



United States Department
of Agriculture



Forest Service

Research and
Development

FS-948

Forest Service Global Change Research Strategy, 2009–2019 Implementation Plan

May 2010



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Executive Summary

Forest Service Global Change Research Strategy, 2009–2019 Implementation Plan

Objective

In keeping with the research goals of the U.S. Global Change Research Program, the climate change strategy of the U.S. Department of Agriculture (USDA), and the climate change framework of the Forest Service, this *Forest Service Global Change Research Strategy, 2009-2019 Implementation Plan* (hereafter called the Research Plan), was written by Forest Service Research and Development to help to define climate change policy and support best management practices for forests and woodlands (both rural and urban), grasslands, and their associated aquatic ecosystems (riparian systems, lakes, streams). The actions the Research Plan identifies will provide the scientific basis to sustain ecosystem health, adjust management for ecosystem services (“adaptation”) and increase carbon sequestration (“mitigation”), all under changing climate conditions. The fundamental research focus of the Research Plan is to increase scientists’ understanding of forest, woodland, and grassland ecosystems so that land managers can manage them in a way that sustains and provides ecosystem services for future generations.

Basis

Climate changes recently observed and those predicted for the future differ considerably from climate conditions of the past. Accordingly, future ecosystem services will differ from those of the past. Land management must be capable of enhancing adaptation of these ecosystems to increasing climate changes while removing carbon from the atmosphere through sequestration in ecosystems and wood/energy products. At the same time, geographic and temporal variability in climate also will increase. These geographic differences manifest in both biophysical conditions and socioeconomic systems. Therefore, land management plans and actions must differ locally to account for this variability. Policymakers must consider the sum of the effects of these local actions, however, which requires that these local actions be linked to national plans.

To address these issues, scientists, land managers, and policymakers need the Research Plan and the concomitant research activities to balance and coordinate scientific responses. This plan is the scientific basis for a unified approach to managing ecosystem services within the range of uncertainty produced by a changing climate and the depth of our global change knowledge. A separate document, the *Forest Service Global Change Research Strategy* (the Research Strategy), is also available (Solomon et al.

2009). Both documents are the result of a meeting of Forest Service scientists and other interested parties, held in Denver, CO, in September 2007, to develop the plan and strategy (see appendix 8.1).

Approach

The Research Plan balances research across a range of management, science, and science delivery actions aimed at developing adaptation and mitigation approaches to sustain healthy ecosystems. The following three research elements serve as organizing themes.

1. **Research To Enhance Ecosystem Sustainability (Adaptation).** The first element focuses on research that will advance management options under a changing climate to enhance ecosystem health and sustainability; ensure the flow of ecosystem services, such as water, wildlife, biodiversity, recreation, forest, and grassland products; and reduce losses of ecosystem function from climate-altered disturbances, such as wildfire, insects, and invasive species.
2. **Research To Increase Carbon Sequestration (Mitigation).** The second element focuses on research that will assist managers in enhancing carbon sequestration via actions that could increase forest growth rates and areas of forested lands, enhance biomass extraction and utilization research, and support understanding of long-term carbon product storage pools. These capabilities cannot be realized without integration with adaptation research.
3. **Research To Provide Decision Support.** The third element integrates the first two research elements by developing decision-support tools for policymakers, planners, and land managers.

Within each research element, the Research Plan reviews the most pressing *research needs*, examines *cooperative activities* to support research needs, documents *science delivery* approaches, and describes the most immediate *action items* to be undertaken, should funding become available. The plan also describes additional activities that support these primary elements, including infrastructure investments needed to implement the plan. As cited above, a companion document, the Research Strategy, distills the information in the plan for rapid examination of the Forest Service global change research approach.

1. Introduction



The *Forest Service Global Change Research Strategy, 2009-2019 Implementation Plan* will help identify best management practices for urban and rural forests, woodlands, and grasslands to sustain ecosystem health and services under a changing climate.

1.1. The Objective

A century of wildland policy and management has helped create wildland ecosystems in the United States that produce a wide variety of goods and services all Americans enjoy. Several rapidly intensifying global forces, including climate change, land use change, invasive species, air and water pollution, and changes in the global competitiveness of the U.S. forest sector, however, are threatening these ecosystem commons. In addition to traditional roles in supplying wood products, clean water and air, wildlife habitat, recreation, and so on, forests also play an important role in reducing the buildup of greenhouse gases (GHGs) in the atmosphere by sequestering carbon (“mitigation”). Now, scientists are viewing the forests as potentially important sources of biomass energy feedstocks. Alternatively, forests, woodlands, and grasslands can become unintended sources of carbon to the atmosphere when large wildfires and insect infestations arise or land is converted to developed uses. Climate change and naturally occurring disturbances altered by climate change threaten ecosystem functions and the suite of ecosystem services from forests, woodlands, grasslands, and their associated aquatic ecosystems (riparian systems, lakes, streams). Adjustments in natural or human systems to the changing environment (“adaptation”) may result in beneficial opportunities or moderately negative effects. In addition, while forest, woodland, and grassland health and productivity are increasingly vulnerable to climate change, these large ecosystem commons are habitats for plants and animals and will serve as landscapes in which the process of natural adaptation to climate change is likely to occur.

Land managers are attempting to address the challenges of climate change with inadequate and often conflicting information. Yet, decisions that public and private land and resource managers make today will have implications through the next century, especially as they relate to the adaptation of ecosystems.

The *Forest Service Global Change Research Strategy, 2009-2019 Implementation Plan* (hereafter called the Research Plan) will help identify best management practices (adaptation) for urban and rural forests, woodlands, grasslands, and their associated aquatic systems to sustain ecosystem health and a range of ecosystem services while also increasing carbon sequestration—all under changing climate conditions. The fundamental research focus of the Research Plan is to increase our understanding of forest, woodland, grassland, and aquatic ecosystems so that land managers can act in a way that sustains and provides ecosystem services for future generations.

This document describes the current and future Forest Service, U.S. Department of Agriculture (USDA), research plan for global change. Global change encompasses all the environmental phenomena related to global scale anthropogenic forces: changing climate and climate variability, shifting land uses, changing concentrations of atmospheric contaminants, increasing nitrogen deposition, and so on. The Research Plan reviews the basic functions the research must serve and the strategy needed to attain those functions. The plan is linked to related Forest Service research program strategies, including those focused on wildfire, invasive species, insects, and biomass and biofuels. The

Research Plan also complements the more broadly conceived Forest Service Climate Change Framework Strategy. Research defined here will support the needs of the broad range of stakeholders (those parties interested in or affected by the research) the Forest Service serves, including National Forest System (NFS) planners and managers; other Federal, State, and local land managers; private landowners; industry; and others. The Research Plan is aimed at informing Forest Service land managers and administrators; land managers and administrators in other Federal, State, and local agencies; global change scientists; and citizens who may wish to examine Forest Service research goals in global change.

We note that global forests provide important environmental services and resources and are crucial to the conservation of biodiversity, water resources, and storing and sequestering of carbon, which has a direct impact on regulating climate. Developing countries, the World Bank and nongovernmental organizations (NGOs), and the United States and other developed nations have a strong interest in reducing deforestation and improving forest management to mitigate climate change and improve rural economies. With support from the wealthier nations, and under offset guidelines emerging from the Intergovernmental Panel on Climate Change, governments and NGOs must develop and implement projects to improve forest management and reduce emissions from deforestation and degradation (REDD). For a country to receive payments or credit in carbon markets, its increased carbon sequestration and reduced emissions must be quantified relative to a baseline. During the next decade, Forest Service Research and Development (R&D) will take these requirements into account in developing the next generation of research activities.

1.2. The Basis

The Earth's climate is changing and will continue to change for many decades in response to the buildup of GHGs in the atmosphere. The "fingerprint" of GHG effects on climate has been known for some time, and includes the following:

- Warming in the lower atmosphere (troposphere) while cooling in the upper atmosphere (stratosphere).
- Warming more at the poles than at the equator.
- Warming more over land than over the sea.
- Warming more in winter than in summer.
- Warming more at night than in daytime.

- Increasing intensity of the hydrological cycle, including more rain in high latitudes and less in the subtropics.
- Increasing climate variability producing more large storms and longer, more intense droughts.

Interaction of these differences with variation in regional surface topography and land cover dictate that the climate changes already measured, and those predicted in the future, differ considerably from place to place. The Southwestern United States is encountering increasing drought; the Northwest is undergoing longer, dryer summers and declining snowpacks; and the Northeast has seen increased rainfall and flooding, warmer winters, and longer growing seasons. In the Southeast, warmer winters with dryer summers are apparent, and in the tropics (Puerto Rico and Hawaii), climate is warming and drying, sea levels are rising, and tropical storms are increasing in intensity.

Forests, woodlands, and grasslands will experience regional and local changes in temperature and precipitation. They are also likely to experience increases in the variability of weather, such as droughts, storms, and heat waves. Moreover, other global forces—such as land use, air pollution, and invasive species—will interact with these climate changes, further affecting forests, woodlands, and grasslands across the United States. Because ecosystems in these regions also differ, land management actions will need to vary widely in response to these differing climate changes and ecological effects.

A fundamental challenge posed by changing climate must be resolved through land management—the need to remove carbon from the atmosphere by increasing its sequestration in ecosystems and wood/energy products while enhancing the adaptation of these ecosystems to increasing changes due to climate. In addition, NFS managers, who are working to maintain the variety of ecosystem goods and services the public demands, may use different approaches in specific locales than other nearby landowners would use because their goals and objectives may differ. For example, a national forest could be in the midst of landowners who are focusing on only commercial timber production, or only wildlife, or only recreation. All of these considerations argue for a landscape-scale approach to land management.

Land managers face increasing public interest in climate change and have conveyed a sense of urgency for information and science to support their decisionmaking. They are faced with planning for and making climate change-related decisions today. They need access to credible scientific information in understandable language and useful forms to

support these decisions. The need for this scientific information will be honed in real time if a healthy learning environment is developed in which researchers and managers testing new adaptation strategies can share their successes and failures across landscapes, regions, and agencies. Land managers recently reported a variety of research needs, which can be divided into four general categories.

1. A simple understanding of the basic concepts associated with global change relevant to land management (e.g., vocabulary, ecosystem responses).
2. An understanding of how climate change can be integrated into multiple-use management (e.g., balancing stocking densities with production of other ecosystem services, climate effects on fire).
3. Tools to implement climate change strategies in the specific forests being managed (e.g., local future climate scenarios, vegetation projection models output, vulnerabilities and risk predictions, implementation of land and resource management plans).
4. Increased interagency cooperation on land management activities and outreach to citizens and other stakeholders (e.g., adjacent land holdings, stakeholder input to decisions and actions).

A Forest Service national global change plan and the concomitant research needed to implement it must be in place



to balance and coordinate the scientific basis for managing ecosystem services within the uncertainty of changing climates, land use, and atmospheric chemistry.

1.3. The Approach

Forests, woodlands, and grasslands must adapt to climate change if they are to continue as sustainable ecosystems while playing a role in mitigating climate change.

Adaptation focuses on the following:

- Identifying ecosystem vulnerabilities to different future climates and disturbance regimes in diverse geographic regions.
- Determining the capacity of ecological, economic, and social systems to adapt to climatic and environmental changes.
- Developing management practices and technologies that will help sustain ecosystem function, minimize losses of ecosystem services, and, where possible, capitalize on new opportunities under climate change.
- Developing strategies and practices that support decisionmaking in the face of multiple sources of uncertainty (e.g., environmental conditions, models, data, resources).

Mitigation addresses the following:

- How ecosystems can sequester more carbon.
- How to increase carbon stored in wood products.
- How to reduce fossil fuel use in manufacturing.
- How forests and woodlands can provide renewable energy from woody biomass to replace fossil fuel consumption.

Mitigation also includes ways the Forest Service can reduce its environmental footprint (e.g., carbon, energy, pollution) and lead by example in greening the agency's practices.

This Research Plan melds adaptation and mitigation inextricably: No sustainable increase in the national inventory of carbon sequestered in our forests, woodlands, and grass-

Forests, woodlands, and grasslands are likely to experience increases in the variability of weather, such as droughts, storms, and heat waves; and changing disturbance regimes.

lands can occur without our maintaining the health of the Nation's ecosystems. The understanding needed to attain these goals also requires integrated research on ecosystem dynamics and the basic terrestrial carbon cycle.

This document balances research across a range of management, science, and technology transfer actions. Research is aimed at developing adaptation and mitigation approaches to ensure that forests, woodlands, grasslands, and the associated aquatic systems have the capacity to maintain health, productivity, and diversity while meeting carbon sequestration goals.

The strategy closely corresponds with the research focus and goals of the U.S. Global Change Research Program (USGCRP), in particular with the needs for management and research identified in the Synthesis and Assessment Product (SAP) 2.2 "The First State of the Carbon Cycle Report: The North American Carbon Budget and Implications for the Global Carbon Cycle"; SAP 4.3 "The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States"; SAP 4.4 report "Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources"; and the unified assessment product, "Global Climate Change Impacts in the United States," all available at <http://www.globalchange.gov>.

This plan contains three integrated elements aimed at enhancing the management of forests, woodlands, and grasslands under changing climate:

1. Research To Enhance Ecosystem Sustainability (Adaptation). The first element focuses on research that will advance management options under a changing climate to enhance ecosystem health and sustainability; ensure the flow of ecosystem services, such as water, wildlife, biodiversity, recreation, forest, and grassland products; and reduce losses of ecosystem function from climate-altered disturbances, such as wildfire, insects, and invasive species.
2. Research To Increase Carbon Sequestration (Mitigation). The second element focuses on research that will assist managers in enhancing carbon sequestration via actions that could increase forest growth rates and area of forested lands, enhancing biomass extraction and utilization research and understanding long-term carbon product storage

Land management must resolve a fundamental challenge—how to remove carbon dioxide from the atmosphere while improving ecosystem adaptation.

pools. These capabilities cannot be realized without integration with adaptation research.

3. Research To Provide Decision Support. The third element integrates the first two research elements by developing decision-support tools and approaches for policymakers, planners, and land managers. Although delivery of relevant scientific findings is part of every research project, the scientific activity of direct use is focused on creating and operationalizing mathematical models that simulate present and future ecosystem structure and functioning.

Within each research element, the Research Plan reviews the most pressing *research needs* for reducing the uncertainties in scientific knowledge. Each element examines *cooperative activities* required to support research needs, including internal Forest Service procedures that can be modified to permit more efficient interstation and inter-agency cooperation that could maximize use of research funds while avoiding duplication of efforts. Each element documents the most appropriate *science delivery* approaches for transferring the available scientific information to land managers and for instituting dialog between managers and scientists. Finally, each element describes the most critical research *action items* that can be undertaken immediately, should funding become available to carry them out.

The Research Plan also describes additional activities that support these primary elements, including a review of the infrastructure investments needed to implement this plan. A companion document, the *Forest Service Global Change Research Strategy, 2009–2019* (Solomon et al. 2009) distills the strategic information in the plan for rapid examination of the Forest Service global change research approach.

2. Research To Enhance Ecosystem Sustainability¹



Adaptation research is aimed at identifying ecosystem vulnerabilities; determining the adaptive capacity of ecological, economic, and social systems; and developing management practices that will help sustain ecosystem services.

2.1. Research Needs

The capacity of forests, woodlands, grasslands, and their associated aquatic systems to maintain current health, productivity, diversity, and resistance to unnaturally severe disturbances will likely be compromised under a changing climate (IPCC 2007, USGCRP 2009). The effects of and opportunities from climate change will vary across the Nation. Understanding and identifying the vulnerabilities of, as well as opportunities in, ecosystems and the social and economic systems in which the ecosystem is found will be the basis for developing adaptation options.

Identifying the key vulnerabilities of the ecological systems and the social and economic systems will require an understanding of the magnitude and timing of the potential effects of climate change, the persistence and reversibility of those effects, the likelihood of the effects and confidence in those estimates, the potential for adaptation, the distributional aspect of effects and vulnerabilities (disadvantaged sectors or communities), and the importance of the system at risk (Schneider et al. 2007). Basic ecological research will be required if we are to understand the changing relationships between climate and ecological systems, across multiple spatial and temporal scales, including an understanding of interactions with multiple stresses and altered disturbance regimes. Understanding and predicting the adaptive capacity of the ecological systems under a changing climate will also be a new area of needed research, as

will a greater understanding of the adaptive capacity of the social and economic systems in which the forests, woodlands, and grasslands are found.

The efficacy of current management practices under a changing climate will depend upon the nature of the climatic changes (spatial, temporal), the effect of these changes on ecosystems, and the current status and degree of human alteration of the ecosystem (e.g., presence of invasive species, departure from historical fire regimes, condition of watersheds). In addition, the interactions of climate change with other major stressors (e.g., invasive species, air quality) could result in the need to revisit extant management practices (e.g., invasive plants, see Ziska 2003). Assumptions about climate that underlie past research and current management will affect the scientific basis for those management practices under a changing climate. These assumptions range from the relationships among climate and natural regeneration and tree-planting practices to the expected seasonal distributions of rainfall and stream flow and associated watershed management. Developing an adaptation strategy to maintain and enhance forest, woodland, and grassland sustainability will involve evaluating different types of uncertainty (e.g., environmental conditions, models, data, resources, planning horizons, adaptive capacity tied to place) so that multiple adaptation options can be identified for the management of forests, woodlands, grasslands, and aquatic ecosystems under a changing climate. Research is needed to test management

1. Written by David Peterson, Danny C. Lee, David Wear, Richard Haynes, Becky Kerns, Marcus Warwell, Donald Dennis, Robert Keane, and Linda Joyce.

and adaptation options on the ground to develop strategies for spreading risk and conserving/enhancing broad-sense ecosystem productivity and health.

2.1.1. Improve understanding of the potential effects of a changing climate on the physical environment and watershed dynamics

The potential effects of changes in water availability (amount, timing) on hydrologic processes and aquatic ecosystems (riparian ecosystems, streams, rivers, ponds, lakes) will affect water yields and many other ecosystem processes. Reduced snowpack, earlier snowmelt, and altered hydrology associated with warmer temperatures and altered precipitation patterns (increases and decreases) are expected to complicate water management and affect other ecosystem services from forests, woodlands, and grasslands (e.g., recreational opportunities). We will need field data across a spectrum of human and natural conditions to support refinement of models that quantify the mean and extreme hydrologic events if we are to correctly design infrastructure (e.g., roads, bridges). We will also need to refine current tools or develop new predictive tools to document the interactions among climate, species shifts and plant growth, and erosion under a variety of conditions—roads, managed forests, and forests recovering from wildfire. Interactions between changes in temperature and precipitation (e.g., changing snowpack) will alter hydrologic regimes and raise questions about the role of upland vegetation management in water yield. Additional needs such as carbon sequestration could affect water yield. We need field experimentation to establish the dynamics of riparian ecosystems and their relationship to aquatic ecosystems under a changing climate. Because hydrologic changes at the scale of a first-order stream may be undetectable at larger stream sizes, it is important to distinguish the response of these changes in hydrological processes at multiple scales. We need to integrate landscape-level effects with the effects on hydrology; (e.g., how thinning stands affect snowmelt holding capacity under a changing climate (and changing snowpack) across spatial scales).

2.1.2. Enhance understanding of the changing dynamics of plant and animal populations and communities under a changing climate

Plants and animals are adapted to local climates and to climate-mediated disturbances such as fire. As climate changes, plant and animal responses will be dynamic, influenced by climate-mediated alterations in disturbances (fire, insects) and climate-mediated surprises (invasive species, climatic extremes). These responses depend on rates of change in driving factors and on the inherent adaptive ca-

capacity of those plants and animals (e.g., physiological, genetic). Understanding the effects of climatic variability and change on plants, animals, populations, and communities is challenging, because these climate-species relationships are changing in real time. Documenting these changes requires intensive and extensive monitoring. The monitoring design needs to be integrated with field, laboratory, and modeling experiments testing hypotheses about the nature of the effects of climate change and potential management responses.

- a. **Determine prehistoric vegetation responses to climate change.** Changing climates over prehistoric timescales have repeatedly reset community structure (species diversity) and composition (relative abundances) as plants and animals have adapted to these changes in their environments. Paleoecological studies, exploring the evolutionary responses to changing climates, provide a larger temporal and spatial understanding of change, dynamism, thresholds, novelty, reversibility, individualistic responses, and extreme conditions. Building on and expanding this current knowledge of paleoecology would increase the Forest Service's understanding of what metrics to monitor under a changing climate, what might constitute restoration, and how the historic range of variability can contribute to management in the future. Such studies might also advance the agency's thinking about what species might be appropriate to assist with migration and where to plant them.
- b. **Identify and quantify the influence of the changing climate on plant and animal species adaptation.** The recent literature on novel future climates and paleoecology demonstrates that plant and animal species respond individually and uniquely in time and space, incorporating competition and ecological disturbance as well as climatic factors in their response. Identifying which terrestrial and aquatic species are most vulnerable will require basic physiological research across multiple species, including plant, pest, and wildlife, and population research exploring life history changes under extreme events and changing environmental conditions. Phenological changes give an indication of the effect of global and local changes in weather and climate. Monitoring and studying these changes may provide the first measure of biodiversity and ecosystem changes on site.

Within aquatic systems, changing temperature patterns will alter stream and lake conditions for fisher-

ies. Climate interactions with altered disturbances such as wildland fires will influence the availability and continuity of both terrestrial and aquatic habitat. An understanding of how species are adapted and attuned to specific environments/conditions will be critical as will field experiments to determine how to sustain ecosystem services under a changing climate. This information will be necessary to refine or develop new wildlife habitat models that currently do not include the influence of climatic factors on terrestrial or aquatic habitat (see sections 4.1.1 and 4.1.5). Understanding potential range and distribution shifts of individual species will inform managers of potential new threats from invasive plant and animal species. In addition, this understanding will identify novel species combinations that may require new approaches to managing for ecosystem services. The creative use of gradients, such as ozone levels, temperature, or elevation, offers opportunities to explore species' responses to changing environmental conditions.

- c. Determine linear and nonlinear threshold responses.** Managing to reduce the vulnerability of populations and ecosystems to the effects of climatic variability and change requires an understanding of thresholds of change. Thresholds may include physiological limits that affect seedling establishment

or tree growth, stream temperatures that affect fish survival, and thermal requirements for insect reproduction. Many biotic responses to exceeded thresholds are probably nonlinear, which makes quantification and prediction more challenging. New experiments, coupled with interpretation of existing data and critical new data, will be needed to assist in determining thresholds and responses to them. This field research sets the stage for decision-support research identified in sections 4.1.4 and 4.1.5.

2.1.3. Quantify the effect of climate change and elevated carbon dioxide on ecosystem productivity and water, nutrient, and energy cycling

Climate change will likely influence productivity of forests, woodlands and grasslands, through both altered climate and elevated carbon dioxide (CO₂). Currently, most information on climate change effects on productivity is quantified at small scales through experiments and intensive observations and at large spatial scales through models and remote sensing (see section 4.1.2). Information about climate change effects at coarse spatial scales is relevant for planning, while such information at fine spatial scales is relevant for operational applications or for understanding processes for parameterizing models.

Climate changes will cause productivity changes within forests, woodlands, and grasslands, which will interact with climate-mediated disturbances and other stressors such as air quality. Revisiting site classes and expectations for site productivity in management guidelines will require fieldwork to determine likely changes in productivity and species composition. Periodic inventories, such as the Forest Service Forest Inventory and Analysis (FIA), will be valuable in analyzing potential changes in productivity over time and space, particularly as FIA measurements are enhanced to meet unique requirements of global change questions. Because these productivity changes will influence ecosystem services produced in forests, woodlands, and grasslands, research on productivity changes must be coordinated with research described in section 2.1.2. The



The Free Air Carbon Dioxide Enrichment Experiment in Rhinelander, WI, has provided a wealth of new insight about how future forests will grow under higher atmospheric Carbon Dioxide and ozone. Photo by David Karnosky, Michigan Technological University.

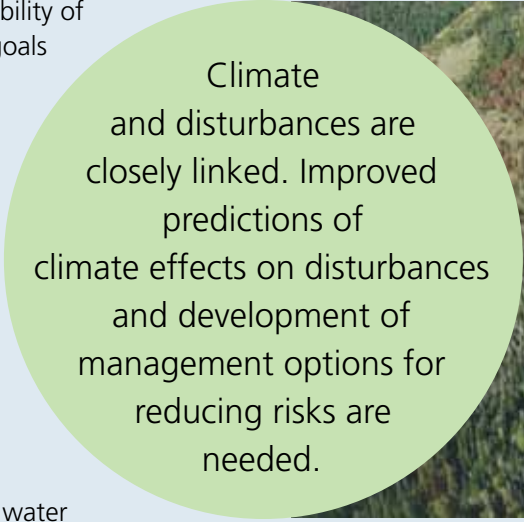
productivity shifts will influence the ability of these systems to address mitigation goals discussed in section 3. It will be important to assess potential tradeoffs between the two approaches and to seek strategies that achieve synergistic benefits. (See sections 2.1.14 and 4.)

Experimental research on the influence of elevated CO₂ on ecosystems has suggested that shifts will occur in the allocation of carbon within plants and the ecosystem, potentially affecting soil quality. Theory suggests CO₂ should increase water use efficiency and productivity, offsetting and even exceeding stresses generated by increasingly variable climates. In contrast, forest survey data detect no significant effect on growth that can be attributed to CO₂ effects even though CO₂ concentrations have increased 30 percent in the past 150 years. The effect of those changes on site productivity is not known for many ecosystems. Although large-scale experiments (e.g., Free-Air CO₂ Enrichment) exist, these experiments are limited in their representation of major ecosystems and the interacting factors that can be included in their experimental designs. Thus, consideration should be given to the future of large-scale ecosystem experiments (see section 5).

2.1.4. Enhance understanding of the changing relationships between climate and climate-mediated disturbances

Climate directly influences disturbances such as wildland fires and indirectly controls disturbances from insects and disease. Quantifying how climate change will influence these disturbance regimes (e.g., timing, intensity) and which disturbances are likely to be affected first or most would enhance the ability of management to reduce risk. Further, associating the response of species, populations, and communities to these altered disturbance regimes would inform management to minimize the loss of ecosystem services. Research will be needed to assess if and how these altered disturbance regimes can be managed to enhance ecosystem resilience under a changing climate.

Analysis of historical data and experiments to collect new data on relationships between wildfire and climate could provide needed information to address future climate change effects on wildland fire dynamics, such as estimating the likelihood of more severe fire weather, lengthened wildfire seasons, and larger sized fires under a changing



Climate and disturbances are closely linked. Improved predictions of climate effects on disturbances and development of management options for reducing risks are needed.

climate. These data also would be useful in projecting likely future climate change and variability, which could be incorporated into long-range wildland fire management plans and strategies (see section 4.1.1). Land managers will need the results of research designed to understand how to manage fire in fire-dependent ecosystems, particularly as the landscape dynamics and land use change.

Insects and disease are likely to respond quickly to changes in climate. These changes may redefine what endemic and epidemic levels are, as well as where insects and diseases are found. Understanding the role of climate (temperature, precipitation, extreme events) in insect life cycles is critical to building models that project the effects of future climate change on potential outbreaks. Asynchrony of temperature thresholds and insect life cycles at individual sites may result in surprise effects. The timing of bird migrations may be altered so as not to coincide with insect population dynamics, resulting in potentially greater impacts to trees that depend upon avian predation on insect pests and on birds for transport of seeds. Similar symbiotic relationships between insects and fungi may be altered by climate change and result in unexpected changes in the dynamics of insects, fungi, and trees. Areas of potential research include the role of drought and major disturbances (e.g., hurricanes and ice storms) in exacerbating insect stress and the uncertainty of the water use efficiency effect of elevated CO₂.

2.1.5. Enhance understanding of landscape dynamics under a changing climate

In addition to climate change, land use and land cover changes alter the dynamics of landscapes. The loss of open space (subdivision of ranches or large timber holdings), the conversion of wildlands to urban and built-up uses in the wildland-urban interface (WUI), and habitat fragmenta-

tion (related to increases in road densities and impervious surfaces) influence the habitat available for wildlife and affect planning for fuels management. In addition, urbanization and fragmentation of habitat facilitate the spread of invasive species. Fragmentation may result in the loss of larger management units, broad habitat corridors, and habitat continuity that many important wildlife species require. Climate change will provide additional stressors, possibly enhancing invasive species advantages, and altering habitat quality and productivity. Research will enhance our understanding of how fragmentation and patterns of public and private landownership are likely to alter animal migration patterns or provide opportunities for adaptation for wildlife. Research on landscape dynamics will be critical in formulating methods to design adaptive and resilient landscapes under a changing climate.

The complex interactions between factors such as species and process-level responses to weather, climate, and disturbances on landscapes are minimally captured in current landscape models. Most modeling efforts lack the understanding and content concerned with simulating the complex interrelationships between climate and the many important ecosystem elements explicitly represented in current models. Many feedback loops and integrating factors are missing from ecosystem simulations. Their inclusion would allow more robust representations of climate interactions. These relationships must be used to answer the most basic management questions, such as “What tree species can I plant here?” to the most complex, such as “What happens to water yield if I plant the wrong species?” Of utmost importance is the relationship of the variability of weather in a climate system and its effect on vegetation, disturbance, fauna, and hydrology.

Mechanistic modeling approaches can provide important insights under changing climates and land use and, therefore, research in basic ecophysiology at the plant species, population, and ecosystem scales must increase significantly in the future. Fundamental ecophysiological properties of plant and animal species are especially needed to construct physical models of species migration to account for species reproduction, regeneration, growth, and mortality. Stand- and landscape-level gas exchange and productivity relationships are critical for developing, parameterizing, and validating complex ecosystem models.

Model developers can take advantage of empirical data, which may be used to constrain system responses to observable ranges. Such approaches are most useful in a predictive context when the future conditions are somehow represented in the available observations. Nonetheless, a great deal of insight into future distributions of ecosystems

and plant communities has been produced using these methods, and more profitable work remains to be done.

Linking empirical models with mechanistic models has long held the promise of providing the best possible information and understanding. In fact, every useful mechanistic model contains a large amount of empirically based information. Much knowledge can be gained by using the two approaches together. Empiricists can improve model formulations by including clear understanding of underlying mechanisms, and mechanist modelers can improve their models by ensuring they can represent relevant observations.

2.1.6. Understand multiple stresses and their interactions

The greatest and most immediate effects of climatic variability and change on ecosystems will likely occur indirectly through their effects on other stressors or in concert with other stressors. Increased temperature will be coupled with various interacting stresses, including multiyear droughts, insect attacks modulated by climate change, and wildfire, also enhanced by warming. Ozone and other industrial pollutants in combination with climate stress are likely to decrease tree growth and increase the magnitude and extent of forest diebacks. For example, although moderate increases in temperature and nitrogen deposition may temporarily enhance growth, in many cases these and other stresses will predispose organisms and systems to increased sensitivity to additional and perhaps more damaging stresses. Field experiments needed here coincide with the goals of quantifying the effect of climate change and elevated CO₂ (see section 2.1.3).

The dynamic interactions among multiple disturbance processes, climate, and vegetation are not yet captured in ecosystem or landscape models. For example, the simulation of mountain pine beetle epidemics is rarely implemented at a resolution that would match subtle changes in simulated tree stress, climate change, and emergent fire regimes. Future models must contain the capacity to explore these interactions and their causal factors, whether they are emergent properties of the models or explicitly coded within the program as inputs or constants. This capacity would require a model that can simulate causal interactions between ecological processes and include an explicit representation of the mechanistic properties that control disturbance dynamics. This capacity also includes but is not limited to the important and profound effects and interactions of humans on landscapes in activities such as fuel treatments, fire exclusion, and grazing. The effects of multiple stressors and their interactions are important if we are to identify nonlinear behaviors and “tipping points”

in ecosystem response. An example would be the effect of blister rust on mountain pine beetle infestation. Rust-infected trees facilitate pine beetle occupancy (Tomback et al. 2000, Waring and Six 2005), and rust infection rates can be altered with changing climates.

2.1.7. Identify species and seed sources to plant through enhanced genetics research

Most projected climate change rates are approximately an order of magnitude more rapid than measured past rates of migration by tree species. Therefore, natural revegetation by local populations that also include climatically appropriate individuals will become very uncertain within a few decades. In addition, if projected rates of accelerated climate change are realized, land and resource managers engaged in reforestation, afforestation, and/or gene conservation will no longer have reliable guidelines for identifying the seed sources to plant and where to plant them. This specific threat exists because present guidelines for predicting adaptation to climate in forest tree species are based on geographic variables that act as surrogates for climate. Consequently, the geographic range of application of these models is limited and will not be reliable under projected climate change. The development of seed transfer guidelines based directly on climate variables is required. The technology, fundamental methodology, and data required to update existing seed transfer guidelines such as seed zones and related expert systems are presently available within the Forest Service (see Rehfeldt 2004). After the data are updated, they can be coupled with downscaled climate output from the most relevant available General Circulation Models of the global climate, with land cover scenarios and with output from ecophysiological models to provide managers with an overlay of predicted climatically suitable seed zones across both space and time.

Most vegetation models and decision tools do not account for change in species adaptation (see, e.g., Crookston et al. 2007). Projected climate change may jeopardize the validity of these models, which depend on constant relationships between species and their limiting climate variables. Yet, if, for example, water use efficiency increases with higher atmospheric CO₂ concentrations, a species could be capable of growing with soil moisture wilting points that are currently lethal. The continued accuracy of plant-environment relationships will require remeasurements of those parameters that currently assume no variation in plant genetic-climate and physiologic-climate responses. Although some new plant genetic-climate knowledge is attainable from reanalysis of existing data sets and provenance studies, these gains will be limited to those species that have been the subject of historical study, primarily oriented to improv-

ing timber production. Present requirements for genetic information will require the establishment of many new short- and long-term studies that use a quantitative genetic, common garden-style approach targeted to a much wider diversity of tree functions.

Ecological consequences of predicted climate change include changes in the phenology (such as timing of bud set) and the distribution of the flora and fauna (Parmesan and Yohe 2003). The timing of phenological events, such as flowering and fruiting, can adversely affect dependent species, such as migrating birds adapted to encountering those food supplies. Mitigating the effects of climate change will require attention to understanding responses by plant phenology. The timing of many phenological events is genetically determined, although that timing varies across species distributions. Hence, the adaptive genetic structure of individual species must be considered in predicting phenology so that available populations are best suited to support productive ecosystems.

2.1.8. Determine traits and life stages critical for adaptation, and document the role and use of genetic plasticity

Climate change may alter the fundamental nature of some contemporary species. Projected rates of climate change will likely subject ecosystems to large-scale evolutionary changes. Although few new plant species have been definitively identified as arising during the past 2 million years of glacial-interglacial climate oscillations, future climate changes occurring at much faster rates could have important genetic effects in eliminating cold-tolerant populations (Solomon and Tharp 1985). Little is known about the evolutionary response of individual species or how they may respond interactively (Davis and Shaw 2001, Rice and Emery 2003). Results from among the few studies conducted indicate that projected climate change trends will likely disrupt the genetic structure of plant species resulting in complex, rangewide responses (Etterson and Shaw 2001, Rehfeldt et al. 1999, Rehfeldt 2004). Accurate prediction of potential evolutionary effects will require, in part, an understanding of species-specific phenotypic plasticity and genetic plasticity (see, e.g., Wang et al. 2006). In both types of studies, significant traits such as fitness and resistance to drought, pests, or diseases will likely be species specific and will need to be determined.

2.1.9. Reduce uncertainties in climate predictions and vegetation and system responses

Uncertainty is a major challenge in designing and implementing strategies to effectively enhance sustainability in the face of climate change. Uncertainty is also a chal-

lenge in estimates of change in ecosystem carbon stocks and wood productions (section 3.1.9). Scientists readily acknowledge that future climate predictions are inherently uncertain, especially long-term predictions at the relatively small geographical scales that are relevant to both ecological and social processes. Considerable research is currently underway within the larger scientific community to improve climatic predictions in terms of overall accuracy and spatial precision. Equally important are research efforts to improve understanding of the effect of climatic changes on (1) influential or otherwise important species; (2) ecosystem processes such as cycling of water, nutrients, carbon, and energy; and (3) socioeconomic interactions among climate, forests, woodlands, grasslands, lakes and streams, and human communities. Such research needs to be coordinated with research outlined in section 3.1.9.

Investments to improve understanding or gather additional information can reduce uncertainty only so far. The combination of complex systems and stochastic events ensures that much uncertainty is inherently irreducible (Levin 2002). The corollary of irreducible uncertainty is the certainty of ecological surprises (Gunderson and Holling 2002). The recognition of such principles should generate research directed at understanding how ecosystems can be made more adaptable and resilient to unforeseen or unanticipated change. Such research is not directed at understanding how a specific system would respond to directional change



such as increased dryness, wetness, or more extreme temperatures, but rather at the general properties of integrated ecological and social systems sustaining ecological function in the face of highly variable climatic conditions and the cascading disturbances that accompany them.

2.1.10. Develop and test risk-spreading strategies to provide flexible management systems

Managing forests, woodlands, and grasslands in the face of uncertainty to continue delivering goods, services, values, and experiences, is not a task unique to climate change response. Many, if not all, important issues facing land managers come with major uncertainties. Wildfire, species invasions, population growth, loss of open space—these are just a few of the many issues that carry inherent and often inestimable risks. What is unique about changing climate and atmospheric chemistry is the scale and severity of the possible impact and the potential for current understanding of ecological and social systems to be fundamentally invalidated.

Risk, risk assessment, and risk management are common and pervasive themes in business and government for dealing with uncertain outcomes or futures. The universal nature of risk and uncertainty essentially has driven the field of decision science, which provides a rich knowledge base from which to draw general principles. Despite having the necessary knowledge and tools available, land managers have not been able to optimally apply formal risk-assessment and risk-management methods to their decision processes (Borchers 2005, Maguire and Albright 2005). The impending threat of climate change, and its associated uncertainties, demands decision processes that explicitly and rigorously address the risks posed by this uncertainty.

The goal of embracing uncertainty in the management decision process is to develop explicit risk-management strategies. In an uncertain future, all options carry risk. The choice available to society may be less about how much risk is involved than about who will bear these risks. Again, decision science offers practical guidance to deal with these difficult questions (e.g., see Borchers 2005, Culp 2004), but the specific application of a risk-management strategy must be tailored to a given social and ecological landscape.


Managing forests, woodlands, and grasslands in the face of uncertainty to continue delivering goods, services, values, and experiences is not a task unique to climate change response.

2.1.11. Develop and test strategies and systems for conserving and enhancing resource productivity and health (e.g., soil, water, habitat, biodiversity, vegetation)

Climate change is already affecting land managers' ability to conserve, sustain, and enhance ecosystem productivity and health. Critical stressors that have been amplified or are projected to be amplified through climate change include wildfire, invasive species, extreme weather events, and air pollution (Dale et al. 2001, Hicke et al. 2006, Westerling et al. 2006). Spatial and temporal changes in hydrologic cycles (e.g., earlier snowmelt, reduced snowpack) associated with warmer temperatures and altered precipitation patterns will complicate water management, particularly in the West. Although the Forest Service, State agencies, and private landowners have strategies and systems in place that are designed to manage current stressors, these programs are only beginning to consider recent and future stressors such as climate change.

Existing management strategies and systems will need to be reevaluated, redefined, or replaced, so that ecosystem productivity and health can continue to be conserved or enhanced. Even the very nature of how ecosystem health is defined may need to be reconsidered under a changing climate. For example, natural resource management, planning, conservation, restoration, and policy are deeply founded on strategies based on the ecological concept of historic range of variability (Landres et al. 1999). Use of such strategies, however, will become increasingly problematic as the potential for conditions beyond historic ranges and "no analog" futures are realized (Millar et al. 2007, Williams et al. 2007). Given the certainty of uncertain changes in conditions, land managers and others will need to rely more on current and future conditions and processes and less on using the past as a benchmark.

Only limited research studies, data, and conceptual models, however, are available to use for new or redefined management strategies and systems for conserving and enhancing ecosystem productivity under a changing climate. Relevant data and models that do exist may need to be incorporated into tools, strategies, and decision-support systems that are relevant, practical, and useful for managers. Development and testing of a suite of practices, systems, tools, or conceptual models that address specific management goals, including the evaluation of various types of uncertainties, are



Climate change is likely to induce shifts in populations, species, and community abundances, structures, and ranges, including potential species extirpation and extinction.

needed. Creation of partnerships between scientists and managers and/or other stakeholders is strongly encouraged for development of practical management tools and for the research proposals needed to generate these tools.

2.1.12. Develop prioritization methods to examine tradeoffs in resource management under a changing climate

Climate change is likely to induce shifts in populations, species, and community abundances, structures, and ranges, including potential species extirpation and extinction. In an environment of limited resources, staffing, and time, we may need to evaluate tradeoffs between the management of different ecosystem resources. Evaluation of these tradeoffs may require additional data and understanding about species, communities, ecosystems, landscapes, and disturbances. For example, analysis of the tradeoffs in air quality between the use of prescribed fire and uncontrolled wildland fire are limited by information on emissions data and predicted fire severity. Similarly, decisions about whether to manage for species whose habitat is disappearing (e.g., alpine species) and species whose habitat is diminishing but manageable will most likely be limited by available information and understanding. A careful examination of current prioritization methods would begin to identify opportunities and barriers to the analysis of tradeoffs and development of priorities under a changing climate.

Developing an adaptation strategy will involve planning for and developing a suite of management practices to achieve multiple goals, along with evaluating different types of uncertainty (e.g., environmental conditions, models, data, resources, planning horizons, and public support), to support decisions about the most suitable adaptations to implement. Another related goal likely to be important to

natural resource managers is mitigation (carbon sequestration, see section 3). Adaptation strategies when developed alone can result in suboptimal carbon sequestration objectives, and, conversely, mitigation strategies must take into consideration future needs for adaptation. Both goals must be integrated to minimize potential negative effects and to take advantage of possible positive effects from climate change. Field experiments quantifying the opportunities and effects of mitigation and adaptation management will be necessary to support decision-support models exploring the appropriate management to meet both goals of adaptation and mitigation.

Exploration of tradeoffs will vary by spatial scale. At the national level, a need exists to provide integrated strategic evaluation of national policies and management actions (environmental/economic) (see section 3.1.8). Adaptation strategies tend to focus on local levels whereas mitigation strategies tend to have a broader geographic focus. Integrated assessments, such as the Resources Planning Act (RPA) assessment, can be used to evaluate strategic options for achieving a suite of national goals (adaptation, mitigation), as well as to provide long-range projections of resource conditions for planning and management.

2.1.13. Understanding adaptation in social and economic systems

New research results will be important if we are to understand the means by which people adapt to change; the resilience of rural communities; changing lifestyles and demand for amenities; and changing expectations, values, experiences, and transitional strategies. Changes in hu-

man population and settlement patterns can have enormous influences on how the Forest Service land base is managed and how the adaptive capacity of the land base may change. The public perception of risk, with respect to wildfire, air quality effects of prescribed fire, or insects and disease, can and does influence the management practices implemented on national forests and rangelands. How people and communities relate to wilderness areas or to recreation on national forests may also be influenced by climate change.

Governmental organization also influences the adaptive capacity of Forest Service lands. Other agencies, such as the U.S. Fish and Wildlife Service, the National Marine Fisheries Service, and the U.S. Environmental Protection Agency (EPA), have certain oversight responsibilities on how the Forest Service manages land. Therefore, they will influence how the Forest Service can adapt its management practices to changing climate.

2.2. Cooperative Activities

2.2.1. Capitalize on current strengths

- a. **Expand expertise and operations within and across disciplines.** The Forest Service has research expertise within and across disciplines, including but not limited to ecological, biophysical, modeling, social, and economic components. Many research work units and programs are interdisciplinary in structure. Enhancing cross-station activity brings additional expertise and experiments in diverse ecosystems to our scientific efforts. Existing cooperative studies with NFS personnel also combines skills and expertise that facilitate the transfer of findings to on-the-ground actions.

We can use the Forest Service's long-term geographically diverse soil productivity and operational scale silvicultural and genetic studies already in place to broaden our understanding of the effects of climate change on ecosystems from multiple vantage points. Forest Service researchers have a long history of

Adaptation to climate change: Pre- and post-thinning of the eastside ponderosa pine forest on the Lassen National Forest. Before thinning, the forest had about 300 trees per acre. To relieve stress on individual trees from warmth and drought, the forest thinned the stand while maintaining the age and size structure of the trees. Thinning to approximately 90 to 110 trees per acre removed 28.5 green tons per acre (40-percent saw-logs and 60-percent chips and biomass), generated \$124 per acre, and increased the amount of water and nutrients available to each remaining tree.




maintaining existing common garden studies in Experimental Forests and Ranges (EFRs) and of continuing to populate databases of ecological genetics on forest species. These current capabilities enhance Forest Service research capacity to address how species will respond to climate change from a genetic standpoint.

The development of strategic plans and evidentiary material for the Strategic Program Areas (SPAs) has increased interest in cross-station activities. This interest could potentially expand the application of results that might otherwise have limited geographic implementation. For example, the development of strategic plans for the SPAs, such as the fire plan strategy, is emphasizing cross-station opportunities. Geographic similarities, a large NFS land base, and common management issues have resulted in scientists in the western stations working more collaboratively across their region, and new impetus exists for the eastern stations to increase collaboration.

- b. Intensify connections to a diverse array of stakeholders.** Forest Service R&D, State and Private Forestry (S&PF), and the NFS together provide an extensive network that is unequalled in its ability to reach a broad array of stakeholders. Forest Service R&D labs are geographically distributed and have working relationships with universities and other research organizations throughout the world. They also provide direct assistance to stakeholders. S&PF has a successful history of assisting public and private forest landowners to address forestry concerns. NFS managers and planners maintain an intimate relationship with local constituents regarding almost all aspects of natural resource management.

The Forest Service has an ongoing, extensive involvement with the public and a strong connection to local communities concerning management of all national forests. The network and process, which are in place and operational, offer unparalleled opportunities to engage in a dialog about all aspects of adaptation to climate change. These aspects include but are not limited to harvesting, thinning, species migration, species change, insects, disease, fire, genetic diversity, and changes in the way people use



Experimental Forests and Ranges and Research Natural Areas offer sites to conduct field experiments testing hypotheses about natural adaptation and the efficacy of management.

forests, woodlands, and grasslands and view natural resource management.

- c. Increase support for innovative technology.** Forest Service researchers and managers have developed or have a clear understanding of numerous technological advances in remote sensing and links to ground inventory, ecosystem monitoring, modeling, and biofuel conversion, among others. These innovations, coupled with the extensive connections to stakeholders previously described, provide substantial opportunities to put in place technological advances to improve our ability to manage for and adapt to climate change.

2.2.2. Coordinate monitoring systems and large-scale experimentation for adaptation to climate change on national forests and grasslands

The Forest Service has managed a very large and varied land base for more than 100 years. The land base includes an array of ecosystem types and species that extend through tropical, temperate, and boreal zones. Because the Forest Service has a mandate to actively manage for multiple resources, the agency administers a wide array of lands for different objectives (e.g., recreation areas, wild and scenic rivers, scenic areas, wildlife preserves, cultural and historic areas, roadless areas, and wilderness). The land base also includes lands designated for research: EFRs and Research Natural Areas. The Forest Service is also integrally involved in the Long Term Ecological Research Network (LTER), the National Ecological Observatory Network (NEON), and the AmeriFlux network of intensive observation sites. These diversely managed lands provide an unequalled opportunity to monitor and track ecosystem

health under virtually all conditions (intensive use to wilderness, tropical to boreal, urban to rural). Extensive historical data are currently available for many areas. This connection with the land offers the ability to monitor and study changes over the long term.

Forest Service lands that have a protected area status (e.g., wilderness and roadless areas) offer a baseline for developing scientific information about the response of ecosystems to climate change where past intensive land management has not occurred. In addition, protected areas offer both opportunities and barriers to climate change adaptation strategies. For example, wilderness designation restricts the use of various management strategies such as mechanical harvest but allows management strategies such as natural fire. These opportunities and barriers could be helpful in developing a better understanding of how the distribution of lands, varying in level of protection, might be optimized to respond to climate change and/or how climate change adaptation strategies should differ with the distribution of lands that vary in level of protection. Understanding the restrictions of adaptation strategies across the boundaries between protected lands (wilderness, roadless areas) and lands managed intensively may be important in implementing landscape adaptation strategies.

EFRs and Research Natural Areas offer sites in which to conduct field experiments testing hypotheses about natural adaptation and the efficacy of management. Land representing a diversity of conditions could be set aside after disturbance events to allow natural regeneration and successional processes to identify the most resistant species and populations. Manipulated landscapes across the EFR network, and possibly other areas within national forests, could be coordinated to evaluate and improve similar management practices

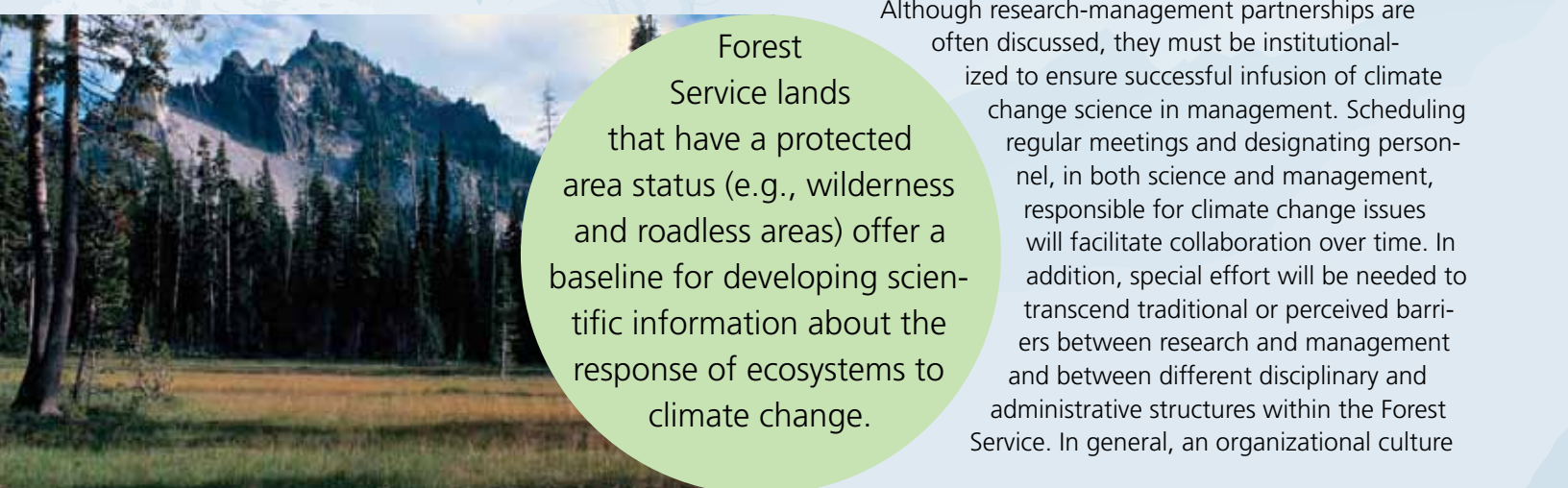
to adapt ecosystems to a changing climate. A gradient from the WUI to unpopulated wilderness, including protected status lands, might be used to explore the efficiency of certain adaptation approaches, such as wildland fire or the location of places appropriate for thinning to reduce fire, drought, or insect risk. Expanding the genetic guidelines for reforestation is experimental by design, thus, using the network of experimental forests and appropriate methods to document the experiment with genetic variations could define successes and failures of such expansion. This use of the experimental forests, however, cannot replace research focused on quantifying genetic variation in response to different environmental stressors (Rehfeldt et al. 1999) or to climate system impacts. It also cannot replace the research to understand tree genomes (Nelson and Johnsen 2008), which should continue so that appropriate genotypes can be selected rapidly with reasonable confidence when needed.

2.3. Science Delivery

2.3.1. Increase research management collaboration

Because climate change science is inherently complex and interdisciplinary, scientists need an exceptional amount of interaction with resource managers to ensure that research products are relevant to various management applications and are applied in an appropriate manner. This necessity implies early and frequent communication with managers to ensure that scientists understand what information is needed for planning and operations at different spatial scales and that managers understand what products are and are not possible. Collaboration is critical for implementing mitigation activities, which include the stream of activities related to carbon accounting and use of biomass. Collaboration is also critical for implementing adaptation strategies from the planning stage to operational actions, including the monitoring that informs the adaptation process.

Although research-management partnerships are often discussed, they must be institutionalized to ensure successful infusion of climate change science in management. Scheduling regular meetings and designating personnel, in both science and management, responsible for climate change issues will facilitate collaboration over time. In addition, special effort will be needed to transcend traditional or perceived barriers between research and management and between different disciplinary and administrative structures within the Forest Service. In general, an organizational culture



Forest Service lands that have a protected area status (e.g., wilderness and roadless areas) offer a baseline for developing scientific information about the response of ecosystems to climate change.

Building the capability of technology transfer and information sharing into the national strategy for climate change will improve the effectiveness and timeliness of incorporating scientific information into management and policy.

of integrated, interdisciplinary science and management will facilitate successful strategies for addressing climate change issues.

2.3.2. Focus on communication and outreach

Clear and consistent use of concepts and terminology is critical for a common understanding of climate change science. For example, because terms such as mitigation, adaptation, landscape, and sustainability mean different things to different people, use of common definitions will facilitate communication. These common definitions will be increasingly important as different scientific and management disciplines become engaged in climate change issues. In addition, outreach efforts and publications will need to be customized for communication with various users; the approach used for public land managers will be quite different than for the general public. It will be especially important to clearly communicate with policymakers who need information relevant to legislation, regulations, and public issues. Although a common lexicon may be desirable, as in other areas of science, definitions may change over time as disciplines evolve.

2.3.3. Intensify technology transfer

Building the capability of technology transfer and information sharing into the national strategy for climate change will improve the effectiveness and timeliness of incorporating scientific information into management and policy. Technology transfer is a challenging interface issue in the Forest Service, even in areas in which technology transfer has a long tradition of occurring with some success, such as in fire science/management. Most of the responsibility has fallen to researchers through individual contacts and training courses, although they are increasingly using Web sites to communicate information with highly varied effectiveness. It may be possible to develop a cadre of technology transfer specialists who could deliver new information and tools, but the Forest Service would need to make a conscious decision about developing this staff and commit to it. Whatever the personnel mechanism may be, it will be useful to have a consistent and well-known approach, including but not limited to a Web-based portal, readily accessible to resource managers.



2.3.4. Enhance integration and synthesis of scientific knowledge

Considerable future improvements can be expected in precision and accuracy of climate predictions and in understanding of complex responses by vegetation and wildlife. Sufficient information on the effects of climatic variability and change on many natural resources, however, is available now for developing inferences about the future effects of climate change (CCSP, 2007, 2008a, 2008b; USGCRP 2009; Joyce et al. 2008). Integration and synthesis of available information has been conducted to some extent in association with national assessments of climate change (e.g., regional assessments, see Joyce et al. 2000) by cooperative efforts between NGOs and scientific experts (Northeastern United States, Frumhoff et al. 2007) and by the Regional Integrated Sciences and Assessments (RISA) teams of the National Oceanic and Atmospheric Administration (NOAA) (e.g., Joint Institute for the Study of the Atmosphere and Ocean/School of Marine Affairs Climate Impacts Group, University of Washington, with respect to climate and hydrology). More specific inferences are needed about effects on vegetation, wildlife, social values, and economics as they relate to natural resources on public lands. Therefore, regular regional assessments of the effects of climate change through integration and synthesis of existing data are a logical first step for any particular management unit wanting to predict how resources may respond. Such assessments may require heroic assumptions about how climate effects data can be scaled, as well as careful consideration of uncertainty, but they represent a low-cost approach that can be implemented quickly and communicated clearly to users.

2.4. Action Items

2.4.1. Develop regional syntheses, integrated assessments, and relevant tools to support decisionmaking

Coordinated syntheses of information on climate and climate change effects will be particularly useful for a common understanding of climate change among Forest Service managers and as a context for broad-scale planning. Integrated assessments are available for most of the United States (e.g., USGCRP 2009), and that information needs to be interpreted and provided to managers in a format that will be useful for application on national forests. It would be highly desirable to produce individual assessments for each national forest or at least for clusters of adjacent national forests with similar resources. These assessments should include narratives describing future regional climate, based on down-scaled climate model simulations, and should project future vegetation responses, based on forest ecosystem models constrained with future climate simulations.

Relevant data sets, models, and decision-support tools are needed to provide a scientifically credible toolkit that can be used to predict climate change effects and potential management responses to those effects. The composition of the toolkit may vary somewhat, depending on regional preferences and desired spatial scales. Current planning and project analysis tools institutionalized in the Forest Service are not “climate smart” and may need to be revised or connected with climate-smart modules to improve their performance. An initial screening of existing analysis models and methods could reveal the best available tools. In addition, the screening could provide information useful for defining a strategy for future development of a robust toolkit with validated climate-smart tools that are considered accurate and reliable in integrating climate change into land planning.

2.4.2. Implement collaborative research on field and laboratory experiments with development or improvement of manager-friendly models at various scales

The current toolbox of quantitative models for natural resources decisionmaking ranges from ecological and economic models used in national/regional assessments to models focusing on processes, such as erosion on roads, or on predicting wildlife habitat at finer spatial scales (see section 4). The novel conditions expected under a changing climate highlight a need to address the role of climate in the underlying assumptions for the entire suite of these models. Further, under a changing climate, the need will arise for

quantitative tools to address complex issues facing resource managers. These issues include, among others, the linkages between ecosystem productivity and water resources; disturbances including drought, fire, insect infestation and disease; regional migration patterns including invasions of both native and exotic species; and local to regional carbon storage and carbon management. Information or data to refine these models may not be available.

Ecological research will be needed to support the refinement or development of these quantitative models and methods—research that is focused on establishing the underlying understanding of how these processes work in ecosystems and are affected by climate change. This research will be most fruitful if done cooperatively among field researchers, modelers, and natural resource managers. In such a cooperative setting, the design of field experiments can aim at testing ecological hypotheses, as well as assumptions within the models, and can ensure that particular model parameters information needs are met.

2.4.3. Design large-scale research for national-scale assessment of climate change effects

Periodic assessment of the effects of climate change at the national scale, perhaps beginning with the RPA climate change assessments, may be useful as a complement to assessments that the Forest Service conducts for other resources such as timber production and forest health. Such assessments would also help the agency track progress toward meeting objectives for adaptation and for carbon sequestration. A research structure that facilitates data collection and data sharing at the national scale will be necessary to accomplish this tracking goal and will provide better information than simply “adding” the individual data components. For example, it may be critical to collect certain types of satellite imagery over time to document trends in specific locations or kinds of ecosystems. Knowing the spatial variability in the trends could affect management and policy responses, as well as resource allocation to specific issues. National-scale research objectives will be more achievable if a small cadre of Forest Service scientists is committed to cooperation and support of this effort at this scale. In addition, it will be critical to collaborate with USDA Agricultural Research Service for its SnowTel network, the U.S. Geological Survey (USGS) for its stream-gauging data, EPA for its Ecological Mapping and Assessment Program watershed classification, NOAA’s RISA program, and with other agencies and universities willing to share data and expertise needed for large-scale assessments.

3. Research To Increase Carbon Sequestration, Biofuels, and Wood Products²

Mitigation research is aimed at increasing the amount of Carbon Dioxide stored for the long term by forest and grassland ecosystems and wood products.



Mitigation research is aimed at reducing greenhouse gas concentration by increasing the amount of CO₂ removed from the atmosphere and stored for the long term by U.S. forest and grassland ecosystems (including agroforested and urban forest ecosystems) and wood products. It is critical to include accounting for carbon losses during removal and processing of biomass for wood products, removed carbon that is sequestered in the products, the effects on fossil fuel use of substituting wood for other material, and the accumulation of carbon on regenerating forest land. Relative to most other construction materials, wood requires less fossil fuel in harvest and production processes. Sustainably managed forest and range resources can replace fossil fuels with fuels derived from biomass, which use carbon already present in the global carbon cycle, rather than obtain new carbon from fossil fuels. Silviculture and genetics research help to increase growth and enhance sustainability. Afforestation and avoiding deforestation and preserving forests also have strategic roles.

3.1. Research Needs

3.1.1. Synthesis and analysis of what we know and don't know with respect to net carbon sequestration in forests and wood products

That increased carbon storage ("sequestration") in ecosystems could play an important role in reducing the rate of atmospheric CO₂ increase has long been suggested (e.g., Cooper 1983, Dyson 1977, Sedjo and Solomon 1989).

Increasing carbon sequestration is a Forest Service goal, but this is a new area for many decisionmakers who lack the knowledge necessary to put this policy into effect. A concise, approachable, and authoritative synthesis of the literature of carbon sequestration and management is urgently needed to inform policymakers, land managers, and citizens on the many issues involved in this strategy. Carbon may be stored in new areas through afforestation, reforestation, and restoration, by increasing carbon storage on presently forested lands and by increases in long-lived wood products. Issues to be addressed include economics of sequestration (e.g., Richards and Stokes 2004); how much carbon can be stored and where; methods for increasing carbon sequestration; validating carbon storage; vulnerability of sequestered carbon to fire, windthrow, insects, or other disturbance; "leakage" (Murray et al. 2004); and other impacts of carbon sequestration on the health of forest ecosystems and the climate system itself. The effect a changing climate would have on the processes of sequestration also would be addressed.

3.1.2. Investigate impact of land management activities (e.g., restoration, silviculture) and climate change on global warming potential, which includes carbon, other trace greenhouse gases, albedo, and evapotranspiration

Land management activities can impact the climate system in many ways. If the Forest Service goal of increasing carbon sequestration is realized, for example, the rate of increase of atmospheric CO₂ will be slowed. Changes in

2. Written by David Hollinger, Kenneth Skog, David Atkins, Richard Birdsey, Warren Cohen, Deborah Dietzman, Richard Haynes, Peter Ince, Kurt Johnsen, Gregory Jones, Richard Pouyat, Alan Rudie, Robert Rummer, Michael Ryan, and Bryce Stokes

land use that affect the amount and activity of vegetation also affect the climate system by altering the production or consumption of other GHGs, the amount of solar radiation absorbed or reflected by the surface (albedo), and the use of this absorbed energy to warm the air or evaporate water. Because of the many and interacting effects of these processes, sophisticated models are needed to determine the overall effect of land management on the climate system. Some studies (Betts 2000, Gibbard et al. 2005) have suggested that at high latitudes the climatic effect of a change in albedo is greater than that of CO₂ removal and have questioned the wisdom of afforestation (Bala et al. 2007). In essence, these studies propose that the warming effect of converting snow-covered fields to dark forests overwhelmed other climate effects. These climate models are complex and require land surface data that are sometimes not available. The absence of land surface data requires us to make many simplifying assumptions. A high priority is to acquire additional data (including trace gas fluxes, albedo, and energy partitioning changes) about the effects of forest management on forest characteristics that affect the climate system. The data are needed to improve the models and to develop the modeling capability to integrate the impact of all of these land surface changes on the climate system. The modeling capability is required for the Forest Service to speak authoritatively about the overall climatic effect of proposed carbon sequestration schemes.



3.1.3. Quantify and model spatial distribution of the forms of carbon in soil and the effects of management, climate, and land use change on the longevity of those forms.

Forests are estimated to contain as much as 75 percent of all carbon in living terrestrial vegetation, with as much as 50 percent of that carbon being stored in soils (Perry 1994). Much of the forest land (and grassland) on Earth is being converted to other uses such as agriculture or urban development, which is responsible for mobilizing and emitting much of the carbon stored in soils (Dawson and Smith 2007). Because carbon is sequestered in soils organically from vegetation decomposition (Chadwick et al. 1994), land use choices that affect vegetation type directly influence whether soils locally are a source or a sink of carbon. Significant additional capacity exists to store carbon in soils by making wise land use decisions. A host of basic unknowns about soil carbon, however, limits our ability to effectively quantify and manage soil carbon. We need information about the spatial distribution of carbon in soils and its forms and longevity, and we need a greater understanding of how management and climate affect the flow of carbon through soils. Additional knowledge can be gained by combining existing data sets, such as those in Carbon Dioxide Information Analysis Center at the Oak Ridge National Laboratory, the USGS, and LTER sites, and integrating results from various soil carbon models. (Examples of these data sets and models appear on the following Web sites:

<http://cdiac.ornl.gov/programs/CSEQ/cseqprojectdata.html>,
http://edcintl.cr.usgs.gov/carbon_cycle/carbonstocks.html,
<http://luq.lternet.edu/data/lterdb110/metadata/lterdb110.htm>,
<http://ctcd.group.shef.ac.uk/science/soil/soil.html>, and
<http://www.greenhouse.gov.au/ncas/reports/tr30final.html>.)

3.1.4. Provide estimates of local woody biomass supply for biofuels and bioenergy

A reliable, sustainable supply of woody biomass is fundamental to developing opportunities for increased use of biofuels, bioenergy, and bioproducts. We must be able to assess inventories and available volumes, given economic and other constraints and opportunities, and to generate

To understand impacts of management on carbon stocks, information is needed about all of the affected carbon pools: live biomass, dead wood, forest floor, soils, and wood products.

long-term estimates based on changes in policy, technology, or climate. We will need tools to inventory, estimate, and project local supplies for consideration of facility location and feedstock development investments. Output must possess the capability for integration with other nonwoody feedstocks over various spatial and temporal scales. Land managers need local projections, but within the context of larger, more regional assessments.

Industrial forest operations have long-lasting effects on carbon sequestration in ecosystems and wood products.

Currently, some woody biomass assessment tools are available that are linked to the FIA database. These tools provide some strategic assessments, but are not sufficient for mill siting or financial decisions. More explicit models are needed that are easy to use and less dependent on large quantities of data. These models need to more fully integrate growth and yield, harvest scheduling, site selection, and wood flow, cost, and delivery models. In addition, a more spatially explicit model is needed that provides flexibility in identifying and delineating zones, boundaries, and areas of operation. Cost-effective, spatially explicit protocols and methods are needed for inventory and projection. Finally, financial analysis tools are needed for assessing biomass availability and costs under various policy, climate, and technology scenarios.

3.1.5. Improve technical, ecological, economic, and carbon performance of forest operations to produce woody biomass for fuels and products

Implementation of management treatments requires physical forest operations such as harvesting, processing or conversion, and transportation of biomass. These operations are a significant consideration in addressing the GHG profile of forestry activities, both through the direct emissions of the equipment and through the relative efficiency of handling biomass volume. Several key areas of research needs are related to forest operations:

a. Reduce emissions of GHG from forest operations. A wide range of equipment and operational methods is available, including manual methods with power equipment, highly mechanized systems for mass production, and various specialized technologies to reduce the effects or costs of reducing emissions of GHGs. Power technologies for forest equipment are changing with EPA-mandated transitions to different fuel types and lower emission diesel en-

gines. Demonstrations of alternative fuel equipment, including hybrids and biofueled machines, have also occurred. It is important that emission reductions be assessed on the basis of their net carbon costs. A low-emission system may be relatively inefficient at processing carbon volume and, thus, a poor choice under climate change scenarios.

The foregoing considerations generate the following requirements. First, the net emissions of forest operations must be quantified as a function of operational conditions and carbon offsets generated. Second, the effect of maintenance practices and equipment ownership patterns on emissions must be assessed. Alternative fuel technologies need to be evaluated to determine their potential applications in different types of equipment, including fuel handling, environmental impacts, and costs. Hybrid power systems for forest operations must be examined, including the possibility of regenerative energy capture in various machine functions. Third, emissions and energy requirements must be quantified for biomass transport in rail, barge, highway truck, and pipeline carriers.

b. Improve operations to increase the recovery and use of biomass. Significant amounts of woody biomass are not easily recovered from forests. Scattered residues, brushland species, understory biomass, and smallwood all present difficulties in cost-effective recovery. The low volume per piece generally means that significant amounts of energy are expended to capture relatively low volume. Therefore, Forest Service scientists and engineers should evaluate the performance of swath harvesters

to improve the efficiency of harvesting smallwood. Small diameter woods conversion through baling or chipping is needed, and efficiency in subsequent handling and transport should be evaluated. Our engineers need to study the compaction systems for slash, chips, and other biomass forms to increase density and the transpirational drying and other in-woods methods to reduce moisture content of biomass. We should conduct system analysis of alternative biomass harvesting methods, including integrated operations, multipass treatments, and separated biomass harvesting. We must determine the effect of biomass form on transportation and handling costs and develop an understanding of ecosystem impacts from biomass harvesting.

- c. Improve the cost-effectiveness of forest operations.** In general, reducing the cost of treating some volume of biomass will increase the amount of that material that can be processed. Conventional forest operations, designed for harvesting sawlogs and pulpwood, are not necessarily optimized for biomass/carbon treatments. The evolution of technology has been driven by matching functional performance for particular products. For example, feller-bunchers have been developed to match skidder capability when the tree size is in a certain (usually large) range. By pushing conventional systems into smaller piece sizes, system performance suffers.

We need research to understand how equipment specifications affect the cost of operations and to model the potential savings that could be achieved by different equipment configurations. Integrated harvesting operations where removal of conventional products and additional biomass is done concurrently should be studied to identify possible


efficiency improvements. Technical evaluation of the source of the costs in equipment (e.g., power plant, operator accommodation, attachments, and so on) could identify new, more cost-effective equipment designs. We should study the productivity of conventional harvesting systems to develop better estimates of biomass harvesting cost. We need to examine the performance of combined function machines such as harwarders (integrated harvester-forwarders) and terrain chippers. Generalized predictors of energy consumption as a function of equipment parameters such as horsepower, gross weight, and load capacity need to be developed. Finally, we need to evaluate technologies for roadside conversion of biomass directly into liquid or other partially refined forms.

- d. Improve special-purpose forest operations for carbon sequestration.** Forest activities can increase carbon sequestration in several ways. Increasing the volume removed and its use is one approach. Increasing carbon storage in the forest is another. Residues can be processed and incorporated into the soil for enhanced carbon pools. Operations that increase growth rate, even without biomass removal, can enhance carbon accumulation. We should examine innovative operations such as subsoiling and tillage; evaluate opportunities to enhance carbon sequestration through operations such as fertilization, thinning, and pruning; and examine short-rotation, intensive forest management to maximize carbon accumulation.

3.1.6. Improve technical, economic, and carbon performance of wood product and wood-based biofuels production and use

- a. Wood products and production.** Production and use of wood products and wood-based biofuels or bioenergy can sequester more carbon or offset more GHG emissions relative to alternative materials and fuels. Research is needed to improve these technologies to increase the benefits of these carbon sequestration and carbon offsets. These technologies may not be competitive with fossil fuels or crop alternatives without improvement in raw material handling, transportation, and conversion, and the improvements may require Government support.

Life-cycle assessment (LCA) of forest management and wood-use alternatives is needed to determine more accurately how



There are abundant opportunities to increase the use of wood for bioenergy, but there are also technical and social challenges to be overcome.

improvements in technology could increase net sequestration and offsets. The benefits of certain technology improvements are sufficiently clear, however, to highlight some specific research needs. We should improve wood use systems such as housing and nonresidential construction so as to increase wood carbon sequestration and carbon emission offsets (e.g., Lippke and Edmonds 2006). Technologies to produce wood-based biofuels need to be developed to be competitive with other transportation fuels. For example, we need new organisms for fermenting 5-carbon sugars at commercially viable ethanol concentrations. We need to increase the yield of glucose from wood by solving the recalcitrant cellulose barrier that currently prevents us from reducing complex sugar compounds to simpler forms useful in ethanol production. These efforts also must include determining the life-cycle inventory (LCI) (e.g., inventories of GHG emissions, energy use, at each stage of production) for wood biofuels and other biofuel technologies and determining economic feasibility of alternate facilities/technologies (business case evaluation). Finally, we should evaluate and improve our understanding of the benefits and costs of carbon sequestration, emissions, and offsets associated with wood plastic composites and other wood composites and with environmentally safe preservation treatments for wood products.

- b. Bioenergy and biofuels.** Using current technologies, we can use woody biomass to provide about 600 million barrels of ethanol annually in the United States. With improved technology, this amount could be increased to 1.3 billion barrels (Perlack et al. 2005). Much more research is needed on yield and cost reduction in producing ethanol from lignocellulosic biomass. It is well recognized that wood waste and agricultural residuals provide a much larger supply of sugars than can be produced from grain and sugar crops. The technologies to convert cellulose to monomeric sugars are inefficient, however, and barely exceed 50 percent of the theoretical yield (Thorpe and Frederick 2007). We should investigate improved pretreatments and/or enzymes to saccharify a higher percentage of the cellulose in woody biomass. Improved organisms for fermenting 5-carbon sugars that work faster and can tolerate high alcohol concentration must be developed.
- c. Thermochemical conversion.** An alternative biomass treatment method involves thermal treatment of the wood to produce a combustible gas.

Gasification is a well-understood technology that can convert biomass or fossil fuels to a mixture of methane, hydrogen, carbon monoxide, CO₂, and water. This low-heat value gas can replace natural gas in many applications, including gas turbines for generating electrical power. The resulting gas product can also be converted into hydrogen, methanol, higher alcohols, or hydrocarbons using thermal catalysts (Hamelinck 2004, Spath and Dayton 2003). The critical concern in gasification is the distributed nature of biomass that limits the scale of the gasifiers and conversion refineries. Several organizations are evaluating processes with small-scale biomass pyrolysis units that would produce an intermediate product known as pyrolysis oil. The higher energy density pyrolysis oil would then be shipped to centralized, large-scale refineries. A similar technology is possible in which the small-scale distributed operations are gasifiers that supply producer gas to a biogas-dedicated pipeline. The biogas pipeline could supply utilities or a petroleum style refinery that converts the gas to transportation fuels and chemical products. We should evaluate the commercial feasibility of biogas pipelines supplied by distributed and possible mobile gasification plants. We need to investigate the effect of biomass variability on producer gas and the conversion to other products. In addition, we must improve gasifier efficiency and the conversion technologies. This research is a priority of the U.S. Department of Energy, and we believe such research should be supported by the Forest Service.

- d. Densified fuels.** Biomass used exclusively for electrical power could displace about 800 million tons of coal annually, or, as wood pellets, it could easily displace all 300,000 barrels of heating oil used in the country. Current costs, particularly transportation of unprocessed biomass, make this an uneconomical use of wood and agricultural residues. Wood as harvested is typically 50 percent water and 50 percent wood. Because the energy content of wood is lower than that of coal, one and a half tons of wood biomass is needed to match the energy content of 1 ton of coal. However, water content of raw biomass requires 3 tons of green wood for 1 ton of coal. Matching the energy content in the volume of one rail car of coal would require six identical rail cars of biomass, based on bulk density. Truck transportation of wood costs 10 times as much as train transportation of coal, 20 times when discounted for water. Research is needed for wood compacting, grinding, and drying systems that can move with logging sites

and minimize the excess weight and bulk for moving wood to utilization points.

- e. **Pressure-treated lumber.** Pressure treatment is used to introduce into the wood, chemicals that retard the decay process. New treatment methods are known to have different levels of decay resistance than the standard chromated carbon arsonate (CCA) treatment that has been abandoned by manufacturers in pressure treatment of wood. Research is needed on these alternatives to determine decay resistance, environmental effects, and carbon storage benefits.
- f. **Composite products.** Information is needed on the energy requirements (carbon emissions) associated with newer composite products that use wood in combination with alternate nonwood materials. Efforts are needed to minimize the carbon emissions profile of composites.

3.1.7. Use life-cycle analysis to improve forest management and wood alternatives for energy and bioproducts

Tools to integrate planning and management processes can allow stakeholders to test the consequences of alternative actions. LCA is one method by which one can examine total system impacts, costs, and benefits of pursuing outcomes through alternative means. For example, one can compare the total amount of energy consumed and

the total emissions produced by substituting wood structural products for concrete and steel in residential and commercial construction (Lippke et al. 2004). According to International Organization of Standardization Standard 14040 (ANSI 2006), the key qualifying characteristic of a LCA, as opposed to a system study, is that LCAs “systematically... address the environmental aspects of product systems, from raw material acquisition to final disposal.”

LCA requires development of extensive inventory databases that account for the materials and energy involved in a given “unit process,” or a phase of a production process. In an LCA of wood-based energy systems, for example, one must take into account the amount of fuel consumed by in-woods processing, transportation, plant operation, etc. Similarly, one must account for the emissions associated with the same machinery. The databases are referred to as LCIs, or life-cycle inventories.

Both LCIs and LCAs often require extensive research to establish. While databases are rapidly being created or improved, the great variability in forest conditions, harvesting systems, processing architecture, and conversion technologies requires that inventory databases be appropriate to the system being analyzed. The most complete example of LCA applied to forest systems and building materials has been developed by the Consortium for Renewable Resources in Manufacturing (CORRIM). The focus of CORRIM’s LCIs and LCAs, however, has been the sequence starting with commercially managed forest systems and finishing with substitution of wood products for concrete and steel in residential construction (Lipkke et al. 2004).

Additional studies collected varying amounts of life-cycle information (Gerilla et al. 2007, Kaipainen et al. 2004, Markewitz 2006). Although CORRIM has made great strides in comparing construction materials based on LCA techniques, a broader range of material and energy substitution scenarios needs to be explored. As other wood products are developed, LCIs need to be documented for the unit processes involved in procurement, production, and use. The use of biomass from fuels treatments, for example, implies a very different configuration of forest management



Life-Cycle Assessment is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by compiling an inventory of relevant energy and material inputs and environmental releases; evaluating the potential environmental impacts associated with identified inputs and releases; interpreting the results to help you make a more informed decision.

From EPA Web site: <http://www.epa.gov/nrmrl/lcaccess/>

strategies and, therefore, different suites of machinery, materials, and products. Much more extensive research is needed to compare processes and products from forest systems that concomitantly provide ecosystem services such as wildlife habitat, water quality, fire-risk reduction, and other social benefits. Research needs in this area are integrated with several other research areas in this strategy document.

Understanding risks and cobenefits is an important part of developing a long-term mitigation strategy.

a. Harvesting of processing and transportation systems.

Fuel consumption, production rates, personnel costs, and other inputs and outputs associated with moving biomass and other products from the stump to the conversion facility should be investigated on a comparative basis to determine the most efficient systems linked to management goals. Collection processing and transportation costs and energy demands will vary widely depending on the ecological and economic objectives of the management strategy or prescription. Research can enhance management's ability to compare systems depending on desired outcomes.

b. Bioenergy and biofuels production. Different conversion technologies should be investigated and compared for their energy efficiencies, material and energy consumption, and total emissions beyond stack emissions. LCI databases should be developed in order to compare different biomass and fossil-based technologies with similar outputs (e.g., kilowatt hours of electrical current, gallons of ethanol, cubic feet of hydrogen).

c. Ecological cobenefits and effects. The Forest Service should improve LCA architectures to include tradeoff analyses of production systems and their effects on other ecological components. This improvement is particularly important in the "interpretive" phase of LCA, in which effects are assigned to biophysical mechanisms, such as sea-level rise or loss of habitat, which are less well understood. We should develop and improve LCI databases for nonconstruction wood products and their end use. We can improve LCA modeling architecture to allow streamlined integration of new inventory databases. Developing uncertainty and data quality indices in LCA modeling would allow better focus of unit process analysis efforts.

3.1.8. Provide integrated strategic evaluation of local, regional, and national policies and management actions (environmental/economic). Identify limitations and capabilities of alternate management and policy tools

The Government Accountability Office (GAO 2007) report on climate change and natural resource management on Federal lands also points to a critical need for scientific tools that can help integrate the big picture (global trends and national policies) into local management decisions and priorities. The GAO report states, "resource managers have limited guidance about whether or how to address climate change and, therefore, are uncertain about what actions, if any, they should take. In general, resource managers lack specific guidance for incorporating climate change into their management actions and planning efforts."

Forest lands can mitigate carbon additions to the atmosphere by carbon sequestration in forests and forest products and by displacing fossil fuels with wood products and wood energy and wood-based biofuels. The need for integrated scientific research to aid in guiding forest management and product use includes needs for models of carbon markets, biomass markets, and bioenergy markets. Such models can help to identify competitive systems that can be adopted locally to produce and harvest biomass and to convert biomass to bioenergy and biofuels.

3.1.9. Quantify the uncertainty in estimates of change in ecosystem carbon stocks and wood products. Conduct risk analysis and build risk estimates into carbon management strategies

To better assess the current role forests are playing in sequestering carbon and to assess the efficacy of future carbon sequestration programs, we need to be able to quantify the uncertainty in change estimates of carbon stocks. Such analyses should provide guidance so that we

may develop a program to reduce the uncertainty of such estimates. Phillips et al. (2000) used FIA data to estimate the total error for the change in growing stock volume for the Southeastern United States and found that the 95-percent confidence intervals on these estimates were surprisingly high (± 40 percent). Heath and Smith (2000) analyzed the uncertainty in the FORCARB model projections used for estimating national carbon stocks and reported a ± 9 percent uncertainty in national carbon stocks and ± 50 percent uncertainty in stock changes to 2010. Smith and Heath (2001) analyzed the contribution of various factors to this uncertainty and indicated that lack of knowledge about soil stocks was currently the greatest source of overall uncertainty in U.S. carbon stocks. The authors also reported that covariances between stock estimates added another and potentially very important component to the uncertainties in stock changes. Analyses that extend and enhance these and related approaches, including investigating stock temporal covariances, should be a high priority.

Because the model assists decisionmaking and enhances the usefulness of models, statistics describing uncertainty in output data for other ecological and physical processes is also required. Important uncertainties in vegetation response to climate and increasing CO₂, soil processes, pests, pathogens, and fire severity remain to be quantified.

Uncertainties in carbon stocks are well documented for aboveground biomass, but less so for other components (deadwood, roots, forest floor, soil carbon, wood products), because aboveground biomass is the pool most often sampled and because techniques for sampling have been refined for more than a century (Bradford et al. 2008). Progress is being made in cost-effective, efficient sampling techniques for deadwood (Gove et al. 2002) but not for forest floor (Yanai et al. 2003) and soil carbon. Risk analysis to determine the probability of carbon loss through fire, insect outbreak, hurricanes, and ice and wind storms is needed to adequately calculate the potential for storing carbon permanently in forests. Our knowledge, however, of the relationship between different types of disturbance and carbon is poor (Ryan et al. 2008). Few studies exist on the effects these disturbances have on forest carbon balance, and no national disturbance inventory exists to quantify the aerial extent of different types of disturbances and relate those disturbances to changes in forest structure and forest carbon balance (Ryan et al. 2008). In addition, forest responses to elevated CO₂ might even increase the ability of some forest types to sequester carbon (LaDeau and Clark 2001, McCarthy et al. 2006).

3.1.10. Assess tradeoffs between maximizing carbon sequestration in living biomass and other land management objectives (e.g., fuels reductions, water yields, wildlife, threatened and endangered species, recreation)

The Forest Service management goals include the entire suite of ecosystem goods and services derived from forests and grasslands described by the Millennium Ecosystem Assessment (2005). These include provisioning services (i.e., timber, fuel, food, other nonwood products, fresh water, and genetic resources), regulating services (i.e., regulating air quality, carbon, climate, water, erosion, water purification and waste treatment, diseases, pests, and natural hazards), cultural amenities (i.e., cultural diversity, spiritual/religious values, knowledge systems, educational values, inspiration, aesthetic values, social relations, sense of place, cultural heritage values, recreation, and ecotourism), and supporting services (i.e., primary production, soil formation, pollination, nutrient cycling, water cycling). Climate change will affect each of these goods and services, but differently from one locale to another. These ongoing effects will require the balance of products that individual forests currently provide to be reassessed and adjusted frequently, particularly to include carbon sequestration goals that Congress may require. Current assessment approaches may be inadequate for this balancing task and will need to be modified to include the increasing uncertainty of climate changes.

3.1.11. Develop cost-effective tools for verification of actual carbon sequestration at a local scale, considering issues such as leakage and sequestration in soil

Carbon management projects often cover small areas (acres), but the reporting requirements and verification needed to obtain carbon credits are difficult and expensive for small landowners (Lichtenfeld 2007). If verification and reporting requirements are more expensive than the credits, carbon credits will likely not be sought by small landowners. Simple tools and protocols for verification of carbon storage are urgently needed to overcome this problem (Johnsen et al. 2004). For soil carbon sequestration, detecting change in soil carbon storage remains an expensive, challenging issue, which currently must be done over long periods of time to have any chance of detecting a significant difference (Yanai et al. 2003). Either new technology needs to be developed to measure carbon in soil cheaply, or a large body of evidence needs to be acquired from many sites, climates, and management practices, and synthesized into scientifically approved sequestration rates that can be generally applied (e.g., see Powers et al. 2005). Leakage, in which a targeted carbon mitigation strategy in a certain place or time indirectly results in loss of carbon storage

elsewhere (Murray et al. 2004), is an issue that needs to be solved at the policy and regional levels (Ruddell et al. 2007).

3.1.12. Identify limitations and capabilities of alternate management and policy tools

Great interest exists in harnessing the power of markets to increase use of forest resources, especially to support hazardous fuel-reduction activities or to increase the production of energy from renewable sources. The relatively rapid increase in forested biomass in parts of the country where traditional forest products production has declined is giving impetus to this growing interest.

The direct relation between sawtimber and non-sawtimber markets suggests that attempts to expand the use of biomass or biofuels will affect sawtimber prices, which will in turn affect the competitive status of forest products producers in some regions. Given that these are relatively inelastic markets, price impacts will be proportionally larger than quantity changes.

Facilitating the use of markets to aid in carbon management requires research to establish measurement units and verifiable measurement methods to support increased carbon sequestration and offsets associated with forests and wood products. It also needs understanding regarding arbitrage of wood energy and wood-based biofuels markets with existing sawtimber and pulpwood markets and the resulting effects on landowner investments in forest management practices.

3.1.13. Evaluate social acceptance of alternate carbon management policies and management practices

The public has altered the Forest Service's and other forest managers' ability to affect forest characteristics through new legislation at local, State, and national levels and through the courts. Most conflicts over forest management, and in particular public forest management, stem from alternative beliefs about sustainability. A critical component of a climate change research strategy is to understand systematically the relationships between definitions of and beliefs about sustainability and preferences for particular

forest management strategies. Social science research often characterizes this relationship as correlations between core beliefs and policy preferences.

The opportunities to mitigate climate change through forest management may be substantial. The need to manage forests to make them more resilient to climate change is important in dealing with carbon management on a global and local scale. Forest management in the light of climate change may again alter forest managers' social contract.

A research strategy should demonstrate work that has been accomplished to date, or work that is ongoing and planned through partnerships and opportunities for interested organizations. Participation of these organizations can help build the confidence and ownership in a new direction, or social contract, for forest management. Hence, we should advance research on advocacy coalitions, social networks, and institutional design frameworks in ways that apply to managing forests for climate change adaptation and mitigation. We also need to understand how the stakeholders perceive the role of forests and forest management in climate change mitigation. That leads to the need to investigate the forms of communication that are most effective in gaining the interested public's (environmental/conservation organizations) understanding and acceptance of forest management to achieve mitigation and resilience goals. Finally, we must investigate emerging forms of governance



Forests managed as emissions offsets may not permanently sequester greenhouse gases. Emerging policies take this into account.

and decisionmaking that can be effective in integrating climate change mitigation and adaptation into forest management strategies.

3.2. Cooperative Activities

3.2.1. Provide synthesis and analysis of what we know and don't know about net carbon sequestration

The Forest Service scientists, research cooperators, and partners have a very broad range of understanding about the carbon cycle and knowledge of information gaps from nearly two decades of research involving experiments, observations, and models. Experiments range from potted-plant studies of carbon allocation to whole-ecosystem studies, such as replicated silvicultural experiments, and Free-Air CO₂ Enrichment studies (Körner 2000). Long-term observations involve statistical sampling, such as that conducted by FIA; remote sensing studies; and more intensive observations, such as those performed at CO₂ flux towers and experimental forests (Bechtold and Patterson 2005, Lugo et al. 2006). Modeling studies range from physiological and ecosystem process models to statistical models such as those used to report changes in carbon stocks to the U.S. GHG inventory (Birdsey and Heath 1995, Turner et al. 2004).

Given the breadth of scientists' involvement using different but frequently complementary approaches, a synthesis activity involving carbon sequestration could be approached in different ways. One way might be to narrow the scope to one or two very critical questions and then select a small team with relevant experience to tackle the issues. At the other extreme, a more comprehensive review would require a large and dispersed team to focus on a larger set of questions, with a strong element of structured coordination.

3.2.2. Quantify uncertainty in change estimates of ecosystem carbon stocks

Approaches to quantifying uncertainty include variance analysis, Monte Carlo simulation, meta-analysis, scenario analysis, and model comparisons. These approaches are typically applied in different situations according to the objectives, scale of analysis, and methods being used. At the regional-to-continental scale, uncertainty of reported estimates based on FIA data are already compiled routinely (Heath and Smith 2000), but scientists need to better understand the uncertainty of factors not included, such as annual insect damage effect or changes in soil carbon. Other approaches at these large scales, such as inverting atmospheric samples or assimilating data involving flux towers and models, give results with widely differing but overlapping error estimates (Pacala et al. 2001). A corporate approach to attacking these issues would require a high level of integration between the greenhouse inventory team and other programs such as the North American Carbon Program (NACP) (Wofsy and Harris 2002). The team would also need to utilize some rigorous model inter-comparisons along the lines of the Vegetation/Ecosystem Modelling and Analysis Project (VEMAP) study (VEMAP Members 1995). At the stand or landscape scales, which are of great interest to carbon managers, standard statistical methods can be used to quantify uncertainty based on measurements, but in practice such methods have not been used extensively. Some work at experimental forest landscapes at the "tier 3" sites described by the NACP science plan (Denning et al. 2005) could be expanded to involve a national network of benchmark carbon management sites representing the major ecosystems and management/disturbance regimes. Integration with LTER, NEON, AmeriFlux, and other existing networks would involve many Forest Service scientists and partners.

3.2.3. Investigate impact of land management activities on global warming potential, which includes carbon, albedo, and trace greenhouse gases

This forward-looking research topic has a strong atmospheric science perspective (climate modeling) more

In addition to its effect on greenhouse gases, land management affects climate directly by reflecting (or absorbing) solar energy and by transpiring moisture that affects cloud formation.



appropriate for other Federal science agencies, so existing capability in the Forest Service is focused primarily on the carbon cycle. Nonetheless, some basic Forest Service climate modeling infrastructure is available to build on, in addition to building on the existing carbon cycle research. Specifically, the Forest Service has consortia of fire weather modeling known as Fire Consortia for Advanced Modeling of Meteorology and Smoke, which have the computing power and climate modeling expertise to make a significant contribution to examine how changes in land characteristics affect global warming potential. The Forest Service also has some direct measurements of critical parameters (in addition to carbon), such as albedo at flux tower sites, trace gas measurements at EFRs, and transpiration measurements at a variety of intensive research facilities. These data sets could be strategically expanded and brought together with enhanced modeling capability to develop a more comprehensive analysis capability for assessing the effects of land management on global warming potential.

3.2.4. Develop science partnerships that permit the quantification of land use change, using models and observations

Forest Service Research and Development, the National Forest System, and State and Private Forestry need to work together closely when case studies are implemented to increase carbon sequestration, both so that researchers are aware of realistic opportunities and problems and so that expertise for implementing such projects can be spread throughout the organizations.

Partnerships are essential to solving complex, pervasive problems such as global change and related carbon dynamics. Evaluating changes in land use is a major focus area of multiple agencies. This fact is best exemplified by the U.S. Global Change Research Program, which is a partnership consisting of 13 individual U.S. agencies. One of this program's key elements is land use/land cover change (<http://www.usgcrp.gov/usgcrp/ProgramElements/land.htm>), and the National Aeronautics and Space Administration is one of the main contributors to this element, through its Land-Cover and Land-Use Change Program (<http://lcluc.umd.edu/>). Many of the agencies within these partnership programs fund research with other agencies and to universities, thereby further broadening the power of these programs. In the international arena, the Global Observation of Forest and Land Cover Dynamics program is focusing on forest change through multiple partnerships (http://www.fao.org/gtos/gofc-gold/int_organization.html). The Forest Service is already engaged in many of these activities at various levels, but its role is often less direct than it could be. Through more direct engagement, the Forest Service

could take advantage of a greater set of observations and models, as well as help to direct some of the critical research needed to understand how land use is changing and its likely effects on carbon dynamics.

3.2.5. Quantify and model spatial distribution and longevity of the forms of carbon in soil and the effects of management, climate, and land use change on residence time of those forms

Both in situ and ex situ carbon sequestration need to be considered in concert (e.g., Johnsen et al. 2001). Research must be prioritized so that the most fruitful avenues that provide medium-term sequestration are well understood, permitting the information to be used in the field as soon as possible. Other research should examine less certain but potentially important processes that can be used to predict and/or increase forest carbon sequestration. The latter research should be combined with other studies to ascertain its potential impact on large systems.

3.2.6. Develop cost-effective tools for verifying actual carbon sequestration at local scales, considering issues such as leakage and sequestration in soil

Ultimately, estimates of forest carbon sequestration must use relatively simple metrics that can be integrated into models. It is likely that the value of a carbon credit will be perceived as proportional to the intensity of sampling (i.e., sampling is increasingly expensive and increasingly reliable), and thus also proportional to the confidence provided by other estimates (Johnsen et al. 2004). Standard methods for deciding the temporal scale for awarding carbon credits need to be assessed as do methods for incorporating the dynamics of above- and below-ground carbon pools into carbon sequestration estimates. Economic analyses and projections will be required to assess the effect on regional forest carbon sequestration if it is considered a financially rewarded ecosystem service.

3.2.7. Quantify the uncertainty in estimates of change in ecosystem carbon stocks. Conduct risk analysis and build risk estimates into carbon management strategies

The Forest Service must make resource planning decisions now if the goal of increasing forest carbon sequestration is to be incorporated into forest plans. Climate is changing rapidly, however, which will likely change the adaptive potential of forests existing today. Where forest conversion or restoration may be a viable alternative, species must be carefully selected to provide forest resilience. The deployment of the species must consider how different ecosystems that provide other important ecosystem goods and services can coexist. Such analyses can only be accom-

plished if ecological and economic forecasts include land managers' and forest biologists' input.

3.3. Science Delivery

A primary force behind Forest Service research is the drive to produce results that make a positive difference in the condition of the Nation's forests. To effectively traverse from researcher to resource manager, scientific knowledge must first meet rigorous standards for scientific quality and credibility. The end user must value, understand, and adopt that new knowledge, however, before it will make a difference. A cycle of activities that ensures effective science delivery includes understanding the users and their information needs, targeting scientific studies to meet those needs, developing research products that make sense to users, and seeking user feedback to create and refine those products.

Successful science delivery efforts share the following common characteristics:

- They engage a broad array of potential information users at all stages of the research and delivery effort, offering interactive and real-time opportunities for participation.
- The delivery process is dynamic, adapting to new developments as they occur.
- They are targeted to meet specific audience needs and deliver information at the technical level appropriate to that audience.
- They include partnerships that are instrumental, offering new perspectives and leveraging both research and delivery expertise.
- The specific techniques employed are tailored to the intended recipient and the product being delivered.

- Techniques are diverse, ranging from personal interactions to electronic methods such as Web sites and Webinars.

Effective science delivery starts with a clear understanding of the information needs of those who ultimately use the research. In the case of carbon management research, those audiences include the following:

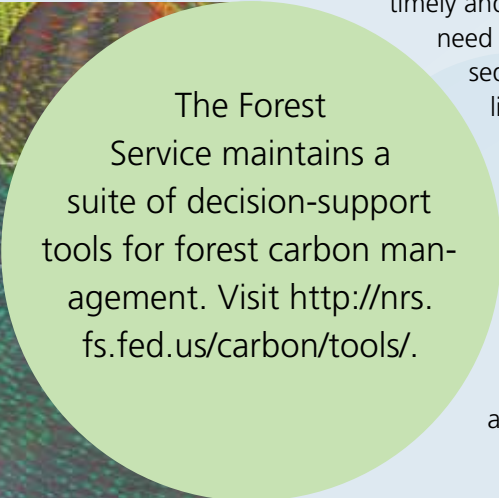
- Land managers—includes private landowners and public natural resource agencies.
- Policymakers—includes State and local governments, nongovernmental organizations (NGOs) that seek to influence governmental policy, and planning agencies/commissions.
- Businesses—includes investors, economic developers, utility companies, and wood products industries.
- Interested public—includes members of environmental organizations, public school educators, recreators, and many others.

Research on using forest management and wood removals to increase carbon sequestration and reduce GHG emissions produces three general categories of products: (1) models/tools, (2) market analyses, and (3) technologies. The following matrix describes examples of a given audience's particular needs. (See table 3.1.)

3.3.1. Defining stakeholders and mechanisms for science delivery

The practitioners (forest managers, planners, urban park managers) and private landowners have been defined as major audiences for carbon sequestration knowledge and scientific information. Scientists will likely continue to communicate among themselves directly or through published literature. A need exists, however, to find ways to deliver this science to practitioners and private landowners in a

timely and efficient manner. A more immediate need is to distill what we know about carbon sequestration for policymakers and the public, as the media appear to be presenting a deluge of information, not all of which is scientifically defensible. The effective delivery of scientific knowledge is a key to marketing the usefulness of Forest Service research. Forest Service R&D should develop a cohesive and effective strategy to deliver the results of our research to Federal, State, and private audiences.



The Forest Service maintains a suite of decision-support tools for forest carbon management. Visit <http://nrs.fs.fed.us/carbon/tools/>.

Table 3.1. Examples of products that increase carbon sequestration and reduce GHG emissions through forest management and wood removals and their different users.

Audience	Models/tools/analyses	Market analyses/ resource assessments	Technologies
Land managers	<ul style="list-style-type: none"> ◦ Tools for local or regional evaluation of biomass production and its economic feasibility ◦ Revised FVS model that incorporates carbon effects of biomass/biofuel production ◦ Tools/analyses for LCA at local regional scale of forest management and wood use alternatives including LCI for fire/ other forest emissions reduction, forest operations, product production, use and disposal 		<ul style="list-style-type: none"> ◦ Improved wood harvest and transport systems ◦ Special forest operations that increase site sequestration ◦ New products to use small diameter timber
Policymakers	<ul style="list-style-type: none"> ◦ LCA of forest management and wood use alternatives at the regional and national scale including LCI for fire/other forest emissions reduction, forest operations, product production, use and disposal 	<ul style="list-style-type: none"> ◦ RPA scenario projections for wood bio-energy/biofuels development through 2060 and carbon impacts/goal attainment/guidance for regional objectives 	
Businesses	<ul style="list-style-type: none"> ◦ LCAs of information, tools, and data on global warming potential and energy use ◦ Tool/analyses to estimate local/regional woody biomass supply/costs to aid in siting bioenergy/biofuels facilities ◦ Evaluation of alternate business cases for wood-based biofuels production 	<ul style="list-style-type: none"> ◦ Potential carbon markets and their impacts on the forest industry ◦ Evaluation of carbon sequestration's competition with other forest products 	<ul style="list-style-type: none"> ◦ Wood harvest and transport systems ◦ Wood-based biofuels ◦ New products to use small diameter timber ◦ Housing/ construction options with superior carbon offset profile
Interested public	<ul style="list-style-type: none"> ◦ Current status and outlook on the economics and net carbon effects of forest management and product removal, including both traditional wood use and wood use for bioenergy /biofuels ◦ Current status and outlook for carbon credit markets and their implications for forest management 		

FVS = Forest Vegetation Simulator. LCA = life-cycle assessment. LCI = life-cycle inventory. RPA = Resources Planning Act.

a. Development of different strategies for different stakeholders. With increasing interest from the public, policymakers, and practitioners to mitigate the effects of global climate change, the Forest Service needs to put in place an effective and timely science delivery system. To accomplish this, the Forest Service must develop different strategies

and a corresponding agency infrastructure for each audience and, perhaps more importantly, must develop partnerships with other agencies (e.g., USDA National Institute of Food and Agriculture, NOAA RISA teams, etc.), consultants, and possibly NGOs to deliver the information.

b. Delivery of information to practitioners and private landowners. The biggest demand for carbon sequestration knowledge and information is from private landowners, forestry consultants, and public forest managers. The GAO has identified a critical need to develop guidance and provide site-specific climate change information for Federal land managers to incorporate into their management actions and planning efforts (GAO 2007). The Forest Service intends to communicate climate change mitigation and adaptation strategies to field units, with FS R&D at the forefront.

Each group of stakeholders will require different information delivery mechanisms, such as user-friendly models (e.g., Carbon On-Line Estimator [COLE]) to assess trends in forest carbon accumulation and release resulting from afforestation or silvicultural practices. Especially valuable will be decision-support tools that help managers develop alternative strategies and select the best integrated mitigation and adaptation options while avoiding potential conflicts among goals. For example, efforts to maximize carbon accumulation in forest stands may increase wildfire size and severity and facilitate the rapid growth of beetle populations. Science should outline alternative strategies for addressing the potential for increased disturbance risks and evaluate tradeoffs produced by specific strategies. In addition, because the demand for information and knowledge from private stakeholders may be beyond the Forest Service's capacity for delivering the science expeditiously, the agency will need to partner with other agencies, such as the Cooperative Extension and NGOs and, in particular, will need to work through private consultant groups, which private landowners often use to seek guidance on matters involving carbon sequestration.

In all cases, the Forest Service would be "teaching the teachers" to transfer the agency's knowledge to a geometrically larger audience. As an example, private landowners are aggregating their resources to pay for consultant services regarding carbon sequestration. By providing information and knowledge transfer to private consultants, Forest Service R&D would in effect be reaching a larger number of private landowners than using traditional technology transfer outlets. Legal issues related to the Forest Service's facilitating private consultants' financial gain, however, will need to be worked out.

Another example of forging partnerships to transfer technical knowledge is the use of modeling tools such as iTree, which is a suite of user-friendly models available online for urban planners, urban foresters, and other practitioners to use in developing urban tree surveys and calculating ecosystem services provided by urban forests (e.g., carbon sequestration). This interface was funded in part by S&PF and developed through a partnership among Forest Service R&D, the private sector, and several NGOs. Although user-friendly model interfaces hold great potential to deliver the Forest Service's scientific information and knowledge, it is critical that the agency have the infrastructure in place to support the appropriate use of these models. A cost-effective way to facilitate the use of future models would be to "piggy back" on existing infrastructures; for example, by delivering customized carbon accounting models through the Forest Vegetation Simulator (FVS) or iTree support structures.

c. Delivery of information to policymakers and the public. Although the biggest demand for carbon sequestration information and knowledge will come from private landowners and forest managers, the delivery of sound scientific information to the general public and policymakers is no less important, especially with the ever-increasing availability of information on the Internet (some of which is not based on scientific fact). An important first step is for Forest Service R&D to synthesize the existing scientific information and knowledge on carbon sequestration, including conducting an analysis of the uncertainties related to this information (e.g., the Intergovernmental Panel on Climate Change reports), and relate it to specific carbon sequestration issues. Forest Service R&D would benefit by partnering with various scientific societies, such as the American Geophysical Union or Ecological Society of America, who see themselves as honest brokers of scientific knowledge. These NGOs can coordinate the synthesis, provide peer review, and develop various products beyond the typical peer-reviewed journal article. These products could include fact sheets, interactive Web site materials, computer simulations/games, and other user-friendly products to deliver the synthesized information more effectively to the public. Moreover, these products also could be used in conjunction with continuing education courses, K-12 teacher training, one-on-one meetings with congressional staff, government briefings, undergraduate college courses, and other events.

3.3.2. Needs within Forest Service R&D to support science delivery

Traditionally, science delivery in Forest Service R&D has been conducted through individual relationships that are typically ad hoc, unstructured, and not formed under an agencywide, coordinated effort. Under such conditions, much depends on the efforts of individual scientists who have limited support and coordination from higher levels of the agency. Inadequate support is unfortunate because the most effective science delivery programs foster individual relationships between scientist and user and at the same time do so under a program that supports the overall delivery of information and knowledge designed for those users. Therefore, every research project at the program or team level would benefit from a strategic plan to deliver science that included the products desired, product life cycle, and chain of responsibility for those products. Large teams would benefit from having science delivery personnel who are closely involved with research, familiar with the team's user community, and able to judge the best mechanism for delivery. The development of such an infrastructure is particularly crucial for the delivery of carbon sequestration information to public and private land managers since these groups have a high demand for this information and often require more personal interactions in the delivery process.

Although Forest Service scientists should be available to communicate their science directly to the public and to policymakers, it is important that trained science communicators at the station and national levels coordinate with individual scientists in the delivery of scientific knowledge to these groups. To implement this communication effort would, in part, require an integrative effort among the deputy areas of the Forest Service. Such an effort should begin when the Forest Service initiates a research project, for example, in carbon sequestration. A coordinated effort to communicate with these groups is particularly important because the public and policymakers have exhibited a general lack of interest and understanding in the use of forest lands to offset emissions.

Another issue identified with the current science delivery process involves the time a scientist spends on science delivery vs. successful completion of the research cycle. Most Forest Service research scientists believe that developing personal relationships with user groups takes time away from their personal research and, in particular, from the enhancement of an individual scientist's Factor IV (research criterion for advancement). The coordinated development of a strategy and infrastructure to deliver science as described would alleviate some of this tension. The current

reality is that scientists are spending less time on research because of increased administrative demands and have little discretionary time to put into science delivery. This reality suggests that meaningful participation by Forest Service research scientists in the science delivery process requires either the addition of knowledge transfer support personnel or a major change in the scientist review process. Forest Service research has developed a number of decision-support tools for carbon management and inventory, but these tools lack available staff and resources to maintain the tools and handle training needs or customer support. In addition, the Forest Service needs to better organize its ability to address customer needs by matching expertise with questions that it receives. An integrated approach to carbon sequestration technology transfer involving all branches of the Forest Service would improve the agency's service delivery. Few cases exist at the regional and national scales in which such partnerships have been very fruitful. For example, Forest Service research has partnered with the Forest Service Management Center to add a carbon calculator to the well-used and well-supported FVS (Reinhardt and Crookston 2003). The carbon calculator includes estimates of carbon sequestration in wood products (Smith et al. 2006). In addition, the carbon calculator has been used to estimate fossil fuel consumption and associated carbon costs of silvicultural activities and transportation (Brinker et al. 2002, Markewitz 2006). In another example, the Northern Research Station, Northeastern Area, the Eastern Region, and the Forest Products Laboratory have begun a partnership to address carbon management needs for the Northern United States. To foster additional cooperation across deputy areas, the highest levels of the Forest Service need to examine national needs and available resources.

3.3.3. Enhanced links between research and information transfer to customize resource management support

Global change information needs will not wait for Forest Service research to become more relevant and applicable. The agency therefore must focus much of its carbon cycle-relevant research on gaining knowledge that can be readily transferred to resource managers and policymakers so they can make near-term decisions. For issues regarding carbon, COLE is one such decision tool (Spinney et al. 2005). COLE enables the user to examine forest carbon characteristics of any area of the continental United States, based on FIA and Forest Health Monitoring data that have been enhanced by other ecological data (<http://ncasi.uml.edu/COLE/index.html>).

The Landscape Fire and Resource Management Planning Tools Project (LANDFIRE), is a 5-year, multipartner project that uses remote sensing to produce consistent, compre-

hensive maps and data describing vegetation, wildland fuel, and fire regimes across the United States (Reeves et al. 2006). The project has a training/technology transfer component that is designed to facilitate national- and regional-level strategic planning and reporting of wildland fire-management activities. Although not directly related to carbon, LANDFIRE products can be translated into carbon stocks and likely emissions under various wildfire scenarios for specific locations.

Remote sensing, another important tool that can provide up-to-date data on forest characteristics, can readily be related to carbon-relevant information. Remote sensing also provides critical data for tracking changes in forest carbon stocks over time. One specific project, which Forest Service R&D is co-leading, is the North American Forest Dynamics (NAFD) Project. An important objective of NAFD is to integrate FIA data with satellite data to map and estimate changes in biomass that have occurred nationally over the past 35 years and to transfer this technology to FIA so that the methods can be operationally applied in the future (<http://www.geog.umd.edu/nacp.goward/>). The Forest Service needs other research that can be transferred to managers and policymakers, including foci on risk assessment and reduction, species adaptability, changing treelines, and carbon verification.

3.4. Action Items

Forest Service scientists need to develop tools and models that integrate information for analyzing carbon sequestration associated with forest management practices at various scales. The FVS (<http://www.fs.fed.us/fmssc/fvs/>), a widely used growth projection tool at the stand level, now includes a carbon module that incorporates various site carbon pools and carbon in forest products. We need to add the effects of climate change on tree growth and mortality to this tool set. We also need the capability to estimate carbon emissions and emission offsets when woody biomass is used for various types of energy production. These estimates include emissions offsets from using wood energy and the emissions associated with fuels used in harvesting, handling, hauling, and manufacturing the wood energy product.

The Forest Service needs tools to evaluate carbon sequestration effects of forest management alternatives at landscape and larger scales. The agency needs this information to aid in regional management decisions and to assess the effects of potential future carbon credit trading. A key need for the landscape scale is the sampling of ecosystem carbon stocks and fluxes for the dominant forest conditions. These data identify the spatial distribution of woody biomass on

the landscape, relate carbon stocks to disturbance history, and help determine the value of current and future sequestration. Some of the most important action items for the Forest Service to address include the following:

- Create tools and models that permit analysis of the harvest, handling, and transportation of biomass to compare alternative approaches for these activities and to estimate the costs and quantities of delivered biomass to various locations.
- Create tools and models to optimize plantation management for the production of biomass from stand-points both of economic and of net GHG emissions.
- Provide information and methods for managers to assess the environmental impacts of alternative approaches to biomass production and removal.
- Develop technologies that generate high yields at a competitive cost in conversion of biomass to biofuels.
- Create tools and models to analyze the net carbon balance of forest biomass used for traditional forest products and for energy production.
- Create tools and models that integrate information in the previous five items at the landscape and other larger scales to analyze the net carbon balance of various forest management prescriptions and long-term forest management regimes, while accounting for the carbon aspects of traditional products, biofuels, and direct combustion for energy production and for the energy consumed in forest management and product removal processes.
- Provide tools to estimate the extent of incentives that may be needed to increase biomass use for products or biofuels.

3.4.1. Develop a synthesis of the knowns and unknowns for forest carbon sequestration

Much is known about many facets of storing carbon in forests: how fast trees grow under a given site and climate, how to measure and monitor tree growth and forest carbon stocks on multiple scales, and how much carbon will be lost with deforestation. Many important unknowns must be learned, however, if we are to systematize carbon sequestration in forests. The basis for carbon accounting systems will depend on the timeline of carbon stored in forests (should carbon stored today be worth more than carbon stored later? [Fearnside 2002]), on the permanence of stored carbon and its value if not permanent (Kirschbaum 2006), on factors that contribute to carbon “leakage” and

the means to reduce it, and, on identification of uniform methods and policies for validating carbon storage. In fact, we know little about the economics of sequestration (e.g., Richards and Stokes 2004).

Many basic scientific questions and uncertainties also need answers before economics can be calculated reliably. We cannot yet predict the ability of forests to permanently increase carbon stores in the face of changes in climate that may change species (Bachelet et al. 2001), increase disturbance (Westerling et al. 2006), and change the process of carbon storage itself (Boisvenue and Running 2006). Indeed, currently, we have no way to quantify the tradeoffs between increasing sequestered carbon and the resulting increase in vulnerability to disturbances such as fire, windthrow, insects, and disease, or how to account for carbon storage 'gained' from management or lost through fire. We have yet to document methods for increasing carbon sequestration or for explaining how much carbon can be stored and where, given the self-replacing nature of forests. We do not know whether saturation of the carbon sink in North America will work against forest carbon sequestration (Canadell et al. 2007), what impacts carbon sequestration might have on the health of forest ecosystems (including suitability for wildlife) and on the climate system itself, and how to quantify the tradeoffs between increased aboveground carbon sequestration and water yield.

An assessment of the importance of these issues is being performed within the framework of the Ecological Society of America's Issues in Ecology Program. This process brings together experts on forest carbon storage, policymakers, and managers within and outside the Forest Service to document the specific issues that will be considered, identify writing teams, and produce two documents: (1) a short article for publication in *Issues in Ecology or Frontiers in Ecology and the Environment* that summarizes the issues and findings in a format for a lay audience and (2) a detailed scientific review for *Ecological Applications*.

3.4.2. Develop a set of regional case studies to serve as examples for managers

The Forest Service needs to develop a series of three to five regional case studies highlighting land management practices that could increase carbon sequestration and provide methodology and examples for managers to follow in implementing their own carbon-positive projects. The development of these case studies, which would include NFS and private landowners, would be followed by (1) workshops to help practitioners implement land management changes or (2) the involvement of case study authors in the development of new projects. The case studies would address planting and silvicultural guidelines, calculation of the

carbon credits generated, how to address both adaptation and mitigation, economic effects, how to manage forests to reduce probability of loss from fire, and uncertainty and risk estimates. It will be imperative for stakeholders (e.g., the NFS, private foresters) to involve their personnel in the case studies at all stages of their development. These personnel would then be valuable in their organizations to lead further projects that incorporate global change into forest management activities. Case studies would be published as General Technical Reports, with coordination among the different groups to ensure common formats and methodology. Proposed case studies include the following:

- Reducing carbon losses from hurricane damage by replacing loblolly pine with more hurricane-resistant longleaf pine.
- Planting trees after stand-replacing fires in ponderosa pine. Stand-replacing fires in montane ponderosa pine have created meadows that are expected to persist for centuries. Planting could restore forests, and the carbon credits could offset costs.
- Gaining carbon credits through fuel treatments by reducing future fire losses and using the removed biomass to offset fossil fuels.
- Applying silvicultural practices that minimize respiration losses of stored carbon while maximizing uptake of CO₂.

3.4.3. Infrastructure for carbon management information transfer

An infrastructure for information transfer of carbon management science and operational strategies could be invaluable. Most likely, the best design for such an infrastructure would be a working group of high-level policymakers, on-the-ground practitioners, and scientists. Possible models of a cohesive approach to climate change include the structure used to address invasive species or regional collaborations such as those that the Northern Research Station, the Northeastern Area, Region 9, and the Forest Products Laboratory carry out in the Northeast.

Current personnel levels within the Forest Service are inadequate for developing these structures. The person designated to successfully lead a working group should have such a task defined as a major or full-time responsibility. For example, one of several individuals currently responsible for technology transfer of carbon management could be assigned. Presidential management fellows who are interested in the information transfer of carbon management science and operational strategies are also good candidates.

4. Decision Support and Integrated Modeling Research³



Decision support research seeks to improve the scientific information and the deliberate processes used to integrate science into decisionmaking.

Decisions involving environmental processes and natural resource management are challenging for several reasons (Brewer and Stern 2005). These decisions involve complexity, incomplete and uncertain knowledge, multiscale management, long time horizons, uncertain and conflicting stakeholder values, linkages among separate, but related, decisions, time pressure, and high stakes. Good science is one input to good decisionmaking. But, good decisionmaking also includes the integration of scientific understanding with deliberative processes to ensure that the range of stakeholders—those parties interested in or affected by the decisions—judges the science to be decision relevant and credible. The National Academy of Sciences' recent report (NRC 2009a) recommended that Federal agencies support a program of research in the decision sciences addressed to improving the analytical tools and deliberative processes necessary for good environmental decisionmaking. Research to enhance and improve decision-support tools for natural resource management and policy is clearly a task for Forest Service R&D.

Decision-support tools typically are based on computer models for assessing phenomena such as (1) status of real-time events (e.g., forest fires, flooding); (2) the relationship between environmental conditions and scientific metrics (i.e., waterborne disease vectors and epidemiological data) (CCSP 2009a); (3) the relationship between historical disturbances and vegetation and landscape dynamics; (4) the relationship among wildlife, their habitat use, and management actions; (5) a summarization of local or regional inventory data (e.g., COLE); (6) tradeoffs among

resource objectives (e.g., optimization models such as the spatial analysis model Spectrum); (7) risk analyses; and (8) the analysis of the uses, demand for, and supply of the renewable resources, including price relationship trends and the international context (e.g., RPA assessment analyses). In developing these tools, analysts use data (inventory, monitoring, experimental), concepts of relations among data, and analysis functions to express relationships (spatial, temporal, and process based) among different types of data to merge layers of data, generate model outcomes, and make predictions or forecast (SAP 5.1).

Although models (mathematical, statistical) can help formulate hypotheses for experimental investigation or test hypotheses about theories as described in the previous two sections, they can also be operated to provide information directly applicable to natural resource management. Hence, a third research element focuses on the development of decision-support tools and approaches that integrate the first two research elements of scientific understanding of ecosystem sustainability and carbon sequestration to support policymakers, planners, and land managers as they manage forests, woodlands, and grasslands under climate change. The Forest Service currently uses a wide variety of decision-support tools to support management and policy decisions; several were mentioned in the previous two sections. This research element addresses the need to enhance these current tools and to develop new tools to inform stakeholders about the influence of climate change on future resource management and policy. This research element requires close interaction between scientists and

3. Written by Robert Keane and Linda Joyce.

practitioners—between the scientist who is familiar with the ecological, economic, or social processes and predictive models and the practitioner who is familiar with the outcomes that management needs to produce or directions that policy needs to implement. This research element seeks to improve the scientific information and the deliberate processes used to integrate science into decisionmaking, with the goal of informing practical decisions. Research activities will involve the environmental sciences and the social and economic sciences.

In the evaluation of existing or new tools, the Forest Service is concerned with the underlying assumptions, precision and accuracy of input data, ability of the model to explore complex interactions and feedbacks at multiple spatial and temporal scales, utility of the tool to explore the impact of uncertainty (from input data, assumptions, or scenarios), and the temporal and spatial scale of the model in its application. A significant challenge in analyzing the future effect of climate on ecological or economic processes is the variability, diversity, and uncertainty of potential future climate changes. Decision-support tools must synthesize this volume of information in a manner that can be valuable in management and planning. Standard measures of reliability and error may not be appropriate for climate scenarios in which the likelihood of each scenario is considered to be the same. New approaches exploring the sensitivity of the ecological or economic models to a wide variety of potential futures (e.g., climate, economic) may offer insights into the nature of the ecological or economic responses to critical combinations of climate such as wet-dry cycles and management actions.

4.1. Research Needs

4.1.1. Improve environmental and biotic monitoring to serve the needs of management and policy decisions

Evaluation, analysis, and interpretation of accurate and continuous monitoring of natural resources are key to adaptive management and policy, and, ultimately, to adaptation to and mitigation of climate change. Natural resource monitoring has typically focused on plant and animal responses in isolation of other environmental changes. Triggers for implementing new management decisions may depend upon the changing relationships between climate and plant and animal responses, necessitating a linkage or a coordination across monitoring networks for climate (e.g., NOAA), hydrology (CUHASI, the Consortium of Universities for the Advancement of Hydrologic Science, Inc.), and plants and animals (Forest Service FIA, the USDA Natural Resources Conservation Service, the USGS Phenology Network). Monitoring networks that can sample before, during,

and after major disturbances will be particularly valuable, because disturbances can facilitate significant changes. Coupling changes in climate with changes in ecological responses will require innovative research to analyze and synthesize large data sets with different sampling schemes, temporally and spatially.

Given that novel management practices for adaptation are likely to be implemented at stand and landscape levels, innovative monitoring network designs are needed to validate the effectiveness of these management strategies over time. The design should meet the timing requirement for when information is needed to make management decisions. Different types of data may be appropriate at different spatial and temporal scales, and it may be appropriate to adjust sampling schemes and intervals as additional knowledge is accumulated or as the rate of the changing climate and effects advances.

Many assumptions about climate, ecological responses, and the role of management may no longer be valid under a changing climate. For example, monitoring regeneration will help identify the continued validity of expectations about successional processes and vegetation management outcomes. Monitoring nonnative invasive species will be critical to identify early and proactive actions at key migration points to reduce and block invasions. Monitoring may also need to address where natural genetic adaptation is occurring with species moving into areas outside of their historical ranges. Enhancing the effectiveness of observation networks and current drought monitoring efforts could provide information with which to make management decisions, particularly in response to the impacts of drought on aquatic ecosystems, wildlife, threatened and endangered species, and ecosystem health.

Coordinating monitoring across multiple contiguous ownerships will enhance information available for decisionmaking on species management. Time series of data must be used by land managers from Forest Service EFRs and Research Natural Areas, as well as from currently unavailable individual FIA sample plots (see sections 3.2.1, 3.2.2, 4.2.3, 4.3.3). Data from other long-term monitoring programs (e.g., LTER, NEON) will supplement monitoring done by national forests.

At the much larger scale of country-level activity, the Forest Service has advanced skills in measuring, monitoring, and verifying GHG emissions and sinks for the forestry sector and is, therefore, in a position to provide developing countries with the tools and analysis to strengthen forest carbon management and monitoring. Specifically, the Forest Service needs to establish baseline GHG inventories,

at the national level, using good estimation and accounting practices. This basic requirement facilitates implementation of programs targeted to Reducing Emissions from Deforestation and Degradation (REDD). In addition to quantifying the GHG baseline, the Forest Service has a developing cadre of experts who quantify ecosystem services in a more general sense. This cadre is important because the benefits of REDD will pertain not only to climate but also to other services such as biodiversity and water.

4.1.2. Enhance the capacity to analyze cross-scale resource interactions and management options

Determining the vulnerability of species, ecosystems, and landscapes to climate change will require a careful association with the relevant spatial processes that most influence these ecological entities, their interactions and response to climate and climate-mediated disturbances. In addition, resource management decisions are made at and sensitive to a variety of spatial and temporal scales. It is important that the species, ecosystem, and landscape dynamics being analyzed with decision-support tools actually do respond to climate at the appropriate scale(s) (Turner et al. 2001).

Perhaps the least simulated interactions in most models of impacts are the complex feedbacks among landscape structure (i.e., pattern), the underlying ecological processes, material exchanges with the atmosphere, and the constraint of these interactions by climate dynamics across multiple time and space scales. Many disturbance initiation and spread processes are dependent on landscape-level patch conditions rather than stand-level characteristics. For example, mountain pine beetle population levels can reach epidemic levels when the landscape is composed of only a few pine species. Wildfires may become large because the landscape has dense, contagious fuels and contains few large, recently burned patches (Minnich and Chou 1997). Many



fine-scale (tree and stand) processes depend on landscape pattern characteristics, and we are only now realizing the importance of spatial interactions at coarser scales (Turner et al. 2001). Interactions of climate, vegetation, and disturbance often occur across various scales of time and space, yet these cross-scale interactions are rarely explicitly simulated in landscape models (Peters et al. 2006). The effect of long-term drought on fire ignition and spread is an example of a cross-scale interaction that has been extensively studied (Allen 2007) but is difficult to implement in a fine-scale landscape model or a coarse-scale continental model.

Also of importance in the integration of scales within models is the creative use of remotely sensed data products as inputs, parameters, or tests of model results. Merging multiscaled remote-sensing imagery, such as AVHRR (Advanced Very High Resolution Radiometer), MODIS (Moderate Resolution Imaging Spectroradiometer), ETM (Enhanced Thematic Mapper), and LiDAR (Light Detection and Ranging), into simulation platform models will allow insightful explorations into scaling processes and their effects and responses to climate change and ecosystems.

4.1.3. Conduct research to identify nonlinear behaviors and response thresholds in ecological systems as affected by climate change, and the interaction of climate change with current stressors, resource management, and social and economic systems

Few empirical studies have described the nature of response thresholds in ecosystems that enable management to anticipate such nonlinear behavior (SAP 4.2). Perhaps the most important reason to include complex abiotic, physical, and ecological interactions in models used to investigate climate change is to determine important thresholds, tipping points, and phase transitions of landscapes under changing climates so that management can change plans accordingly (Neilson et al. 2005). Many nonlinear responses caused by ecosystem interactions convert or elevate ecosystems to alternative phase states such as the grasslands now covering sites of massive tree mortality in arid woodlands as a response to drought-enhanced beetle infestations (Breshears et al. 2005). Few models have the capacity to identify and forecast these behaviors. Potential opportunities exist to

Monitoring networks that can sample before, during, and after major disturbances will be particularly valuable.


draw from fields such as engineering and epidemiology to improve the quantitative expression of these behaviors (SAP 4.2).

Although available statistical tools can be more widely applied than they are currently, new tools will be needed to understand, interpret, and compare nonlinear behaviors. A new statistical paradigm may be needed to analyze simulated future trends because the assumptions of parametric statistics may no longer be met in rapidly changing dynamic ecosystems, especially when the ecosystem responses are autocorrelated in space and time. Time series, nonparametric statistics, Bayesian methods, stochastic processes, and other advances in statistics may be possible alternatives (Berryman 1992, Jassby and Thomas 1990). The risk and hazard of large disturbance events must be evaluated using novel approaches that account for nonlinear behavior and thresholds. Many analyses will cross multiple spatial scales, requiring novel spatial and nonspatial statistics for objective comparisons across simulation alternatives or scenarios. Novel research approaches will also be needed to understand climate change effects; observational or empirical studies may not provide enough information to fully predict species shifts and nonlinear behaviors, thereby requiring modeling to be integrated with field studies and phenomenological understandings to expand the range of observational conclusions. In short, future research may need to measure the underlying causal mechanisms along with the observed responses.


4.1.4. In partnership with land managers, identify and develop decision-support tools that facilitate management decisions under a changing climate

Resource managers have identified the need for tools to implement climate change strategies in the specific forests being managed (e.g., local future climate scenarios, vegetation projection models, vulnerabilities and risk predictions, implementation of land and resource management plans, section 1.3). The spread of new technology is closely linked to the knowledge networks with each resource field (CCSP 2009b); hence, close partnership with land managers is needed to identify the specific tools that are needed or the modifications of existing tools that could support decisions under climate change.

In addition to providing new tools, all Forest Service global change modeling efforts should aim to provide stakehold-



Close partnership with land managers is needed to identify the specific tools or the modifications of existing tools that could support decisions under climate change.



ers with the information they need to manage natural resources. This result could be a computer program complete with user-friendly interfaces and an easily understood input structure and synthesized output summaries. It could be an alternate form of a publication (e.g., best practices manuals, Web instructions) or a database that synthesizes simulation results into readily available information. It could even be a theoretical construct to prove or disprove scientific hypotheses about the functioning of the ecosystems or populations that are to be managed. Managers need products that incorporate scientific understandings into simulation results in a structure and format useful to their needs. The Fire Effects Information System is an excellent example of organizing scientific information into an expert system that will summarize research results in formats land managers require.

The program structure, modeling approach, and program design will often govern the value of the model for diverse applications in management. For example, a poorly designed program can require execution times that are so long that management simulations are intractable, whereas multithreaded well-designed programs have the potential to simulate large areas over long time spans at fine resolutions in a timespan useful to managers. Well-designed programs, such as those using object-oriented approaches, are also more easily modified as additional research information and data become available for managers to have the most up-to-date information in their simulations. Input requirements for models should include data that are easily obtained from standard, readily available databases. Future cooperative efforts in modeling will require programming architectures that facilitate code sharing across agencies and universities (an example is the use of JAVA in USDA

Agricultural Research Service to facilitate multiplatform implementation and standardized model development).

4.1.5. Assess tradeoffs between maximizing carbon sequestration in living biomass and other land management objectives

The Forest Service management goals include the entire suite of ecosystem goods and services derived from forests and grasslands described by the Millenium Ecosystem Assessment (2005), including provisioning (i.e., timber, fuel, food, other nonwood products, fresh water, and genetic resources), regulating services (i.e., regulating air quality, carbon, climate, water, erosion, water purification and waste treatment, diseases, pests, and natural hazards), cultural amenities (i.e., cultural diversity, spiritual/religious values, knowledge systems, educational values, inspiration, aesthetic values, social relations, sense of place, cultural heritage values, recreation and ecotourism), and supporting services (i.e., primary production, soil formation, pollination, nutrient cycling, water cycling). Each of these goods and services will be affected by changing climate, but differently from one locale to another. These ongoing effects will require the balance of products currently provided by individual forests to be reassessed and adjusted frequently, particularly to include carbon sequestration goals that Congress may require. Current assessment approaches may be inadequate for this balancing task and will need to be modified to include the increasing uncertainty induced by climate changes.

4.1.6. Develop decision-support tools to examine tradeoffs and uncertainties in resource management under a changing climate


Potential responses to climate change are likely in populations, species, and community abundances, structures, and ranges, including potential species extirpations and extinc-

tions. An environment of limited resources, staffing, and time may need to evaluate tradeoffs among the management of different ecosystem resources. Evaluation of these tradeoffs may require additional data and understanding about species, communities, ecosystems, landscapes, and disturbances. For example, an analysis of the tradeoffs in air quality between the use of prescribed fire and wild-land fire is limited by information on emissions data and predicted fire severity. Similarly, it is likely that decisions about whether to manage for species whose habitat is disappearing (e.g., alpine species) and for species whose habitat is diminishing but treatable will be limited by available information and understanding. A careful examination of current prioritization methods would begin to identify opportunities and barriers to the analysis of tradeoffs and development of priorities under a changing climate.

Developing an adaptation and mitigation strategy will involve planning for and developing a suite of management practices to achieve multiple goals, along with evaluating different types of uncertainty (e.g., environmental conditions, models, data, resources, planning horizons, and public support), to support decisions about the most suitable adaptations to implement. Taken in isolation, mitigation or adaptation practices can have negative effects on other ecosystem services. For example, adaptation strategies when developed alone can result in suboptimal carbon sequestration objectives. Both strategies must be integrated to minimize potential negative effects and to take advantage of possible positive effects from climate change. Field experiments quantifying the opportunities and effects of mitigation and adaptation management will be necessary to support decision-support models exploring the appropriate management to meet the goals of both adaptation and mitigation.

Exploration of tradeoffs will vary by spatial scale. At the national level, a need exists to provide integrated strategic evaluation of national policies and management actions (environmental/economic) (see section 3.1.8). Adaptation strategies tend to focus on local levels whereas mitigation strategies tend to have a broader geographic focus. Integrated assessments, such as the RPA assessment, can be used to evaluate strategic options for achieving a suite of national goals (adaptation, mitigation) and to provide long-range projections of resource conditions for planning and management.

Uncertainties add a new dimension to the tradeoff criteria as hedging options begin to be



As a flexible Web-based tool for forest carbon analysis, the Carbon On Line Estimator (COLE) can be used to generate forest carbon inventory estimates for any area of the continental United States.
<http://ncasi.uml.edu/COLE/>

considered. For example, consider the problem of selecting stock for replanting a site in the presence of climate change. A large variety of future climate scenarios might lead us to an adaptive alternative where we diversify our planting stock to hedge against the possibility of complete regeneration failure. Alternatively, our interest in sequestering carbon as a mitigation strategy might lead us to select only fast-growing stock. Ultimately, we are faced with a tradeoff between adaptation and mitigation and must choose the degree to which we will hedge against regeneration failure. Numerous methods exist for managing in the presence of risk and uncertainty, but much research remains in how to embody these methods in Forest Service and other natural resource decision-support tools. Finding feasible management solutions and managing for reliable outcomes will require greater investment in management science as we recognize greater uncertainties in the ecosystems we manage and in the social, economic, and political systems within which managers work.

4.1.7. Provide integrated strategic evaluation of local, regional, and national policies and management actions (environmental/economic)

The GAO report on climate change and natural resource management on Federal lands (GAO 2007) also points to a critical need for scientific tools that can help integrate the big picture (global trends and national policies) into local management decisions and priorities. The GAO report states, “resource managers have limited guidance about whether or how to address climate change and, therefore, are uncertain about what actions, if any, they should take. In general, resource managers lack specific guidance for incorporating climate change into their management actions and planning efforts” (GAO 2007, p. 2).

Forest lands can mitigate carbon additions to the atmosphere by carbon sequestration in forests and forest products and by displacing fossil fuels with wood products and wood energy and wood-based biofuels. The need for integrated scientific research to aid in guiding forest management and product use includes needs for models of carbon markets, biomass markets, and bioenergy markets. Such models can help to identify competitive systems that can be adopted locally to produce and harvest biomass and to convert biomass to bioenergy and biofuels. They also can permit us to identify limitations and capabilities of alternate management and policy tools.

Integrated assessments allow policymakers to evaluate tradeoffs and deal with the challenges of balancing multiple management goals. Broad assessments, such as the RPA assessment, may be the best way to synthesize knowledge

about climate change, market change, forest ecological goals, and forest management alternatives. The RPA assessment models are used to project national and regional trends in forest resources, resource markets, and forest conditions and can be used to analyze the potential for increased carbon sequestration in forests and wood products. The RPA assessment (e.g., Smith et al. 2009) provides a readily available scientific framework to analyze alternatives to achieve proposed national goals and describes how to translate those goals to actions at the regional and local levels. By applying scientific resource analysis at the national and regional levels, the RPA models can be used to do the following:

- Evaluate strategic options for achieving the national goals.
- Provide long-range projections of resource implications and interactions associated with resource management strategies, taking into account projected nationwide and regional markets for biomass and bioenergy, carbon markets (e.g., Karjalainen et al. 2002), and implications of improvements in technology for biomass production, carbon sequestration, bioenergy, and biofuels.
- Aid managers of both public and private forest lands in determining local management priorities.

A key need exists for integrated scientific research focused on themes that account for the prospective international and national development of biofuels markets. The need extends to the response of markets for wood and agricultural biomass and markets for traditional timber and agricultural products and of prospective markets to certify and trade carbon emission offset credits. These market requirements must be linked to national goals to mitigate carbon emissions by changing sequestration/emissions associated with forests and wood products. Forest management can reduce the extent and severity of wildfire, adapt to changing climate conditions, and attain other ecological outcomes required by carbon markets.

General integration research objectives include the need to determine the technological, economic, and social implications of the Forest Service carbon sequestration and wood-based biofuels goals. This need requires, in turn, that we evaluate how best to integrate carbon sequestration and carbon offsets into forest management. We must estimate the cost of harvesting small-diameter woody biomass for biofuels, identify policy-responsive biomass energy market models for long-range forecasting, identify competitive forest management systems to produce biomass for energy,

and, using existing technology, identify near-term solutions for biomass energy.

To meet these integrated research objectives, specific improvements in RPA models could include modeling global and national development of wood-based biofuels and bioenergy, modeling biomass supply interactions between the agriculture and forest sectors, and modeling forest carbon markets and future forest carbon market trends. The models must include projections of biomass cut, fire and restoration for NFS and other public lands, estimates of the effect of alternate scenarios on carbon sequestration and carbon offsets, and evaluation of alternate ways to meet national carbon sequestration and biofuel goals, including the possible need for incentives. Identifying possible local management priorities to meet national carbon sequestration and biofuels goals must precede model applications.

4.1.8. Create effective processes to integrate the information from analytical tools into the decisionmaking process

Most environmental decisions involve a broad range of participants with varying roles in those decisions. A recent National Academy of Sciences report (NRC 2009b) highlighted a number of questions relevant to integrating scientific information into environmental decisions: What are good indicators for key attributes of success for analytic-deliberative processes such as decision quality, legitimacy, and improved capacity for future decisionmaking? How are these outcomes affected by the ways the processes are organized, the ways they incorporate technical information, and the environmental, social, organization, and legal context of the decision at hand? How can decision processes be organized to ensure that all sources of relevant information, including the local knowledge claims of nonscientists, are gathered and appropriately considered? How can these processes be organized to reach closure, given the challenges of diverse participants and perspectives? How can decision-analytic techniques be used to the best advantage in these decision processes? How can technical analyses be made transparent to decision participants who lack technical training? These questions will not be easily answered, but their answers will be critical to integrating science into decisionmaking.

4.2. Cooperative Activities

4.2.1. Build communications structure

Although considerable collaboration and communication already exist between modelers and among scientists and modelers in the Forest Service research and management communities, more can be done to facilitate and improve

collaborative studies. Low resources may not permit a formal structure at this time, but an informal structure would surely help modelers interact with other modelers, climatologists, ecologists, hydrologists, natural resource planners and managers, and other specialists. This structure could be a Web-based communications system where the latest in modeling science would be posted and an electronic bulletin board would be provided for real-time discussion with these other constituencies. Other ideas include (1) a biennial conference, (2) a committee to disperse the latest modeling findings and provide direction for future Forest Service modeling work, (3) a newsletter that is emailed to modelers and model users, with the list organized by the Forest Service Global Change Program (FSGCRP), and (4) a set of workshops and symposia held separately or at other conferences.

This communication structure would be designed to do the following:

- Inform Forest Service modelers and collaborators on the latest efforts and projects.
- Facilitate cooperation between modelers to improve and expand existing systems.
- Provide direction and guidance to modelers on
 - Model inputs and outputs needed by management and stakeholders
 - Model design and structure to facilitate use by others
 - Latest science to guide construction of new models and model components.

A possible example of this structure can be found on the FRAMES Web site (<http://www.nbii.frames.gov>) where managers and researchers in the fire community interface to share problems, solutions, and assistance.

4.2.2. Survey modelers

The first step to coordinating a national Forest Service strategy for modeling climate change effects is to inventory current modelers and modeling projects in the global change field. This survey could be as simple as asking modelers to submit publications, study plans, or one-paragraph abstracts for all their projects via email, or as extensive as providing a Web-based framework for entering desired data. It is important that this survey not only inventory specific projects that are in progress or completed, but also the skills, interests, collaborations, and resources (e.g., computers, staff, and disk storage) of the modelers. The survey will allow the FSGCRP the ability to describe Forest Service modeling skills and expertise and target special tasks to

specific groups of modelers. Moreover, the survey will provide information to modelers so that they can communicate, collaborate, and consult with other modelers on their current studies and rectify potential problems.

4.2.3. Coordinate data

The collection, consolidation, and collation of data for modeling are quickly becoming the most important challenges for developing comprehensive, empirical, and mechanistic simulations of climate change effects. Complex simulations are only possible and realistic if field data are available for creating, initializing, parameterizing, and validating the models. As models are ported across large geographic areas and to new ecosystems, the Forest Service has a critical need for extensive spatial databases with standardized formats. For example, the databases of ecophysiological parameters by Hessel et al. (2004) and White et al. (2000) have greatly increased the potential for parameter standardization and have decreased the time modelers spend on parameterization. Field data useful in simulation modeling should be stored in standardized databases, such as Natural Resource Information System: Field Sampled Vegetation (NRIS FSveg) and Fire Effects Monitoring and Inventory Protocol (FIREMON) (Lutes et al. 2006), and stored on Web sites so that they are easily accessible for complex modeling tasks. Monitoring and inventory methods, such as those used in FIREMON, NRIS FSveg, and Terra, should be modified to record ecosystem characteristics that are relevant for assessing climate change effects but are not yet included.

Other types of spatial and nonspatial data that the Forest Service needs to consolidate into standardized systems for modeling include the following:

- **Topography.** A nationwide digital elevation model (DEM) must be maintained at multiple resolutions to ensure modeling efforts are consistent. The National Elevation Dataset is an excellent example of a 30-meter DEM. (<http://seamless.usgs.gov/index.php>).
- **Climate.** Nationwide fine-scale (e.g., 1 km resolution) maps of climate variables, measured in the past, and projected into the future by standardized methods applied to global climate model ensembles, are critical to predictive modeling of future conditions of vegetation and ecosystem services (see: <http://seamless.usgs.gov/index.php>).
- **Biomass.** Periodic maps of aboveground biomass are necessary for tracking changes related to natural and human-induced disturbances and for providing baseline conditions for linking to integrated carbon

and climate models. These maps should be related to disturbance monitoring.

- **Soils.** Comprehensive soils data across large regions are becoming invaluable to many modeling efforts, but current State Soil Geographic (STATSGO) database products may not contain the detail required for most modeling projects. More comprehensive soils data layers are necessary to fully simulate the interactions between ecosystems and soils.
- **Ownership.** A national standardized ownership map is a critical need for model simulations of economic and social issues. This need includes delineation of the wildland-urban interface, towns, and State lands.
- **Fuels.** Comprehensive descriptions of surface and canopy fuels are essential for describing fire hazard, fire occurrence, and fire severity; carbon pools; and wildlife habitat. Comprehensive maps, such as those produced by LANDFIRE (Keane et al. 2007), along with inventory and monitoring databases, are critical.
- **Human populations.** Finer resolution data are necessary for describing the distribution of people across landscapes.
- **Disturbance atlases.** Comprehensive data layers describing recent and historical disturbance events are critical for evaluating climate interactions with disturbance at multiple scales. An example is the National Burn Severity Mapping project that maps fire severity for all U.S. fires larger than 500 acres.

The Forest Service FIA programs have the most complete and comprehensive monitoring database in the world, and these data are used in many research and management projects, yet many modelers find it difficult to use this extensive data set in the spatial domain. Moreover, the FIA could collect many types of important data at minimal cost to improve modeling and climate change efforts. Several useful changes concerning the use of FIA in climate change research include the following:

- Continue extending security clearances to other Forest Service scientists and cooperators to use FIA plot location data and encrypt location data sets to permit relating FIA data locations to other environmental data at those sites, while maintaining location integrity.
- Allow the sampling and measurement of additional ecosystem characteristics as modeling needs evolve. For example, take tissue samples for deltaC13,

sample fuel loadings, describe canopy cover and structure, measure crown characteristics to characterize canopy fuels, and associate sample points with climate data.

- Create a sampling system that adequately measures rare ecosystems (e.g., riparian woodlands, pocosin bogs, and upper subalpine communities) and rare events (e.g., the rapid decline of rare species, or changes in the borders of ecosystem types).
- Revise policy to increase cooperative efforts with scientific organizations and institutions to sample on FIA plots to obtain estimates of ecosystem characteristics that are important to them.

Moreover, the Forest Service collects extensive data each year for other inventory, monitoring, and special emphasis projects and a significant portion of the data remain difficult to obtain and use because of nonstandardized formats and local storage issues, requiring research scientists to learn new data protocols and standards each time a new database is accessed. These data and their metadata need to be made available to the climate change community at large to facilitate future work in the detection, monitoring, and modeling of climate change effects. The Forest Service research community could also help by publishing databases on readily accessible Web sites such as FRAMES (<http://www.nbii.frames.gov>).

Perhaps the most critical data for exploring climate change is an expression of the climate itself across large regions and long-time scales. Some modeling efforts require coarse representations of climate such as monthly temperature averages across 10 km pixels (Iverson and Prasad 1998), or in the climate surfaces used by Rehfeldt (2006), whereas many mechanistic modeling projects require fine-scale daily estimates of temperature, humidity, precipitation, wind, and radiation at 1 km resolution or less in mountainous ar-

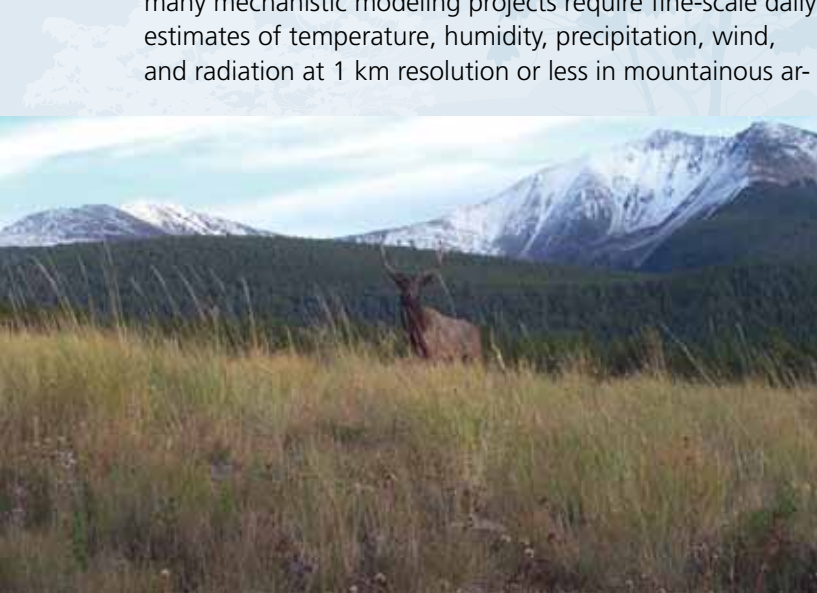
reas (Thornton et al. 1997). What is needed is a downscaled climate database that contains comprehensive weather data for a variety of future scenarios at multiple resolutions of both time and space (e.g., Daly 1998, Strandman et al. 1993). Next, climate databases need to be developed that implement these scenarios in space. Many investigators believe that downscaled output from General Circulation Models of the atmosphere contains so much uncertainty that it is of limited use for investigating ecosystem response to climate. Others believe that the mechanisms of climate processes embedded in these models make their projections more reliable, even if uncertain. An alternative would be to develop a range of climate change and climate variability weather scenarios designed to detect major thresholds of ecosystem response rather than allowing the General Circulation Models to dictate the climate domain, thereby missing important tipping points.

4.2.4. Compare models

Some of the most interesting work in modeling over the last 10 years has involved comparative modeling studies in which a suite of similar models are applied to the same landscape and input requirements are standardized across all models so results can be compared for relative differences. These “ensemble” modeling exercises, such as the Vegetation/Ecosystem Modelling and Analysis Project, have been highly successful and have yielded some insightful results (Cary et al. 2006, Cramer et al. 2001, Schimel et al. 2000). Each model emphasizes different process mechanisms and reduces other mechanisms to assumptions, depending on the modeler’s concepts and hypotheses. The general concept of using multiple models is that more of these “educated guesses” are better than one when predicting the future of a highly complex and uncertain system such as responses to global climate changes, themselves containing considerable uncertainty (i.e., the wisdom of crowds according to Surowiecki 2004). The advantages of comparison studies are numerous. Comparison studies can:

- Assess the strengths and weakness of each model. This assessment can be done by ecosystem and geographic area, which can then lead to an evaluation of where each model is most reliable and what individual models should model.

The RPA Assessment reports on the status and trends of the Nation’s renewable resources on all forest and rangelands, as required by the Forest and Rangeland Renewable Resources Planning Act of 1974. Since 1990, the effects of climate change on forest resources have been an additional focus of assessment research.



- Provide an assessment of uncertainty. For example, if each model predicts a different outcome, then uncertainty is high. But if all models agree, then uncertainty may be lower, or all of the models may be similarly wrong.
- Eliminate the dependence on one model or one style of modeling. Agencies avoid the problem of putting all their “eggs in one basket” by making a decision using results from several models. Models are a reflection of the modelers and their knowledge of the system being modeled, so it is better to use more models to reduce the influence of personal bias and knowledge gaps in model architecture. Yet, this approach should not eliminate the need to evaluate whether any one modeling type or specific model might be most appropriate for a given purpose, space, and time scale.
- Foster collaboration and cooperation among modelers. Comparative exercises allow modelers to critically evaluate models under novel situations resulting in improvements in existing models. Comparing models under a structured simulation experiment can yield new knowledge that will be helpful in understanding climate change effects (Cary et al. 2006). Anomalous (unexpected) results, derived from comparisons among models and between models and the observations they simulate, are most valuable for understanding which phenomena models do not simulate correctly.

Natural resource agencies should pool expertise, knowledge, data, and resources to more effectively conduct research and deliver the science.
<http://www.fs.fed.us/ccrc/>

The FSGCRP should encourage and support comparative modeling efforts and initiate communication between modelers to ensure this activity is accomplished. A Web-based data repository for the simulation landscape, initial conditions, and available parameters should be developed to deliver the input data modelers need to run the models.

4.2.5. Identify objectives

The FSGCRP must articulate a set of objectives for future modeling work that clearly directs the construction, testing, and implementation of complex models to science and management applications. A clear objective will aid future modeling efforts and provide the context for managers to interpret modeling results. For example, the FSGCRP could support the development of a single modeling platform to simulate climate change effects for all management

decisionmaking. This platform could integrate the best modeling technologies across the wide range of models currently available into one system, and managers could use this system to simulate climate change effects. One disadvantage of this approach is that the model may become so complex that its usefulness to management will become compromised. Another is that managers experienced with one model will have to learn yet another, probably more complex, model. A third is that new ecological situations (“surprises”) will arise that are not covered by the model. Yet, a single modeling platform would relieve the modelers of the tedious and expensive task of modifying their models for management application and allow them to concentrate on developing new methods and models for simulating ecosystem processes.

A similar modeling philosophy would support a pool of Forest Service modelers, along with help from other agencies, universities, and NGOs, to build a single modeling system for predicting climate change effects across large landscapes taking a mechanistic, biophysical approach (i.e., a “mission to mars” or “Manhattan Project” tactic). Most modelers, however, appear to prefer independent development of separate modeling systems, in part to encourage the advancement of new ideas and techniques.

Another approach would focus on a defined set of nested and linked models, beginning with very fine scales of space and time to manage forest stands and rangelands (e.g., Busing et al. 2007), nested within regional models, either or both of which use downscaled climate model output and regional land use forces (e.g., Neilson et al. 2005), nested yet again within a global Integrated Assessment Model (e.g., Alcamo et al. 1998, Bouwman et al. 2006), which incorporates the international processes and forces

defining the global trade economics and related national policies that affect, and may affect in the future, national and regional forest management decisions.

4.3. Science Delivery

4.3.1. Identify user needs

The first critical step in delivering science involves identifying exactly what information stakeholders need if we are to understand the problem and decide on a solution. Clearly the most pressing need most managers have is the ability to integrate current information and models on climate change into management planning and analysis. A more extensive survey of users' needs is greatly needed, however, so the Global Change Research Program can respond to managers' requests. A Web survey may be an appropriate tool to record land managers' wishes and desires, but this survey would only be a short-term solution. Scientists must become involved in a continuing two-way dialog with users to identify potential future issues that managers may encounter. The long-term solution to a comprehensive science delivery plan is to integrate current managers' needs with science-based anticipated issues to form a strategy for dealing with public land management in the face of changing landscapes (see section 9.3).

Another step toward identifying users' needs is to conduct an intensive review of our users and their jobs to provide the context for summarizing and conducting modeling efforts. This inventory of stakeholders would describe their characteristics so that simulation results can be synthesized to the appropriate level of detail and depth.

4.3.2. Modify existing and develop new delivery systems

Currently, managers have no means available to integrate climate change research findings into management activities, such as the National Environmental Policy Act analysis and forest planning. An urgent need exists for science delivery conduits to funnel current knowledge into a format that managers can use. For example, the most urgent questions include the following: "What trees do I plant on this site?" "Should I treat the fuels in this stand and, if so, to what extent?" "Is the concept of historical range and variation still viable?" Answers to these questions will be produced by models that calculate seed source matches with spatial distributions of future climate variables, predicted growth patterns under increasing climate stresses, and projection of differences between historical ranges and future ranges of species and vegetation structure.

Better methods are needed to synthesize simulation results to stakeholders and the public. In collaboration with the

Forest Service communications team, modelers need to develop the vehicles to transform model output into general information statements. Some traditional vehicles that may be useful include media exposure, brochures, Web site pages, and news releases. New ideas include interactive video and Web sites that display model results and speak to their implications. The following list summarizes a set of potential science delivery vehicles useful to transfer information to the ultimate users:

- Centers of excellence. These centers could locate teams of Geographic Information System/modeling/climate change specialists around the country to provide managers with the resources and information they need to successfully complete a project. Many of these centers already are established and are extremely successful in the Forest Service, such as the Enterprise Units (<http://www.fs.fed.us/enterprise>) and the Fire Modeling Institute at the Missoula Fire Sciences Lab in Montana (<http://www.fs.fed.us/fmi>).
- User-friendly models. Computer models, both qualitative and quantitative, could be developed to simulate, synthesize, and summarize climate change effects into desirable formats that are easy to use, easy to parameterize, and easy to initialize.
- Training courses. A set of training courses could be developed to teach managers (1) how to integrate climate change into common analyses and (2) how to run the models. Forest Service Fire Aviation Management has an excellent example for this goal in its Training, Development, and Leadership courses taught locally, regionally, and nationally. In addition, altering current training courses, such as Cost-effective & Environmentally Friendly Energy Systems (CEFES) and Continuing Education in Ecosystem Management, to include modules on climate change, is essential for linking to other resource issues and management knowledge. The Forest Health Protection program has an excellent series of training courses for land management into which climate change impact modeling and output considerations could be inserted.
- Certification programs. A set of requirements could be developed so that a manager or researcher could be certified to deal with climate change issues. These requirements would include training courses, modeling exercises, and practica and could be patterned after the certification courses (CEFES) developed for silviculturalists.

- Conferences and workshops. Although the publication and dissemination of research results is essential in the climate-warmed future, it is important that those who use this research understand it. Along with helping users by presenting research at symposia and conferences, the Forest Service could hold training workshops during conferences to help users digest current research findings. Independent workshops that train resource professionals are also important.
- Extension scientists. NFS and State and Private Forestry, perhaps jointly with Forest Service R&D, should hire scientists and technicians specifically to perform the science delivery to managers so that the science will be used correctly. These people will relieve research scientists of those tasks, which rarely are included among their performance objectives, so they can concentrate on the research.
- Informational press releases. Scientifically credible news releases are critical to keep the public informed on emerging issues. Those employees who are part of the Forest Service's communication structure must be sufficiently schooled in climate change issues so they can put any new research results into the proper context for public interpretation. They should include measures of uncertainty, along with any caveats, with these informational tidbits.

A large gap has always existed between the researchers' production of science and the delivery of that science for management applications. The narrowing of that gap will require additional funding and resources, especially when describing climate change effects. Future science delivery vehicles will need to synthesize science information into multiple scales of detail depending on the user audience and the objective of the request for information. Moreover, managers have the responsibility to succinctly describe their objectives when using climate change research so that results will be used appropriately and the bounds of data extrapolation are not exceeded due to the limitations of the model or input data.

4.4. Action Items

4.4.1. Modify existing models

The easiest and quickest way to integrate climate change effects into current management is to modify the computer programs currently in use to integrate climate change effects into the architecture. Examples include current efforts that are underway to modify the FVS to incorporate climate variation via the construction of a new variant (ESSA 2007)

called Climate-FVS and the implementation of new vegetation development pathways in SIMPPLLE (Simulating Patterns and Processes at Landscape Level Scale) to account for changes in climate (Chew et al. 2003). Some management models, such as the fire behavior models of Behave and FARSITE (Andrews 1986, Finney 1998), are already climate driven; therefore, because weather variables are input in their internal structure, they are already able to simulate future conditions. All models, however, need an explicit representation of future climate to use as input to simulate climate change effects. This need implies that comprehensive climate scenarios need to be developed for use in both research and management.

4.4.2. Apply climate-sensitive models to management issues

Many mechanistic ecological models already can simulate the effects of climate on ecosystem processes and elements. These models, however, lack a user interface and are so complex that managers would find them difficult to apply to common management issues. We need a focused effort to produce user-friendly model interfaces, or else we need to apply these complex models to important management concerns to yield information and data that stakeholders can use in their decisionmaking process. These efforts involve providing model output in novel forms such as interactive maps (e.g., Google Earth), Web-based delivery systems (COLE), and expert systems.

4.4.3. Build data libraries

As mentioned previously, a comprehensive effort to consolidate existing data is essential for future climate work. Many legacy long-term studies by the Forest Service will be critical for quickly evaluating and describing climate change effects. Examples include continuing the remeasurement of provenance experiment studies and common garden studies. Historical stand examinations, range assessments, and photography will also be important for monitoring climate change effects across large landscapes. Repeat historical photography (Gruell 1983, Turner et al., 2003) will be important to display landscape effects to the public and to modelers trying to conceptualize the phenomena they are abstracting as models. A General Circulation Model downscaled climate data library, along with a collation of ecophysiological parameters, is critical for future modeling efforts.

4.4.4. Compare existing models

Comparative studies are an excellent approach for (1) prioritizing the development of future management models, (2) qualitatively describing uncertainty, (3) developing efficient

simulation architectures, and (4) fostering collaboration between modelers for future modeling opportunities. These comparisons can be done today with little effort and minor model development.

4.4.5. Collaborate and coordinate across agencies

The Forest Service does not have the expertise, resources, and time to form a completely comprehensive program investigating climate change effects on the Nation's public lands. The agency's continuing loss of scientists, coupled with budgeting barriers to acquiring the necessary computer equipment and field data, make it impossible to consistently cover all important resource issues involved in exploring climate change effects. Instead, the effort must depend on other Federal agencies for a significant portion of the information needed. For example, the downscaling of climate data from ensemble General Circulation Model runs is a time-consuming task for the few Forest Service research personnel capable of producing credible results, yet NOAA Regional Integrated Sciences and Assessments program, regional consortia, and individuals are already

constructing these climate scenarios. Similarly, climate integration into the vegetation model FVS by Forest Service will be of great value to Bureau of Land Management resource managers.

Therefore, a coordinated effort should be made across the natural resource agencies to pool expertise, knowledge, data, and resources to more effectively conduct research and deliver the science. This effort would involve novel approaches to working together across agencies, such as multiagency memoranda of understanding, university involvement through CESUs (Cooperative Ecosystem Studies Units, National Park Service) collaboration through cooperative publication, and the lowering of administrative barriers to equipment procurement. Research funding programs that cross all Government agencies, such as the Joint Fire Science Program and the National Aeronautics and Space Administration, need to include climate change in their requests for proposals.

The foregoing discussion of decision-support research is summarized in table 4.1.

Table 4.1. The effect of important issues in the focus areas across all four subject areas of the decision-support element.

Important issues	Research needs	Corporate	Science delivery	Action items
Build data libraries	Publish research data on Web site	Make Forest Service data available for modeling efforts	Create extensive multiscale climate database	Modify FIA requirements to facilitate modeling requirements
Compare models	Identify important factors to include in simulation	Foster collaborative modeling efforts	Describe level of uncertainty for managers	Compare ensemble of models
Modify existing models	Add algorithms that include disturbance interactions, spatial influences, and climate feedbacks	Inventory current models to determine if they need to be modified	Quickly create management models that include climate change effects	Pick a common model and modify for managers
Coordinate and collaborate	Create teams of modelers to more effectively represent climate-ecosystem interactions	Eliminate current administrative barriers to effective collaborative studies	Use other agencies and institutions to perform the tasks that the Forest Service does not do well.	Identify scientists, managers, and institutions that are available for collaboration
Apply climate-sensitive models to management	Improve climate-sensitive models to answer management questions	Develop training, centers of excellence, and extension scientists who can apply these models	Develop user-friendly GUI interfaces to current climate-sensitive models	Synthesize results from climate-sensitive models into expert system

GUI = graphical user interface.

5. Infrastructure Needs⁴

Implementing this global change research strategy will require maintaining basic research capacity and strategically addressing new research needs.



The research support required to generate the science and applications previously described is best considered within each research component. Certain programmatic, infrastructure, and personnel needs, however, sustain all research components and require a coordinated national effort within the Forest Service. These include adequate staffing; access to new technology, which increases the efficiency of field research and monitoring; shared data and technology; enhanced computing facilities; and innovative methods to transfer science to field resource managers.

Capacity within Forest Service and university programs regarding forestry research is at risk. Forest Service R&D today has only about one-half of the research personnel of a decade ago, yet the unmet needs for global change research described above suggest the need for the opposite trend: perhaps twice the scientific personnel as a decade ago. Although that level of staffing may not be feasible, it is critical that a sizeable increase in research personnel be sought in the next few years. Already mentioned is the need to strengthen the Forest Service R&D workforce to specifically recruit and retain researchers trained in the traditional disciplines (e.g., silviculture) and critical emerging fields of forestry and ecological science. These new fields include (1) using molecular genetics, (2) managing responses of ecosystems in order to increase carbon sequestration, (3) determining the changes in ecosystems under the chang-

ing climate, and (4) exploring of the social and economic effects of climate change on natural resources and the social and economic systems in which they exist. The Forest Service might seek to develop joint programs with universities to expand expertise in these new areas and to emphasize a broad, integrative, and interdisciplinary programmatic approach to curricula at the graduate level.

The Forest Service should develop means to more effectively communicate existing and new knowledge to users, managers, and planners in forestry. One approach would be to establish nonresearch grade positions jointly funded and administered by the Forest Service R&D and national forest regions, perhaps at each station, to focus on transferring climate science-related, climate impact-related, and carbon/mitigation-related research into NFS and S&PF operations. Given the round of the National Forest Land Management Plan revisions that are being launched throughout national forests, the timing for a liaison position is ideal to assist the development of comprehensive evaluation reports and actual land management plan revisions. After the plans are revised, this position will be extremely useful in helping NFS develop new climate-tuned project plans stemming from the forest plans. This position is needed also to interpret and guide public interaction, scoping, and education in regard to NFS and S&PF climate-related work.

4. Authors include Allen Solomon, Richard Birdsey, John Bradford, Warren Cohen, Andrew Groover, Gregory Hayward, David Hollinger, Kurt Johnsen, Robert Keane, Randy Kolka, Mark Kubiske, Kevin McKevey, Ron Neilson, Neil Nelson, Lindsey Rustad, Christopher Swanston, Marcus Warwell, and Jianwei Zhang.

New remotely sensed long-term data sets are critically needed for a variety of programs such as assessing carbon sequestration capability, forest resilience, bioproduct generation, and decision support. The Geospatial Service and Technology Center and Remote Sensing Applications Center are designed to sustain all Forest Service resource applications with primary emphasis on managing ecosystems. The addition of the capability to collect, curate, and analyze repeated digital imagery in national forests is but one task an upgraded remote sensing center could accomplish. For example, given the challenges and costs of maintaining field monitoring within national forests, a top-notch remote sensing and modeling capability to continuously monitor all forests and grasslands in the United States would be invaluable. Currently, Landsat data can accomplish this, but the infrastructure is lacking. Forest Service scientists have developed methods to take advantage of annual views of the Earth from Landsat over broad areas to track trends in forest condition. They track the obvious phenomena visible, such as stand-replacing disturbances from clearcuts and fires, but also thinnings, insects/disease, mixed intensity fire, and forest growth and recovery after disturbance. The availability of annual time series data greatly reduces noise and increases signal relative to the 3- to 5-year intervals that the scientists relied on in the past. The Forest Service could routinely produce forest change maps since 1984 (even back to 1972 is possible) and maps of forest condition at any point in time over the satellite record, combined with FIA data and modeling work, all for a cost of approximately \$1 million a year.

Additional comprehensive measurements and monitoring of U.S. forest density and structure is a critical, expensive, and largely unmet need. Measurements must be detailed

(e.g., individual tree growth/mortality, fine spatial scales), frequent (annual is essential and seasonal is preferred) and sustained (over decades). FIA can be strategically expanded, as pointed out in many elements of this plan (see sections 2.1.7, 3.2.1, 3.2.2, 4.2.3, and 4.3.3). FIA is a \$60 million a year effort to provide repeat measurements, once every 5 or 10 years, at approximately 325,000 sites across the United States. Although the data are the basis for national carbon storage estimates, little of the data have been used to evaluate the fine temporal and spatial scale changes in forests over the years since the first surveys were conducted in 1928. More intensive and continuous monitoring of critical ecosystem carbon pools and fluxes could be focused on EFRs, including annual measurements of tree and forest growth, which are surprisingly rare. Even the long-term experimental forest research studies typically measure growth in 5- to 10-year intervals. These same studies, however, provide an excellent opportunity to initiate such measurement across a broad array of forest types and silvicultural treatments. The addition of EF&R monitoring, and of FIA measurement protocols to include information specifically aimed at documenting carbon sequestration, storage, and release, is an expensive undertaking, perhaps \$5 to \$10 million each year.

An additional area in need of comprehensive measurements and monitoring is the aquatic systems in relation to forests, woodlands, and grasslands. The benefit of long-term measurements of stream temperatures has been demonstrated in terms of assessing the potential impact of climate change on cold-water fisheries, but these types of measurements are rare.

The intensive forest-monitoring network of flux towers provides continuous information about the exchange of water, energy, and carbon between forests and the at-



The Forest Service Climate Tower Network

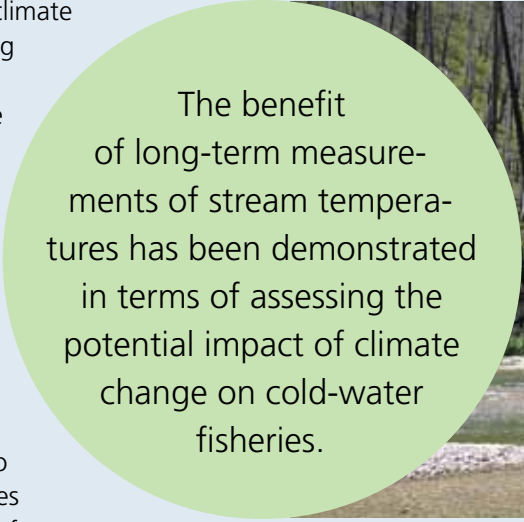
A forest-monitoring network of climate towers provides continuous information about the exchange of water, energy, and carbon between forests and the atmosphere, tracking the influence of climate and helping improve predictive capacity.

Photo from John Lee, University of Maine.


mosphere, tracking the influence of climate change on forest function and helping to develop a capacity to predict how forests will respond in the future. The Forest Service shares the network with other agencies and needs additional funding to implement intensive sampling campaigns by Forest Service participants in the North American Carbon Program. The Forest Service maintains more than a dozen of these facilities, with declining support from other agencies. Long-term records are needed to understand slower biological processes and facilities are needed in additional forest types. Many gaps exist in the AmeriFlux network that the National Ecological Observatory Network will not address. For example, in the Lake States, considerable area is covered by aspen or other hardwoods from 0 to 20 years old, but no systematic measurements have been taken in these young stands.

Wetland ecosystems are also underrepresented. Expansion of the network to include multiple towers in a geographical region investigating stand composition, age, and soil status could permit the flux measurements to be the basis for carbon models covering the diversity of forest ecosystems with unparalleled accuracy. In addition, measurement of new variables could provide critical information. Portable instrument development started since inception of these sites now makes these measurements possible. Stable isotopes of carbon dioxide in air and respiration streams can be used in separating key processes such as gross photosynthesis and respiration and also in estimating carbon turnover. Similarly, measurements of isotopes of water can be used to better understand physiological processes and sources of plant water. Previously, the only way to analyze for $^{13}\text{CO}_2$, or water isotopes, was by mass spectrometer. Very recently, however, new instrumentation has become available that can analyze gas streams in real time and continuously for $^{13}\text{CO}_2$, monodeuterated water (DHO), or H_2O^{18} . Flux tower equipment currently costs about \$50,000 per site, plus equivalent annual costs for maintenance, data retrieval, and analysis.

The U.S. Department of Energy, primary sponsor of the Free-Air CO_2 Enrichment (FACE) experiments, in which forest stands are continuously fumigated with high concentrations of CO_2 over many years, is phasing out these experiments. The Forest Service has shared sponsorship of FACE sites in Rhinelander, Wisconsin, and Duke Forest, North



The benefit of long-term measurements of stream temperatures has been demonstrated in terms of assessing the potential impact of climate change on cold-water fisheries.



Carolina. To date, the several years of continuous data from these sites (starting in 1997 and 1994, respectively) and the several other FACE sites in the United States have generated definitive answers on carbon cycle responses by forests to the increasing atmospheric concentration of CO_2 . The longer term responses, however, are as yet ambiguous. In addition, no FACE sites are located in tropical vegetation, despite the importance of carbon cycling and the paucity of data in these forests. New FACE experiments that include the effects of warming, precipitation change, ozone, and soil nutrients on specific genotypes, would be extremely useful. FACE site expenses include approximately \$500,000 for equipment and installation and about \$1 million a year for gas supplies and maintenance.

Current Forest Service computational environments for running climate and weather models, and for developing, testing, and adding decision-support interfaces to ecosystem models, are of minimal capacity and speed. Additional facilities are critical for modeling fine temporal- and spatial-scale vegetation futures. The ability to bring scientists, modelers, and programmers together in the same location to build practical predictive models is absolutely critical to making rapid progress in the creation of new models. A new computing center should be developed and occupy a central location. It should be aimed at housing modelers and programmers, archiving and formatting data sets, developing natural resource models, creating user interfaces, and educating users in applying models to land management problems. The center would also be aimed at creating best practices manuals, instructional Web pages, specialized graphical user interfaces to predictive models, specialized local assessments of future conditions, and lesson plans/teaching modules to provide natural resource manag-

ers with the support required to deal with global change impacts. Hence, facilities and space for classrooms and a lecture hall, in addition to meeting rooms, data storage, and computer lab facilities, will be important. The facility could parallel and complement the new USGS Climate Change and Wildlife Center currently under development by the U.S. Department of the Interior, and could perhaps be shared with USGS and NOAA scientists and computer personnel. An investment of \$20 to \$40 million would be needed for startup, with \$5 to \$10 million a year needed to maintain the center and its personnel.

A central problem in dealing with global change, as discussed in sections 2.1.8 and 2.1.9, is to understand the genetic basis of adaptive traits that determine how forest trees, wildland plants, and wildlife react to environmental change. A rapidly maturing approach is the use of genomic tools to identify genes that determine the ability of a given plant to grow under specific environmental conditions. Examples include work with pines in the United States identifying genes regulating drought tolerance and timing of bud flush/set. This technology can rapidly and thoroughly assess natural genetic variation underlying adaptive traits for species of interest and use that information to guide management and conservation plans. The Institute of Forest Genetics at Placerville, CA, and the Southern Institute of Forest Genetics in Saucier, MS, already have facilities that can be expanded to support these analyses. Traditional field studies of wildlife habitat needs, while yielding important information, are expensive and time consuming. One recent technological advance that has improved wildlife managers' ability to make inferences regarding wildlife populations comes from the field of molecular biology. Genetic indices are relatively simple to obtain and have been shown to be a strong reflection of population change. Landscape genetics provide new ways to more precisely define animal movements, evaluate corridors, and define population substructure using molecular genetics data. The Wildlife

Genetics Laboratory, Forest Service, in cooperation with the University of Montana, already has facilities that can be expanded to support these analyses. Other Forest Service research facilities could provide additional support in the form of cooperative and closely integrated research activities to both the plant and wildlife genetic analyses.

In addition to the laboratory activities described above, field trials and transplant garden studies are critically needed. Forest Service maintains plantation gardens throughout the country in which seed provenances from the geographic ranges of tree species have been planted, some more than 30 years ago. These gardens contain trees that could permit quantification of potential responses to warming in the future. For example, during the past 30 years of increasing CO₂ and warmth, annual growth rings of trees from seed provenances originating to the north of a plantation garden may document enhanced growth. Equally, trees from south of the garden may provide quantified measures of decreased growth. The current gardens require rejuvenation and enhanced maintenance, and the network requires enhancement after careful study of the gaps in both locations and species/provenances that are most relevant to climate change concerns. The costs for laboratory and field facilities are difficult to estimate, but may range from \$5 to \$15 million annually.

Other specialized research laboratories are in great need of expanded facilities and increased personnel to take on specialized global change issues without reducing their current important work. These laboratories include the three Wildland Fire Sciences Labs, the Forest Products Laboratory, the regional Fire Consortia for Advanced Modeling of Meteorology and Smoke, and Eastern and Western Threat Centers, the latter having been suggested as foci for a reorganized eastern and western Forest Service global change research effort.

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7. Glossary

afforestation: The establishment of forest or forest stands on lands that have not been recently forested.

biofuels: Liquid fuels and blending components produced from biomass (plant) feedstocks, used primarily for transportation.

agroforestry: A land-use system that involves deliberate retention, introduction, or mixture of trees or other woody perennials in crop and animal production systems to take advantage of economic or ecological interactions among the components.

anthropogenic: Refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that are affected by human activities.

avoided emissions: The greenhouse gas emission reductions that occur outside the organizational boundary of the reporting entity and as a direct consequence of an increase in the entity's activity.

biomass: Nonfossilized organic matter available on a renewable basis, including organic material (both living and dead) from above and below ground (e.g., trees, crops, grasses, tree litter, roots, and animals and animal waste). Biomass includes forest and mill residues, agricultural crops and residues, wood and wood residues, animal wastes, livestock operation residues, aquatic plants, fast-growing trees and plants, and the organic portion of municipal and relevant industrial wastes.

carbon cycle: The flow of carbon through the atmosphere, ocean, terrestrial biosphere, and lithosphere. Carbon exchange between pools is driven by chemical, physical, and biological processes.

carbon dioxide equivalent: The amount of carbon dioxide by weight emitted into the atmosphere that would produce the same estimated radiative forcing as a given weight of another radiatively active gas. Carbon dioxide equivalents are computed by multiplying the weight of the gas being measured by its estimated global warming potential.

carbon flow/carbon flux: The movement of carbon from one carbon pool to another. Expressed as a quantum transfer (flow) or as a rate per unit time (flux).

carbon pool: Any reservoir of carbon. The four pools are atmosphere, biosphere, oceans, and sediments.

carbon stock: The quantity of carbon stored in biological and physical systems, including trees, products of harvested trees, agricultural crops, plants, wood and paper products, and other terrestrial biosphere sinks, soils, oceans, and sedimentary and geological sinks.

deforestation: The removal of a forest stand whereby land is put to a nonforest use.

ecosystem carbon components:

live tree—a large woody perennial plant (capable of reaching at least 15 feet in height) with a diameter at breast height greater than 2.5 cm (1 inch). Includes the carbon mass in roots with diameters greater than 0.2 to 0.5 cm (note the specific diameter threshold will depend on sampling/estimation methods), stems, branches, and foliage.

tree seedlings—trees less than 2.5 cm (1 inch) diameter at breast height.

standing dead tree—dead trees of at least 2.5 cm diameter at breast height that have not yet fallen, including carbon mass of coarse roots, stems, and branches.

understory vegetation—roots, stems, branches, and foliage of tree seedlings, shrubs, herbs, forbs, and grasses.

forest floor—fine woody debris (smaller than 7.5 cm), tree litter, humus, and fine roots in the organic forest floor layer above mineral soil.

down deadwood—logging residue and other coarse deadwood on the ground (greater than 7.5 cm diameter) and stumps and coarse roots of stumps.

soil—includes fine roots and all other organic carbon not included in above pools, to a depth of 1 meter.

harvested wood—wood removed from the forest ecosystem for processing into products. Logging debris (slash) left in the forest after harvesting is not included.

estimation method: The technique, including key assumptions and data sources, used to derive reported emissions, emission reductions, and/or sequestration where actual measurement is not possible or practical.

emissions: The direct release of greenhouse gases to the atmosphere from any anthropogenic (human induced) source and certain indirect emissions (releases) specified in this part.

forest land: Land at least 10 percent stocked by forest trees of any size, or formerly having such tree cover, and not currently developed for nonforest uses. Minimum area considered for classification is 1 acre.

forest management: The practical application of biological, physical, quantitative, managerial, economic, social, and policy principles to the regeneration, tending, protection, harvest, access, use, and conservation of forests to meet specified goals and objectives while maintaining the productivity of the forest.

global warming potential (GWP): An index of the warming potential of various greenhouse gases relative to one unit of CO₂ for the purpose of calculating CO₂ equivalency in the context of global warming.

greenhouse gases (GHGs): (1) Carbon dioxide (CO₂), (2) Methane (CH₄), (3) Nitrous oxide (N₂O), (4) Hydrofluorocarbons (HFCs), (5) Perfluorocarbons (PFCs), (6) Sulfur Hexafluoride (SF₆), and (7) other gases or particles that have been demonstrated to have significant, quantifiable climate forcing effects when released to the atmosphere in significant quantities.

Intergovernmental Panel on Climate Change (IPCC): A panel established by the World Meteorological Organization and the United Nations Environmental Program to assess scientific, technical, and socioeconomic information relevant for the understanding of climate change, its potential impacts, and options for adaptation and mitigation.

inventory: A quantified account of an entity's total GHG emissions.

life cycle: The progression of a product or facility through its service life.

managed carbon stocks: Stocks that are affected by human decision or action. For example, forest management, engineered carbon sinks, or certain agricultural undertakings.

natural disturbances: Processes or events such as insect outbreaks, fire, disease, flooding, windstorms, and avalanches that cause ecosystem change.

offset: An emission reduction that is included in a report but is achieved by an entity other than the reporting entity.

permanence: The longevity of a carbon pool and the stability of its carbon stocks.

prescribed fire: Intentionally set and managed forest burns to further specific resource management objectives.

process models: Mathematical representations of ecosystem processes, such as nitrogen and carbon cycles.

reforestation: The reestablishment of forest cover, naturally or artificially, after a previous stand or forest was removed or lost.

regeneration: The natural (by natural seeding, coppice, or root suckers) or artificial (by direct seeding or planting) process of reestablishing tree cover on forest land.

sequestration: The process by which CO₂ is removed from the atmosphere, either through biologic processes or physical processes.

silviculture: The art and science of controlling the establishment, growth, composition, health, and quality of forests and woodlands.

sink: An identifiable discrete location, set of locations, or area in which CO₂ or some other greenhouse gas is sequestered.

source: Any land, facility, process, vehicle, or activity that releases a greenhouse gas.

sustainable forest management: Forest and forest lands stewardship and use that integrates the reforestation, management, growth, nurture, harvest, and use of the trees for useful products with the conservation of soil, air, and water quality; wildlife and fish habitat; and aesthetics to meet present and future needs.

terrestrial sequestration: Biotic sequestration of carbon in aboveground and below-ground biomass and soils.

verification: A process by which an organizationally independent source assesses the accuracy, completeness, and conformity with U.S. Department of Energy guidelines of proffered entity reports of emissions and emission reductions, in accord with 1605(b) guidelines.

wood products: Products derived from the harvested wood from a forest, including fuel wood and logs, and the products derived from them, such as cut timber, plywood, wood pulp, and paper. Includes both products in use and in disposal systems such as landfills (but which have not yet decayed, releasing carbon to the atmosphere as CO₂ and/or CH₄).

8.1. Genesis of the Current Forest Service Global Change Research Strategy

The Forest Service Global Research Strategy (hereafter called the Research Strategy) outlined⁵ in the fall of 2006 replaced the research strategy written in 2001 and last modified in 2003. Rather than considering the separate “stovepipes” in that plan, the discussions centered on a more top-down strategy. Specifically, the fundamental question was posed: What is Forest Service global change research funded to accomplish? The answer clearly was to manage forests under changing climate, to improve and maintain the production of their goods and services.

It was evident that this objective can be reduced to three basic research areas. First, research must facilitate land management actions to increase vegetation resilience to increasing environmental stresses, including climate and climate variability (adaptation role). This facilitation does not invoke a requirement for maintaining ecosystems of the past, but rather to retain the most productive vegetation and biotic communities in terms of ecosystem services that changing climate permits. Second, research must permit natural resource managers to increase carbon sequestration from the atmosphere into forests and ranges and then into forest products (mitigation role). Congress is considering bills that call on Federal agencies to reduce their “carbon footprint” and for land management agencies to increase the carbon sequestered by the lands they administer. Third, research must provide the basis for policymaking and decisionmaking, based on information developed by experimentation, environmental monitoring, data analysis, ecological assessments, and information technology. These three basic divisions of the Forest Service global change research goal underlie the research strategy outlined in the synopsis and the detailed plan that follows.

During the winter of 2006–07, the three-part concept was formulated as a potential global change research strategic plan by melding it with ideas from the Global Change Research Plan of the Northern Research Station, and the WestWide Global Change Research Plan of the Rocky Mountain Research Station, Pacific Northwest (PNW) Research Station, and Pacific Southwest Research Station. The plan included the now familiar (1) increased ecosystem resilience as adaptation, (2) increased carbon sequestration as mitigation, and (3) decision support for policymakers and

land managers. In addition, the plan included the goal to reduce biomass stored in forests by (4) transfer of sequestered carbon into more long-lived forest products and into biofuels to replace fossil fuels, and (5) consideration of current and new research support facilities and organizational changes needed. This document was modified in the early summer of 2007 by a larger ad hoc committee that included Richard Haynes (PNW) and Ariel Lugo (International Institute of Tropical Forestry) to produce a draft strategic plan for the Forest Service.

These elements of a global change research strategy were developed and extended at a meeting of approximately 95 global change scientists, administrators, and land managers from Forest Service and other agencies, universities, and nongovernmental organizations in Denver, Colorado, September 17–20, 2007. The *Forest Service Global Change Research Strategy, 2009–2019 Implementation Plan* presented as the main report in this document is largely the result of that meeting. A list of the participants who attended the meeting appears in appendix 8.4.

The goals of the conference were to expand the draft research plan to evaluate its general concepts, to modify them as needed, and to describe the particulars of the general concepts. The meeting product had to provide the science to develop management strategies, systems, and options for predicting, mitigating, adapting to, and capitalizing on changes in climate. The workshop aimed to produce clear statements based on the following:

- a. What forest and range management must be able to do under future climate changes that it cannot currently do.
- b. What research is already underway and what research is necessary to provide the needed science.
- c. What Forest Service organizational characteristics are needed to deliver the needed science to managers.
- d. What Forest Service Research & Development (R&D) can do to meet the needs for science and organization.
- e. What natural resource support can R&D develop and deliver to resource managers now and in the coming decade.

5. Based on several teleconferences by an ad hoc committee comprised of Forest Service scientists Richard Birdsey, Linda Joyce, Stephen McNulty, Connie Millar, Ron Neilson, and Allen Solomon

The questions on what managers must be able to do in the future were approached through an initial set of plenary talks and panel presentations. The remaining questions were each the sequential subject of four separate concurrent sessions devoted to adaptation, mitigation (as sequestration and as bioproducts), and decision support (primarily as model development). The products of these sessions are discussed in sections 2, 3, 4, and 5.

The outcome of the meeting was visualized as a separate research strategy and research plan. The Research Strategy could be shown to Congress to support their deliberations on current and new appropriations. The strategy could be provided to scientists and decisionmakers in other agencies, whose cooperative efforts are needed for the Forest Service research strategy to succeed. And, the strategy could be used to explain to land managers in the National Forest System and State and private forests what Forest Service research products are expected to do for them. The Research Plan could serve some of these purposes and, in addition, could guide the content of Forest Service global change research activities, including requests for proposals when funding for grants becomes available, and could be used within Forest Service R&D to measure the utility of subsequent research products and progress.

The Research Strategy and Research Plan were visualized as flexible documents. The fundamental components deal with the overall strategy and hence would not change as new knowledge appears: efforts to increase vegetation resilience, carbon sequestration, and removals for long-term product pools, and decision support to apply the scientific products to managing the land would always be central. Rapid changes can be expected, however, in the underlying understanding of the research that must be undertaken and the products that need to be provided to support the fundamental framework. The flexibility of the Research Strategy and Research Plan was expected to be conferred by regularly scheduled reanalysis of the assumptions that underlie them and of new information since the last writing. The strategy and plan also are expected to be modified at any time significant changes in understanding take place (e.g., new insights into relations between climate change and tree growth; establishment of bark beetles into boreal forests).

A comprehensive, detailed Research Plan, based on the efforts of the participants in the conference, describes the issues that must be solved, the research underway to deal with them, and the activities needed to implement solutions. This Research Plan is presented in sections 1 through 5 in this document. From this detailed base document,

a succinct Research Strategy was written to provide to Forest Service leadership, leadership in other agencies, and Congress, the information they need to understand what the *Forest Service Global Change Research Strategy, 2009-2019 Implementation Plan* must accomplish and the steps needed to reach those goals. The Research Strategy is available as document FS-917a on the Web (<http://www.fs.fed.us/climatechange/documents/global-change-strategy.pdf>) and as a hard copy from Vegetation Management Sciences, 4th Floor RPC, 1601 North Kent Street, Arlington, VA 22209.

8.2. Brief History of the Forest Service Global Change Research Program

The Forest Service Global Change Research Program (FSGCRP) began in 1990 following a decade of air pollution and ecosystem health research. Initial program goals were developed to—

- Provide technical input to global change policy questions.
- Learn how to maintain the productivity of U.S. forests.
- Provide international forestry leadership.
- Determine the nature and magnitude of climate change effects.
- Provide methods for detection of changes.

The following original questions guided the first decade of the FSGCRP:

- What processes in forest ecosystems are sensitive to physical and chemical changes in the atmosphere?
- How will global change influence the structure, function, and productivity of ecosystems, and to what extent will ecosystems change?
- What are the implications for forest management and how can management activities be altered to sustain productivity, health, and diversity?

The FSGCRP made many significant contributions to science and policy during the first decade, including the following:

- Understanding how climate, increasing atmospheric carbon dioxide, and air pollution interact to affect growth and survival of tree species.
- Linking with inventory and monitoring programs to determine the role of U.S. forests in the global carbon cycle and to analyze the inventory and monitor-

ing data to reveal opportunities to increase carbon sequestration in forests.

- Understanding how changes in forest productivity and health affect water quantity and quality at the watershed scale.
- Initial understanding of how disturbances such as wildfire, drought, and insect epidemics may be affected by climate change and the resulting impacts on forests.

The second decade of the FSGCRP began with a strong international scientific consensus that the effects of climate change on forest ecosystems will be significant, but much uncertainty remained concerning the precise nature of changes that may occur, how fast they may occur, and what might be done to mitigate or adapt to changes. The FSGCRP targeted ecosystem productivity, health, and diversity as key elements of sustaining our forest resources for use in providing timber, recreation, wildlife, water, and clean air. The FSGCRP emphasized research at multiple scales, from providing support for national policy development, to working with States, industry, and other private landowners who manage and produce goods and services from our Nation's forests.

The original strategic plan was issued as a draft in 2000 and updated in 2003, and it identified several key issues for future program emphasis:

- Developing, testing, and evaluating technologies to maintain or increase productivity and carbon storage in forests and wood products.
- Developing and disseminating management practices that meet society's needs for a variety of forest products under a changing climate.
- Improving the ability of land managers to minimize the impacts of disturbances on forest productivity and sustainability.
- Identifying watersheds that are sensitive to global change, and developing suitable monitoring and management practices.
- Developing strategies for maintaining species and genetic diversity in the face of global change.

In February 2002, President George W. Bush announced the formation of a new management structure, the Climate Change Science Program (CCSP), to coordinate and direct the United States' research efforts in the areas of climate and global change. These research efforts include the U.S. Global Change Research Program (USGCRP), authorized by the Global Change Research Act of 1990, and the

Climate Change Research Initiative (CCRI), launched by the President in June 2001 to reduce significant uncertainties in climate science, improve global observing systems, develop science-based information resources to support policymaking and resource management, and communicate findings broadly among the international scientific and user communities. The CCSP aims to balance the near-term (2- to 4-year) focus of the CCRI with the breadth of the USGCRP.

The FSGCRP is a \$22 million per year effort that includes base Forest Service R&D, traditionally conducted by Research Work Units, which was labeled "Global Change" upon program initiation. Base research supports not only the Global Change Research Program but many programs such as the National Fire Plan, silviculture, and hydrology. The FSGCRP also includes a small percentage of overall funding targeted specifically to address global change issues.

8.3. Needs of Land Managers and Policymakers for Scientific Support

At the Denver global change strategy meeting in September 2007, natural resource managers described the kinds of global change information they would find most useful in carrying out their responsibilities. Their concerns could be classified into four different but related topics.

8.3.1. Basic instructions in global change concepts and outcomes

- Global change is a very complex subject, and one that managers have a hard time understanding. Clear explanations of the three or four most important processes and ideas that managers need to know about climate change would be useful.
- Visits are most useful from experts who arrive with several future climate and vegetation change scenarios and can talk about adaptation strategies to cope with the prospective futures.
- The language of global change science alone can be intimidating to nonexperts. A framework of concepts and glossary of terms (a primer) aimed at helping managers to understand the processes and language of global change would be very helpful.
- A series of frequently asked questions and answers could be created that examine such management questions as how to thin stands while sequestering more carbon, what the difference is between burning fossil-fuel carbon and burning recently living forest products, and so on.

- Delivery of information to land managers must be more clearly focused and targeted so that they know what to react to immediately and what can be worked into longer term plans (prioritization of needs).

8.3.2. Approaches to multiple use planning with climate change

- Managers have many forces in addition to climate change to take into account. They need a means to calculate and balance the effects of climate change and of management on other ecosystem services and products for which they are responsible.
- A significant need exists to document the litigation potential of management actions taken to enhance carbon; what are the cumulative effects on the other goods and services that have legal standing such as wildlife, water yield, endangered species, timber production, and so on?
- For managers who have a 2-year planning horizon, assessments would be useful on the tradeoffs among needs to increase carbon sequestration, reduce fire risk, and account for interactions of climate change with water supply and forest productivity, etc.
- Managers need the means to evaluate how current land management practices (e.g., silviculture, fish management, riparian buffers) exacerbate, are neutral to, or improve ecosystem resilience under increasing climate change and associated problems.

8.3.3. Tools needed to integrate climate change into planning

- Strategies for dealing with uncertainty and risk must be employed. Ways of dealing with what is unknown are available, so the difficulty is in applying the body of knowledge while dealing with uncertainty. This difficulty has always been part of adaptive management.
- Global and continental climate change models must be downscaled to the local-regional scale; climate scenarios and vegetation models are needed that can be applied to specific planning areas.
- The simplest information could be quite useful, such as a qualitative evaluation in tabular form of whether climate change effects will be positive, neutral, or negative on the goods and services each forest is expected to provide, such as tree growth, water supply, wildlife habitat, and so on.

- A means, such as an integrated assessment model at the scale of a national forest, is needed to integrate resource costs and benefits of adaptation actions.
- A time series of species' range boundaries is needed to describe current and future distributions of plant species, wildlife, fish, pests, and invasive species; the time series should be based on several climate scenarios to show the potential range of geographic variation to be expected.

8.3.4. Outreach and cooperation

- Forest Service needs to interact with other agencies to share information and efforts. Other agencies are generating global change information and policies without Forest Service input or partnership. Forest Service needs to create a presence and be a player in this dialog.
- Forest Service must involve State foresters in education and climate change integration activities as they link forest health with private landowners who understand the economic value of forest management practices.
- Forest Service needs to provide help for State foresters who often have more interest in the economic perspective offered by carbon markets and other services. State foresters also may be more interested in spatial analyses, ownership issues, and land use issues.
- How climate changes will affect the public perception of natural resources and our use and management of them must be documented. The socioeconomic factors that will influence management may be more important to implementing adaptation and mitigation strategies than the science or funding to do it.

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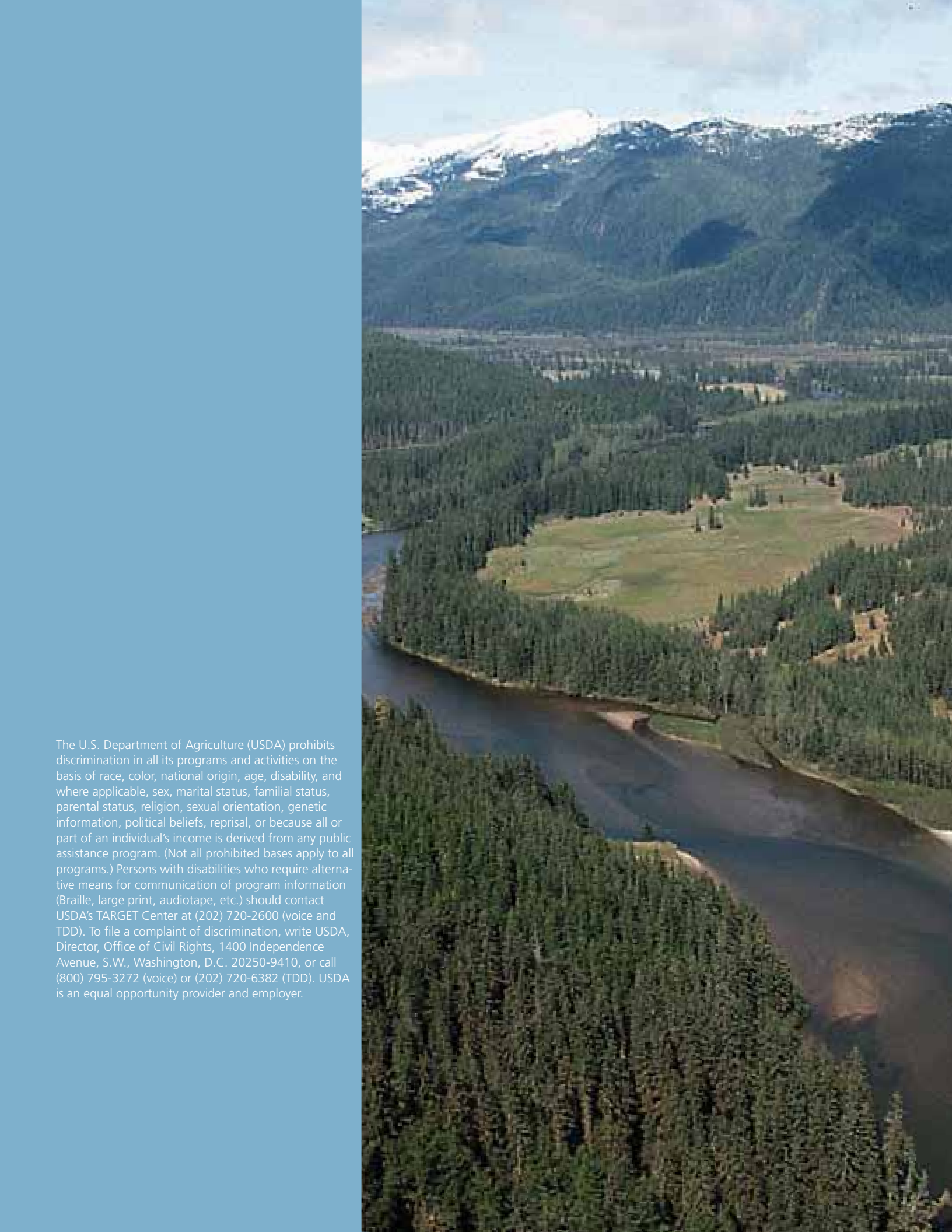
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An aerial photograph of a river winding through a lush, green valley. The river is dark and flows from the upper left towards the lower right. The valley is filled with dense evergreen forests, with some open grassy fields interspersed. In the background, a range of mountains is visible, with the highest peaks covered in snow under a blue sky with light clouds. The overall scene is a beautiful representation of a natural landscape.

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