research and data for improved modeling of weather variability and extreme cyclical events (wildfire, insect and disease; cyclonic storms; etc.).	Understanding ecosystem change and degradation: individual behavior and community resilience			

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Research Needs and Priorities*

Decision Science	Conceptualizing and Modeling Complex Systems	Adaptive Strategies and Management	Greenhouse Gas Mitigation and Soil Carbon Sequestration and Monitoring	Communication	Policy Analysis
Risk perception, investment decision making under uncertainty, and the role of temporal discounting.	Characterizing and analyzing climate uncertainty and impacts on system productivity; demand for water, nutrients, and other resources; and the environment.	Develop adaptive strategies for livestock, including managing weather extremes; accounting for costs and constraints of renovation or relocation of facilities; information on breeds more tolerant to stresses; managing waste; and biofuel production.	Systems and BMPs to reduce greenhouse gas emissions for crops, animals and animal waste systems, and food processing and other food system activities beyond the farm gate.	Identification of gaps in knowledge, socioeconomic biases, and other factors constraining effective communication to target audiences.	Economic impacts of mitigation policies on agriculture and the food sector, including costs of energy and other inputs, environmental impacts, and regional and social equity.
The role of participatory processes in scenario development.	Spatial and temporal dynamics of production systems.	Develop new, more tolerant crop varieties through conventional breeding, molecular-assisted breeding, and genetic engineering. University emphasis on crops not currently being addressed by commercial seed companies.	Systems and practices to offset emissions by sequestering carbon in trees and soil and also methods to quantify offsets, including measurement uncertainty.	Evaluate framing of issues for optimum communication effectiveness for target audiences.	Evaluate policy mechanisms, including tax incentives, environmental and land use regulation, agricultural subsidy and trade policies, insurance policies and disaster assistance, soil and water conservation policies, and energy policies including those involving carbon trading and biofuel production.
Test and design decision support tools for adaptation and mitigation measures appropriate for different producers and consumers.	Systems characterization, including a comprehensive coverage of farm sizes and types, commodity transportation and storage systems, and food processing and distribution.	Develop new, rapid breeding technologies to quickly respond to emergent vulnerabilities to previously nonthreatening diseases and pests.	Greenhouse gas and carbon accounting tools for farmers and food system users.	Use new technologies and social networking for communication with target audiences.	
		Develop improved water management systems and irrigation scheduling technology.	Policy mechanism design for greenhouse gas mitigation.		
		Develop adaptive strategies for weed and pest control, such as improved regional monitoring and IPM communication regarding weed and pest range shifts; enhance real-time weather-based systems for weed and pest control; develop nonchemical options for new pests; and develop rapid-response action plans to control invasive species.			
		Develop adaptive strategies for storage and transport system (e.g., redesign and relocation of infrastructure, and assess impacts of rises in sea levels on port facilities).			
		Develop adaptive strategies for food processing and marketing systems			

Appendix C (cont'd.)

Research Needs and Priorities*

Improve Understanding of Costs and **Benefits of Energy Development and Use** and Public Perceptions Related to Energy to Better Inform Policy and Advance Environmentally and Economically Friendly Renewable Energy	Identify New and Alternative Renewable Resources	Minimize Impacts of Increasing Energy Demands on Natural Resources
Conduct full life-cycle analyses of costs and benefits of different energy sources at local through national scales.	Identify and test new biofuel products from waste streams of land management activities.	Develop uniform indicators of environmental effects of energy development and use.
Quantify trade-offs among land/sea-use alternatives (i.e., fisheries, forestry, grazing) in areas that may be developed for energy production.	Identify and test new or more efficient energy extraction methods from existing biofuel products.	Quantify biodiversity impacts of energy development and use (e.g., slash and coarse woody debris removal for biofuels; fish passage and hydrological changes at hydropower facilities; etc.).
Quantify public perceptions regarding energy development and land/sea-use alternatives.	Develop marine renewable energy sources.	Quantify behavioral changes and mortality of organisms associated with energy development and use (e.g., bird mortality at wind turbines; marine mammal and fish attraction or avoidance of tidal energy facilities; relationship of animal movements to electromagnetic field changes; etc.).
Conduct economic analyses regarding present and future energy production costs compared to the projected costs of renewable energy.	Identify and develop markets for renewable energy. Many such markets require process, transportation, or combustion modifications.	Identify sources and quantify water and air pollution associated with energy production.
		Quantify water demand for steam production and cooling of geothermal, biofuels, solar and traditional energy sources (coal, natural gas, nuclear).
		Understand public's perceptions of alternative energy sources and barriers to adoption of energy conservation practices.

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Research Needs and Priorities*

Maintain Available Energy and Increase **Efficiency to Reduce Ecological Footprint**	Education	Energy Security and the Bioeconomy
Increase water-use efficiency in steam production and cooling systems.	Develop K-12 science programs to engage youth in renewable energy and support teachers that explain the social, political and environmental challenges associated with fossil fuels and the challenges and opportunities for transitioning to renewable sources.	Devise agricultural systems that utilize inputs efficiently and create fewer waste products.
Increase efficiency and use of existing energy sources/infrastructure (e.g., hydrofracking for natural gas production).	Promote college and post-graduate programs that develop a capable and diverse workforce through mentored research internships and fellowships. Energy development and production will require well-trained scientists from diverse STEM-related disciplines. The need for graduate degrees in this sector necessitates increased funding for internships and fellowships.	Assess the environmental, sociological, and economic sustainability of biofuel and coproduct production at local and regional levels.
Increase fuel conversion efficiency for biofuels.	Promote renewable energy outreach programs through the university land-grant system that enable the public to better understand the sustainability and environmental impacts of their energy choices and increase energy conservation practices.	Develop technologies to improve production-processing efficiency of regionally appropriate biomass into bioproducts (including biofuels).
		Expand biofuel research with respect to non-arable land, algae, pest issues that limit biofuel crop yields, and emissions of alternative fuels.
		Restructure economic and policy incentives for growth of the next generation domestic biofuels industry.

Education Challenge

Appendix C (cont'd.)

Research Needs and Priorities*

Include Natural Resources in K-12 Education by Incorporation into STEM Curriculum and Activities.	Strengthen Natural Resources Curricula at the Higher Education Level	**Improve the Scientific Literacy of the** Nation's Citizens
Evaluative mechanisms to assess effectiveness of K-12 natural resource curricula that assess the degree to which concepts are retained over multiple years and used in multi-faceted, integrated critical thinking exercises.	Federal agencies must maintain support for applied research.	Include in K-12 standards a demonstration of the process through which new scientific knowledge is realized.
Evaluate the most effective suite of experiential activities that maximize understanding of natural resource science and management and address key components of STEM requisites, and develop and evaluate integrated programs for effectiveness in knowledge retention, critical thinking, and application over the long-term.	Understand the factors affecting undergraduate and graduate enrollments and career opportunities in natural resources-related fields.	Conduct pedagogy research to determine what is needed to more effectively include active inquiry into teaching and learning at both the K-12 and higher education levels.
Understand the potential use of technology as a bridging tool for connecting youth to the outdoors, and develop a better understanding of the role of social science and use of social indicators in youth that lead to behavior change.	Expand university training to include both traditional base of technical knowledge, skills, and behaviors, and problem-solving, quantitative reasoning, critical thinking, and communication skills.	Train more science journalists.
Engage underrepresented populations in STEM, natural resources and sustainability curricula in our schools and develop curricula recognizing differences in cultural and racial values regarding natural resource use, and evaluate the effectiveness of these curricula over the long-term.	Continue research on pedagogy to produce professionals ready to face modern natural resources management challenges.	
Specific topics needing empirical research include: surveys to better understand what youth are concerned about; longitudinal studies to determine if increased knowledge and awareness leads to behavioral change, and to address promising strategies and practices for natural resources education that are accessible to school administrators, decision makers and funders; understanding how adult constructs such as "climate change" might be translated into actionable items for youth; understanding how adult learning and fears about science impact the way youth perceive natural resources education; and developing and analyzing practices in systems thinking and complexity education..		

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Research Needs and Priorities*

Communicate Scientific Information to the General Public in Efficient and Effective Ways	Promote Natural Resource Stewardship	Promote Diversity in the Natural Resources Profession
Fund research to understand the linkage between ways that decisions are made and ways that scientific information is communicated and broaden strategies for science communications, which will require teams of experts in communication, decision science, and natural resources scientists.	Integrate natural resources management with natural sciences and engage knowledge about the cutting edge science (e.g., genetic engineering, atmospheric dynamics, biological control, fire physics, etc.), not as separate courses, but as issues integrated into applied natural resources courses.	Understand the factors that lead to women and minorities choosing natural resources curricula and careers in numbers far below their proportion in the population.
Develop better methods of communicating uncertainty and probability to the public because these terms are interpreted as meaning a lack of understanding.	Integrate quantitative modeling with monitoring and data assimilation and increase future leaders' ability to work with quantitative models.	Understand the factors contributing to the imbalance in enrollment of women and minorities among various natural resources disciplines, and how this imbalance may affect the availability of highly qualified professionals in the workforce.
Develop methods to lessen the influence of conformational bias in order to effectively communicate uncertainty and probability in natural resources.	Integrate natural science with social sciences and humanities within the human context that determines policy and practice.	
Understand how to communicate effectively and efficiently using new media platforms, and integrate teams of scientists and experts in technological aspects of new media with communication experts.	Develop communication and collaboration skills that enable leaders to understand and engage groups with highly divergent values systems.	
Revised reward structures within scientific agencies and universities so that communicating scientific information to decision makers is appropriately valued. Federal grants should require a comprehensive plan for communication of the results of natural resources research to decision makers and communicating research results to non-scientific audiences at a level that makes a real difference, not as an afterthought or "add-on."	A cross-APLU study might recommend alternative exploratory structures to enhance interdisciplinary engagement across university campuses and lead to more innovation in educating our future natural resources stewards.	


Beach Vehicle Accessibility
Vehicles Prohibited
Vehicles Allowed
P a c i f i c   O c e a n
The Dalles
Hood River
Florence
Coos Bay
Brookings
Christmas Valley
C A L I F O R N I A