# Chapter 4
# Adaptation and Mitigation

Constance I. Millar, Kenneth E. Skog, Duncan C. McKinley, Richard A. Birdsey, Christopher W. Swanston, Sarah J. Hines, Christopher W. Woodall, Elizabeth D. Reinhardt, David L. Peterson, and James M. Vose[1]

## Strategies for Adapting to Climate Change

Forest ecosystems respond to natural climatic variability and human-caused climate change in ways that are adverse as well as beneficial to the biophysical environment and to society. Adaptation refers to responses or adjustments made—whether passive, reactive, or anticipatory—to climatic variability and change (Carter et al. 1994). Many adjustments occur whether humans intervene or not; for example, plants and animals shift to favorable habitats resulting in range expansion or contraction, as well as changes in gene frequencies for traits that enable persistence in warm climates. Here we assess strategies and tactics resource managers can use in the process of reducing forest vulnerability and increasing adaptation to changing climates (Peterson et al. 2011). Plans and activities range from short-term, stop-gap measures, such as removing conifers that are progressively invading mountain meadows, to long-range, proactive commitments, such as fuels management to reduce the likelihood of severe wildfire or of beetle-mediated forest mortality.

[1] **Constance I. Millar** is a research paleoecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 800 Buchanan St, West Annex Building, Albany, CA 94710; **Kenneth E. Skog** is a research forester, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726; **Duncan C. McKinley** is an ecologist, U.S. Department of Agriculture, Forest Service, Research and Development, 1400 Independence Ave. SW, Washington, DC 20250; **Richard A. Birdsey** is a program manager, U.S. Department of Agriculture, Forest Service, Northern Research Station, 11 Campus Blvd., Suite 200, Newtown Square, PA 19073; **Christopher W. Swanston** is a research ecologist, U.S. Department of Agriculture, Forest Service, Northern Research Station, 410 MacInnes Drive, Houghton, MI 49931; **Sarah J. Hines** is a resource specialist, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 240 West Prospect Road, Fort Collins, CO 80526; **Christopher W. Woodall** is a research forester, U.S. Department of Agriculture, Forest Service, Northern Research Station, 1992 Folwell Avenue, St. Paul, MN 55108; **Elizabeth D. Reinhardt** is a national program leader for fire research, U.S. Department of Agriculture, Forest Service, Research and Development, 1400 Independence Ave. SW, Washington, DC 20250; **David L. Peterson** is a research biological scientist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, 400 N, 34th St, Suite 201, Seattle, WA 98103; **James M. Vose** is a research ecologist, U.S. Department of Agriculture, Forest Service, Southern Research Station, Center for Integrated Forest Science and Synthesis at North Carolina State University, Department of Forestry and Environmental Resources, Campus Box 8008, Raleigh, NC 2769.

## Principles for Forest Climate Adaptation

The following principles apply broadly in developing new perspectives on forest climate adaptation:

### Successful Climate Adaptation Planning and Implementation

In the context of this chapter, adaptation strategies, plans, and management actions are implicitly tied to broad goals of ecosystem sustainability. Restoration, maintenance, and promotion of natural ecological processes and ecosystem services define the mission of most public land-management agencies as well as many private (e.g., nongovernmental organizations) forest reserves. These goals often underlie economic and utilitarian goals of the forest industry and other special-use forest land owners as well. Climate adaptation efforts that benefit and promote goals of ecosystem sustainability are considered successful. Successful implementation of climate adaptation plans occurs when projects are developed and deployed for specific places with concrete treatments and prescriptions, explicit objectives, and for definitive time periods. Successful implementation also implies that monitoring and adaptive management schedules are integrated in out-year efforts, and are secured with funds and capacity needed for completion.

### Education and Training

Given the limited inclusion until recently of climate-science and climate-effects courses in college curricula for forest managers, a knowledge vacuum exists among practitioners and decisionmakers about basic scientific principles. Training for practitioners in the fundamental concepts of climatology and physical and ecological sciences related to climate change is essential. Such knowledge will increase the institutional capacity to understand potential effects of climate change and associated irreducible uncertainty, and to construct appropriate strategies and actions. A multilevel approach facilitates climate change education and dialogue for practitioners. A regional education program in the Northern United States incorporated several elements (Peterson et al. 2011), including basic education, intensive training, and discipline-specific and targeted workshops (fig. 4.1). Short (1- to 2-day) basic educational seminars convey fundamental principles of climate change and the effects of climate change on ecosystems and generate discussion of how different resources under management consideration can adapt to projected changes. Intensive training includes week-long courses providing indepth information and detailed explanations of fundamental climate processes and interactions, as well as greater detail on mechanisms of forest response to climate stressors. Participants have the opportunity to evaluate issues or resources by using available (e.g., online) tools. Discipline-specific trainings allow focused presentation and discussion of climate change implications for specific resource issues (e.g., silviculture, wildlife).

## Science-Management Partnerships

Partnerships between scientists and managers are needed to improve understanding of climate science and increase experience in developing adaptation strategies. These collaborations can develop in different forms. For example, science information might reside with staff within an agency, but in different program areas than those traditionally involved with forest management. University extension specialists have a long history of spanning boundaries between science and applications (e.g., providing genetic expertise in developing seed-transfer rules), and can be brought into partnerships. Research scientists with universities and agencies increasingly participate in resource management collaborations. A key element in all collaborations is that they maintain interactive dialogue, with managers and scientists reciprocally learning from and informing each other about relevance.

## Risk and Uncertainty

Given the environmental complexities of forest ecosystems, and their diverse and often conflicting institutional and societal roles, decisionmakers have long confronted challenges of risk and uncertainty. Climate change adds further dimensions of uncertainty, increasing the complexity of risk analyses. Although trends in climate and ecosystem response

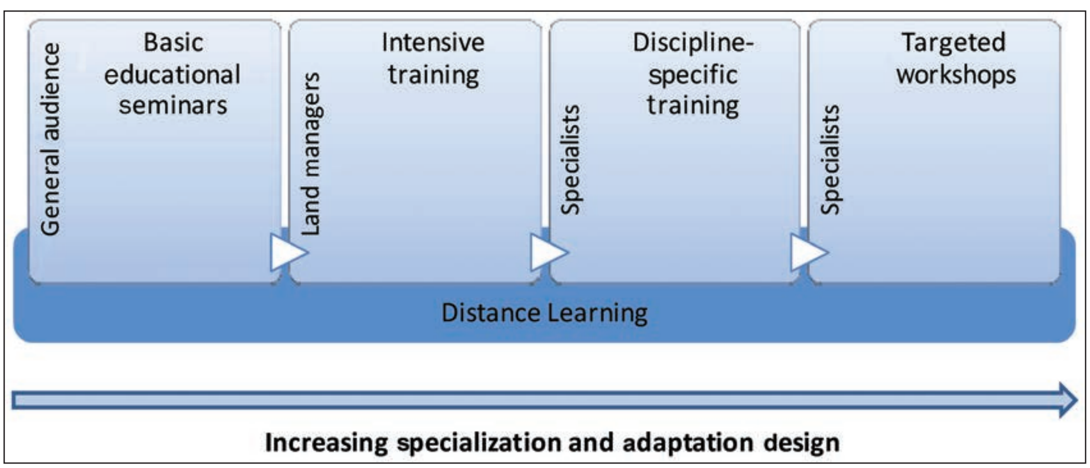


Figure 4.1—Conceptual diagram of educational and training efforts leading to increased complexity of adaptation planning and activities. These elements are integrated but need not be taken consecutively. Distance learning can be incorporated into all activities. (From Peterson et al. 2011.)

usually can be bounded with probabilistic envelopes, these are often wide and should be considered as only a guide for evaluating local decisions; unexpected conditions and surprises are especially important at local scales. In developing forest adaptation strategies, effort should be made to (1) be aware of risks, (2) assess vulnerabilities, (3) develop adaptation responses that are realistic yet minimize uncertainties, and (4) incorporate new knowledge and learning gained over time to modify decisions as appropriate (adaptive management) (Moser and Luers 2008). Adaptation responses to risk include (1) no action—continue conventional practices, (2) contingency planning—develop a response strategy (e.g., to anticipated major disturbance), and (3) anticipatory and proactive strategies—curtail or diminish potential impacts (e.g., of a major disturbance) while optimizing attainment of goals (Joyce et al. 2008).

## Toolkit Approach

Novelty and surprise in climate-change effects, combined with a diversity of management objectives and of spatial and temporal management scales, mean that no single approach will fit all situations. A toolkit approach to adaptation strategies recognizes that, from a wide array of available methods in the literature or in practice, the best strategy will require selecting appropriate methods for the specific situation. Tools include resource management practices, educational and reference modules, decision-support aids, and qualitative and quantitative models that address adaptation of natural and cultural resources to climate change (Peterson et al. 2011). Tools include existing management practices, perhaps used in new ways, as well as novel approaches developed specifically to meet climate challenges.

## No-Regrets Decisionmaking

"No-regrets" decisionmaking refers to actions that result in a variety of benefits under multiple scenarios and have little or no risk of socially undesired outcomes. This would include (1) implementing fuel treatments in dry forests to reduce fire hazard and facilitate ecological restoration, while creating resilience to increased fire occurrence in a warmer climate, and (2) installing new, larger culverts in locations where peak flows during flooding are expected to be higher in a warmer climate, thus protecting roads and reducing maintenance costs. These types of actions benefit resources and values regardless of climate-change effects and can be implemented in the near term (Swanston and Janowiak 2012).

## Flexibility and Adaptive Learning

Uncertainty about future climates and ecosystem responses, and limited experience to date in developing forest adaptation strategies, imply that flexibility, experimentation, and adaptive learning should be incorporated into all efforts to develop adaptation strategies. Ideally a formal adaptive-management program will be developed in conjunction with projects implemented, but other approaches to monitoring that enable change of management practices are also appropriate.

## Mixed-Models Approach

Climate- and ecosystem-response models are proliferating rapidly. Regional and locally downscaled climate-change scenarios logically seem useful for conducting vulnerability analyses and developing adaptation responses at scales relevant to forest sector needs. However, given the many processes about which we know very little, output from projections should be used cautiously and in conjunction with other filters. Models are often useful for examining forest-response correlates with recent historical events and for attributing influence or causality (e.g., dissecting climatic factors that might have influenced large wildfires or insect outbreaks). Models are often less useful for forecasting at small spatial scales or over long time periods, and in regard to complex biological processes. Output from models is useful as background information for envisioning a range of potential futures rather than to project a single outcome. The use of different types of models to address the same area and issue is recommended, such as models built with different assumptions, process interactions, and input data. Both quantitative (algorithm-based) and qualitative models (e.g., flow charts, indices, and verbal tools) should also be considered, and differences and similarities in projected futures can be evaluated. In recent years, it has been suggested that, if a model (or several models) hindcasts observed historical conditions well, it will also accurately predict future conditions. This is not necessarily true, because a given result can be reached via multiple pathways; in other words, a model can produce a correct historical reconstruction for the wrong reasons (Crook and Forster 2011), which means that forecasts could also be wrong. The experience and judgment of resource professionals are also important for evaluating potential future climate conditions and ecosystem responses. A recently developed summary of frequently asked questions (Daniels et al. 2012) can guide the effective use of models.

### Integration With Other Priorities and Demands of Forest Management

Mitigation, involving actions to reduce human influence on the climate system, is another fundamental approach for addressing climate challenges (Metz et al. 2001), and integrating mitigation activities with adaptation strategies is important. The best approach is usually to address mitigation and adaptation goals concurrently, although in some situations, strategies may conflict, and compromise choices may be required. Climate change remains only one of many challenges confronting forest management, and other priorities must be evaluated at different temporal scales. For example, managing under the Endangered Species Act of 1973 (ESA) can invoke actions that, by regulatory imperative, are required in the short term but make little sense, given long-term projections of the effects of climate change. For forest lands where ecological sustainability is the central goal, ecosystem-based management as practiced in land management since the late 1980s (e.g., Kohm and Franklin 1997, Lackey 1995) provides a foundation for addressing most aspects of climate-change effects. Ecosystem-based management acknowledges that natural systems change continuously and that such dynamics bring high levels of uncertainty. Ecosystem-based management concepts are therefore appropriate foundational principles in developing forest adaptation strategies.

## Placing Adaptation in Context

Forest ecosystems in the United States occur in diverse environmental, institutional, and regulatory contexts. Socially beneficial outcomes for climate adaptation depend on matching the best strategy with the context.

### Biogeography and Bioclimate

Composition, structure, and processes of forests are influenced by their location, which determines the continental-to-local climatic regimes of forest ecosystems, physical context (geomorphology, soils, tectonics, topography), biogeographic constraints and opportunities (corridors or barriers to movement), ecological legacy (historical and prehistorical ecosystems), and a myriad of societal influences, such as land ownership, regulatory context, and land use histories. Adaptation strategies will differ in detail, if not always overall approach, for forest ecosystems in different parts of the United States.

### Scale

Climate change affects forest ecosystems at many temporal and spatial scales, for example, from its influence on timing of bud burst to the evolution of ecotypes, and from trophic interactions on a rotting log to shifts in biome distribution across continents. The longevity of forest trees, combined with their significant influence on the physical landscape (e.g., soil development, watershed quality) and role as habitat, adds complexity to scale issues. Analysis at the correct spatial scales is especially important for assessing trends of climate change and ecological response, given that averages and trends on broad scales (e.g., continental) can mask variability at fine scales (e.g., watershed).

An adaptation framework based on appropriate temporal and spatial scales (e.g., Peterson and Parker 1998) ensures that plans and activities address climate effects and responses effectively. Because scales are nested, the best strategies focus on the scale of the relevant project and include evaluation of conditions and effects at scales broader than the project level, as well as analysis of effects at finer scales (tables 4.1 and 4.2). Broad-scale analysis establishes context,

**Table 4.1—Factors that affect the relevance of information for assessing vulnerability to climate change of large, intermediate, and small spatial scales**

| | Relevance by spatial scale | | |
|---|---|---|---|
| **Factor** | **Large**[a] | **Intermediate**[b] | **Small**[c] |
| Availability of information on climate and climate change effects | High for future climate and general effects on vegetation and water | Moderate for river systems, vegetation, and animals | High for resource data, low for climate change |
| Accuracy of predictions of climate change effects | High | Moderate to high | High for temperature and water, low to moderate for other resources |
| Usefulness for specific projects | Generally not relevant | Relevant for forest density management, fuel treatment, wildlife, and fisheries | Can be useful if confident that information can be downscaled accurately |
| Usefulness for planning | High if collaboration across management units is effective | High for a wide range of applications | Low to moderate |

[a] More than 10 000 $km^2$ (e.g., basin, multiple national forests).
[b] 100 to 10 000 $km^2$ (e.g., subbasin, national forest, ranger district).
[c] Less than 100 $km^2$ (e.g., watershed).
Source: Modified from Peterson et al. 2011.

**Table 4.2—Factors that affect the relevance of information for assessing vulnerability to climate change of large, intermediate, and small time scales**

| | Relevance by time scale | | |
|---|---|---|---|
| **Factor** | **Large**[a] | **Intermediate**[b] | **Small**[c] |
| Availability of information on climate and climate change effects | High for climate, moderate for effects | High for climate and effects | Not relevant for climate change and effects predictions |
| Accuracy of predictions of climate change effects | High for climate and water, low to moderate for other resources | High for climate and water, moderate for other resources | Low |
| Usefulness for specific projects | High for temperature and water, low to moderate for other resources | High for water, moderate for other resources | Low owing to inaccuracy of information at this scale |
| Usefulness for planning | High | High for water, moderate for other resources | Low |

[a] More than 50 years.
[b] 5 to 50 years.
[c] Less than 5 years.
Source: Modified from Peterson et al. 2011.

including recognition of processes and effects that manifest only at large scales (e.g., species decline, cumulative watershed effects), potential undesired consequences that could be alleviated by early action, and the need for large management units and collaboration across ownerships.

### Institutional and Regulatory Contexts

Forests are managed for many goals. Most publically administered forest lands are managed for long-term ecological and physical sustainability. Within that broad goal, emphasis differs by designation for protection level (parks, wilderness, and reserves) and ecosystem services (national and state forests, Bureau of Land Management [BLM] forest and woodlands, and tribal forest lands). The focus on maintenance of ecological and environmental conservation on public lands is subject to strict legal and regulatory direction, such as the National Environmental Policy Act [NEPA] of 1969, Clean Air Act of 1970, Clean Water Act of 1977, Endangered Species Act [ESA] of 1973, and their state counterparts. The goals, tactics, and time horizons of climate adaptation strategies for lands under these jurisdictions and legal mandates differ considerably from those of private forest lands. Adaptation on industrial forest land focuses on strategies most effective to sustain productive output over the period of economic analysis (Sedjo 2010), whereas adaptation on nonindustrial private forest lands differs by the diverse goals and capacities of landowners. Other institutional considerations that influence adaptation relate to educational and technological capacities, staff resources, and funding. Choices also depend on the quality of collaboration, because support, trust, and interaction among stakeholders influence the type of risk accepted and commitment to novel or experimental approaches.

## Adaptation Strategies and Implementation

### Overview of Forest Adaptation Strategies

The literature on conceptual approaches to forest adaptation strategies (Baron et al. 2008, Joyce et al. 2008, Peterson et al. 2011, Swanston and Janowiak 2012) (table 4.3) includes broad conceptual frameworks, approaches to specific types of analyses (e.g., vulnerability assessments, scenario planning, adaptive management), and tools and guidance for site-specific or issue-specific problems. An umbrella approach for addressing adaptation at the highest conceptual level in

**Table 4.3—Climate adaptation guides relevant to the forest sector**

| Category | Emphasis | Reference |
|---|---|---|
| Adaptation framework | General options for wildlands | Millar et al. 2007 |
| | Options for protected lands | Baron et al. 2008, 2009 |
| | Adaptation guidebooks | Peterson et al. 2012, Snover et al. 2007, Swanston and Janowiak 2012 |
| Vulnerability analysis | Climate change scenarios | Cayan et al. 2008 |
| | Scenario exercises | Weeks et al. 2011 |
| | Forest ecosystems | Aubry et al. 2011, Littell et al. 2010 |
| | Watershed analysis | Furniss et al. 2010 |
| Genetic management | Seed transfer guidelines | McKenney et al. 2009 |
| | Risk assessment | Potter and Crane 2010 |
| Assisted migration | Framework for translocation | McLachlan et al. 2007, Riccardi and Simberloff 2008 |
| Decisionmaking | Silvicultural practices | Janowiak et al. 2011b |
| | Climate adaptation workbook | Janowiak et al. 2011a |
| Priority setting | Climate project screening tool | Morelli et al. 2011b |

forest ecosystems focuses on resistance, resilience, response, and realignment strategies (Millar et al. 2007) (box 4.1). These general principles help in early phases of planning to dissect the range and scales of appropriate options at the broadest levels (Spittlehouse 2005), and they apply to many management and land-ownership contexts, but they do not provide guidance for developing site-specific plans. Similarly, broad discussions focus on other fundamental principles relative to forest adaptation planning, such as reinterpreting the role of historical variability, ecological change over time, and use of historic targets in management and restoration (Harris et al. 2006, Jackson 2012, Milly et al. 2008).

Special concerns for adaptation in parks and protected areas were developed by Baron et al. (2008, 2009) and Stephenson and Millar (2012), who emphasize the need to acknowledge that future ecosystems will differ from the past, and that fundamental changes in species and their environments will be inevitable. Given anticipated nonanalog climates and ecosystem responses, science-based adaptation will be essential. Baron et al. (2009) emphasized the need to identify resources and processes at risk, define thresholds and reference conditions, establish monitoring and assessment programs (adaptive management), and conduct scenario planning. They emphasize that preparing for and adapting to climate change is as much a cultural and intellectual challenge as an ecological issue. Diverse regulatory and value contexts dictate what will be desired for future ecosystem conditions, which drive decisions about goals, strategies, and actions.

The reality of change and novelty in future forest ecosystems under changing climates underscores the importance of vulnerability assessments in developing adaptation strategies (Aubry et al. 2011, Johnstone and Williamson 2007, Lindner et al. 2010, Littell and Peterson 2005, Littell et al. 2010, Nitschke and Innes 2008, Spittlehouse 2005). Vulnerability assessments can differ in terms of subject matter, geographic focus, level of detail, and quantitative rigor, but usually require a science-management partnership to ensure that current science is used to evaluate climate-change effects. Regional-scale assessments can be cautiously downscaled to smaller management units, recognizing there will be tradeoffs in accuracy. Some of the most detailed approaches to vulnerability assessment in response to climate challenges have focused on watersheds (e.g., Furniss et al. 2010), as described in the examples below. Scenario planning as a tool for vulnerability assessment has been well developed for forested ecosystems in U.S. national parks (Weeks et al. 2011). Tools developed for setting priorities in forest planning and for assessing risks are especially applicable for near-term decisionmaking (Janowiak et al. 2011a, Morelli et al. 2011).

Several efforts have taken comprehensive approaches to incorporate both conceptual strategies and specific tools into integrated guidebooks for developing adaptation strategies in the forest sector (Peterson et al. 2011, Swanston and Janowiak 2012). These guidebooks encourage education and training in the basic climate sciences and describe how to proceed from assessment to on-the-ground practices.

### Box 4.1

A general framework for adaptation options suitable for conditions of forested ecosystems. Options range from short-term, conservative strategic approaches to strategies for long-term, proactive plans. (From Millar et al. 2007.)

**Promote resistance**

Actions that enhance the ability of species, ecosystems, or environments to resist forces of climate change and that maintain values and ecosystem services in their present or desired states and conditions.

**Increase resilience**

Actions that enhance the capacity of ecosystems to withstand or absorb increasing impact without irreversible changes in important processes and functionality.

**Enable ecosystems to respond**

Actions that assist climatically driven transitions to future states by mitigating and minimizing undesired and disruptive outcomes.

**Realign highly altered ecosystems**

Actions that use restoration techniques to enable ecosystem processes and functions (including conditions that may or may not have existed in the past) to persist through altered climates and in alignment with changing conditions.

**Strategic steps for forest climate adaptation**—The following steps represent broad consensus that has emerged on developing forest climate adaptation strategies (review in Swanston and Janowiak 2012).

***Step 1: Define location (spatial extent), management goals and objectives, and timeframes***—Determining spatial and temporal scales and site-specific locations is essential for developing appropriate strategies. Management goals and objectives (box 4.2) for climate adaptation should be explicit and integrated with mitigation and other nonclimate-related management goals. This does not necessarily mean that goals are stated in narrowly specific quantitative terms; indeed, many forest adaptation goals and objectives can be defined broadly (e.g., sustaining ecosystem services).

***Step 2: Analyze vulnerabilities—***Vulnerability to climate change can be defined as "the degree to which geophysical, biological, and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change" (Solomon et al. 2007). Vulnerability is a function of the degree to which a system is exposed to a change in climatic conditions, its sensitivity to that change, and its adaptive capacity (Gallopín 2006, IPCC 2001, Solomon et al. 2007). Climate-vulnerability assessments are a central step in developing adaptation strategies and can take different forms (Glick et al. 2011, USGCRP 2011). Whichever approach is used, the intent is to determine how climatic variability and change might affect resources of concern, and to aid in developing appropriate priorities, strategies, and timeframes for action.

***Step 3: Determine priorities—***Priority actions for climate adaptation often differ from those for traditional forest management contexts. Furthermore, given rapidly changing conditions and emerging understanding of trends, priorities need to be reassessed regularly. When conditions are urgent and resources limited (e.g., a species in rapid decline), triage methods can be useful (Joyce et al. 2008); in longer term planning, no-regrets assessments (National Research Council 2002, Overpeck and Udall 2010) minimize risk.

***Step 4: Develop options, strategies, and tactics—***Swanston and Janowiak (2012) present a framework approach for developing adaptation plans. This process begins at a broad conceptual level and steps down to regional and local, site-specific project planning, as reflected by the increasing specificity of the following terms (fig. 4.2). **Adaptation options** are fundamental concepts and the broadest and most widely applicable level in a continuum of

## Box 4.2

**Management Goals**

Management goals are broad, general statements that express a desired state or process to be achieved. They are often not attainable in the short term and provide the context for more specific objectives. Examples of management goals include:

- Maintain and improve forest health and vigor
- Maintain wildlife habitat for a variety of species

**Management Objectives**

Management objectives are concise, time-specific statements of measurable planned results that correspond to preestablished goals in achieving a desired outcome. These objectives include information on resources to be used for planning that defines precise steps to achieve identified goals. Examples of management objectives include:

- Regenerate a portion of the oldest aspen forest type through clearcut harvest in the next year to improve forest vigor in young aspen (*Populus* spp.) stands.
- Identify and implement silvicultural treatments within 5 years to increase the oak (*Quercus* spp.) component of selected stands and enhance wildlife habitat.

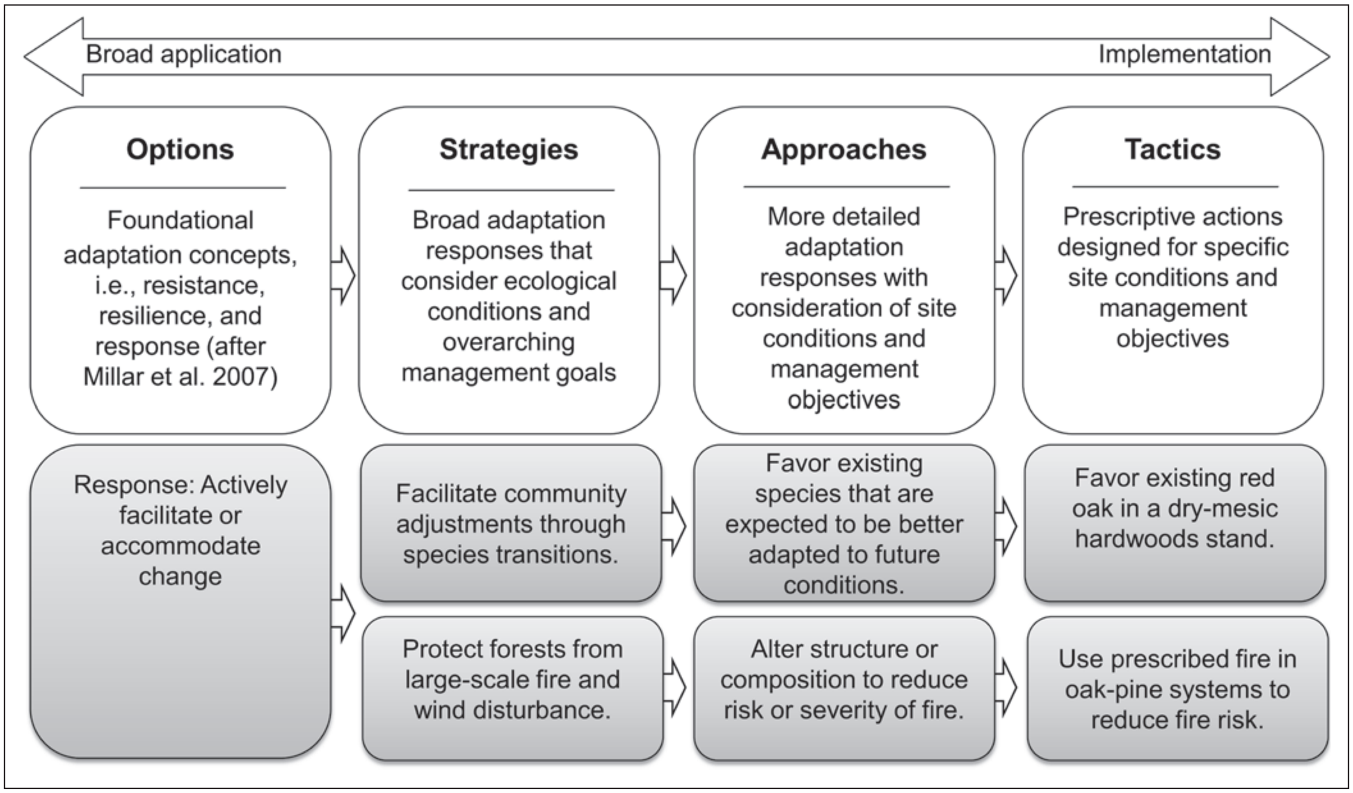


Figure 4.2—A continuum of adaptation options to address needs at appropriate scales, and examples of each (shaded boxes). (From Janowiak et al. 2011.)

management responses to climate change. Options include resistance, resilience, response, and realignment, which reflect conservative, short-term categories to proactive, long-range ones (Millar et al. 2007) (see box 4.1); they can be general or specific and focused on the local situation. **Adaptation strategies** illustrate ways that options can be used. Similar to options, strategies are broad and can be applied in many ways across different forest landscapes (table 4.4). **Approaches** provide greater detail on how forest managers can respond, and differences in application among specific forest types and management goals become evident. **Tactics** are the most specific adaptation response, providing prescriptive direction in how actions are applied on the ground. The culmination of this process is development of a plan, such as a NEPA document or other project plan, prescription, or treatment description.

***Step 5: Implement plans and projects*—**Implementation of projects should include replication, randomization, and other experimental design elements, as possible, which sets up the value of the final step.

***Step 6: Monitor, review, adjust*—**Formal adaptive management is often advocated as a key element in forest climate-adaptation planning (Baron et al. 2008, 2009; Joyce et al. 2008). Adaptive management involves a comprehensive set of steps developed in an experimental framework. Monitoring is tied to predefined thresholds and other target goals. These are developed to test hypotheses about project effectiveness and appropriateness, and, if thresholds are exceeded, trigger review and adjustment of plans (Joyce et al. 2008, 2009; Margoluis and Salafsky 1998; Walters 1986). In practice, many constraints exist to implementing the full adaptive management cycle in forest ecosystems (Joyce et al. 2009). However, informal monitoring keyed to assessing treatment effectiveness and enabling adjustment of practices is essential because of dynamic conditions driven by climate change.

**Table 4.4—Climate change adaptation strategies under broad adaptation options**

| Strategy | Resistance | Resilience | Response |
|---|---|---|---|
| Sustain fundamental ecological conditions | X | X | X |
| Reduce the impact of existing ecological stressors | X | X | X |
| Protect forests from large-scale fire and wind disturbance | X | | |
| Maintain or create refugia | X | | |
| Maintain or enhance species and structural diversity | X | X | |
| Increase ecosystem redundancy across the landscape | | X | X |
| Promote landscape connectivity | | X | X |
| Enhance genetic diversity | | X | X |
| Facilitate community adjustments through species transitions | | | X |
| Plan for and respond to disturbance | | | X |

Source: Butler et al. 2012.

## Tools and Resources for Adaptation and Implementation

Until recently, few guides to implementing climate adaptation plans were available, but many active projects now exist, including in the forest sector. The examples below are not exhaustive, but represent the type of tools available and the meta-level databases and Web resources that assist in finding relevant tools for specific locations and needs.

### Web Sites

**Climate Change Resource Center (CCRC)**—
Described more below, the CCRC (http://www.fs.fed.us/ccrc) is a U.S. Forest Service-sponsored portal dedicated to compiling comprehensive, credible information and resources relevant to forest resource managers (USDA FS 2011a).

**Climate Adaptation Knowledge Exchange (CAKE)**—
This is a joint project of Island Press and EcoAdapt (CAKE 2011) (http://www.cakex.org). Its main feature is a retrievable knowledge base that can assist in managing natural systems in the face of rapid climate change by compiling relevant information. The CAKE maintains an interactive online platform, creating a directory of practitioners to share knowledge and strategies, and identifying data tools and information available from other sites. Case studies, toolboxes, and reference materials are relevant to forest sector issues.

**NaturePeopleFuture.org**—
This is The Nature Conservancy (TNC) knowledge base for climate adaptation (TNC 2011a) (http://conserveonline.org/workspaces/climateadaptation). The Web site is used to collect input on climate-adaptation projects, summarize relevant products and ideas, and communicate about TNC efforts to draw together scientific research and innovative conservation projects. Geographically diverse forest ecosystem situations are presented, and adaptation tools and the methods discussed are relevant to forest sector issues.

**Tribes and Climate Change**—
Developed by the Institute for Tribal Environmental Professionals and Northern Arizona University, Tribes and Climate Change (http://www4.nau.edu/tribalclimatechange) summarizes information and resources to help Native people better understand climate change and its effects on their communities (NAU 2011). The site provides basic climate science information, including climate change scenarios and vulnerability assessment background, profiles of tribes throughout the United States that are addressing climate change effects, audio files of elders discussing adaptation from traditional perspectives, and resources and contacts to develop adaptation strategies. A section is devoted to forest ecosystems.

## Tools

**Climate Wizard**—
Sponsored and developed by TNC, Climate Wizard is a Web-based tool that uses select climate projections relevant to the time and space resolution of inquiries, enabling users to visualize modeled changes at several time and spatial scales (TNC 2011b). Used with scenario exercises, the Wizard can assist development of forest adaptation strategies.

**Vegetation Dynamics Development Tool (VDDT)**—
Developed by the TNC Southwest Forest Climate Assessment Project, VDDT is a user-friendly computer tool for forest resource managers (ESSA 2011). VDDT provides a state-and-transition landscape modeling framework for examining the role of various disturbance agents and management actions in vegetation change. It allows users to create and test descriptions of vegetation dynamics, simulating them at the landscape level. VDDT provides a common platform for specialists from different disciplines to collectively define the roles of various processes and agents of change on landscape-level vegetation dynamics, and allows for rapid gaming and testing of ecosystem sensitivity to alternative assumptions.

**Template for Assessing Climate Change Impacts and Management Options (TACCIMO)**—
This Web-based tool connects forest planning to climate-change science providing access to relevant climate-change projections and links to peer-reviewed scientific statements describing effects and management adaptation options (North Carolina State University 2011). The tool is intended for all forest planners with a need for public and private land management information. Input is given by the user on management conditions and capabilities to address climate change, which is linked with available physical and biological information on climate impacts and management options. TACCIMO produces a customized report that synthesizes user input needs with available science and related planning options.

**Climate Project Screening Tool (CPST)**—
This verbal interview tool helps resource managers explore options for ameliorating the effects of climate in resource projects (Morelli et al. 2011b). The CPST also acts as a priority-setting tool, allowing managers to assess relative vulnerabilities and anticipate effects of different actions. It also helps managers identify and assess projects that are soon to be implemented but have not benefited from serious consideration of climate influence. Through a set of guided questions and development of answers based on available climate and ecosystem information, the CPST reduces uncertainty by identifying possible effects of both climate change and adaptation actions on resources.

**Climate Change Adaptation Workbook**—
The Climate Change Adaptation Workbook is designed to help forest managers more effectively bring climate change considerations to the spatial and temporal scales where management decisions are made (Janowiak et al. 2011a). The workbook is an analytical process built on a conceptual model for adaptation derived from adaptive management principles. It draws on regionally specific information, filtering climate and vegetation projections through professional judgment and experience. Using a five-step process, the workbook can help incorporate climate change in resource management at different spatial scales (e.g., stand, large ownership) and levels of decisionmaking (e.g., planning, problemsolving, implementation). By defining current management goals and objectives in the first step, the process integrates climate change adaptation into existing management efforts. It is not intended to provide specific guidance or replace other forms of management planning; rather, it relies on the expertise of natural resource professionals and complements existing management planning and decision-making.

**System for Assessing Vulnerability of Species (SAVS)**—
This verbal index tool identifies relative vulnerability or resilience of vertebrate species to climate change (Bagne et al. 2011). Designed for resource managers, SAVS uses a questionnaire with 22 predictive criteria to create vulnerability scores. The user scores species attributes relating to potential vulnerability or resilience associated with projections for their region. Six scores are produced: (1) an overall score denoting level of vulnerability or resilience, (2) four categorical scores (habitat, physiology, phenology, and

biotic interactions) indicating source of vulnerability, and (3) an uncertainty score, which reflects user confidence in the predicted response. The SAVS provides a framework for integrating new information into climate change assessments and developing adaptation plans.

## Institutional Responses

### President's Directive

Executive Order 13514 (2009), "Federal Leadership in Environmental, Energy, and Economic Performance," directs each federal agency to evaluate climate change risks and vulnerabilities to manage the short- and long-term effects of climate change on the agency's mission and operations. An interagency climate change adaptation task force includes 20 federal agencies and develops recommendations for agency actions in support of a national climate change adaptation strategy. The task force recommended that federal agencies establish climate change adaptation policies, increase agency understanding of how climate is changing, apply understanding of climate change to agency mission and operations, develop an adaptation plan and implement at least three adaptation actions in 2012, and evaluate and share "lessons learned" with other agencies.

Some of the more successful adaptation efforts to date have involved collaboration among different institutions. Collaboration can take many forms, such as between federal agencies, between federal and state agencies, between various agencies and Native American tribes, and between various land management agencies and a wide range of stakeholders. There is no standard model, and effective collaborations will differ by landscape and local institutional relationships.

### U.S. Forest Service

The U.S. Forest Service climate response is led by the climate change advisor's office, which develops guidance and evaluates progress toward climate adaptation. Agency goals and actions are described in a strategic framework document (USDA FS 2008). Forest Service research and development also has a climate change strategic plan (Solomon et al. 2009). These documents state the conceptual visions for science-based adaptation on the 175 national forests and national grasslands. Of seven key goals in the overall framework, five pertain to climate adaptation:

**Science**—
Advance understanding of the environmental, economic, and social implications of climate change and related adaptation activities on forests and grasslands.

**Adaptation**—
Enhance the capacity of forests and grasslands to adapt to the environmental stresses of climate change and maintain ecosystem services.

**Policy**—
Integrate climate change, as appropriate, into policies, program guidance, and communications and put in place effective mechanisms to coordinate across and within deputy areas.

**Education**—
Advance awareness and understanding regarding principles and methods for sustaining forests and grasslands, and sustainable resource consumption, in a changing climate.

**Alliances**—
Establish, enhance, and retain strong alliances and partnerships with federal agencies, state and local governments, tribes, private landowners, nongovernmental organizations, and international partners to provide sustainable forests and grasslands for present and future generations.

Tactical approaches and implementation are outlined in the National Roadmap for Responding to Climate Change (USDA FS 2011b). The roadmap identifies 10 steps along four major dimensions, namely, agency and organizational capacity, partnerships and conservation education, adaptation, and mitigation (fig. 4.3). The process includes (1) science-based assessments of risk and vulnerability; (2) evaluation of knowledge gaps and management outcomes; (3) engagement of staff, collaborators, and partners through education, science-based partnerships, and alliances; and (4) management of resources via adaptation and mitigation. To assist in these tasks, the CCRC (USDA FS 2011a) serves as a reference Web site with information and tools to address

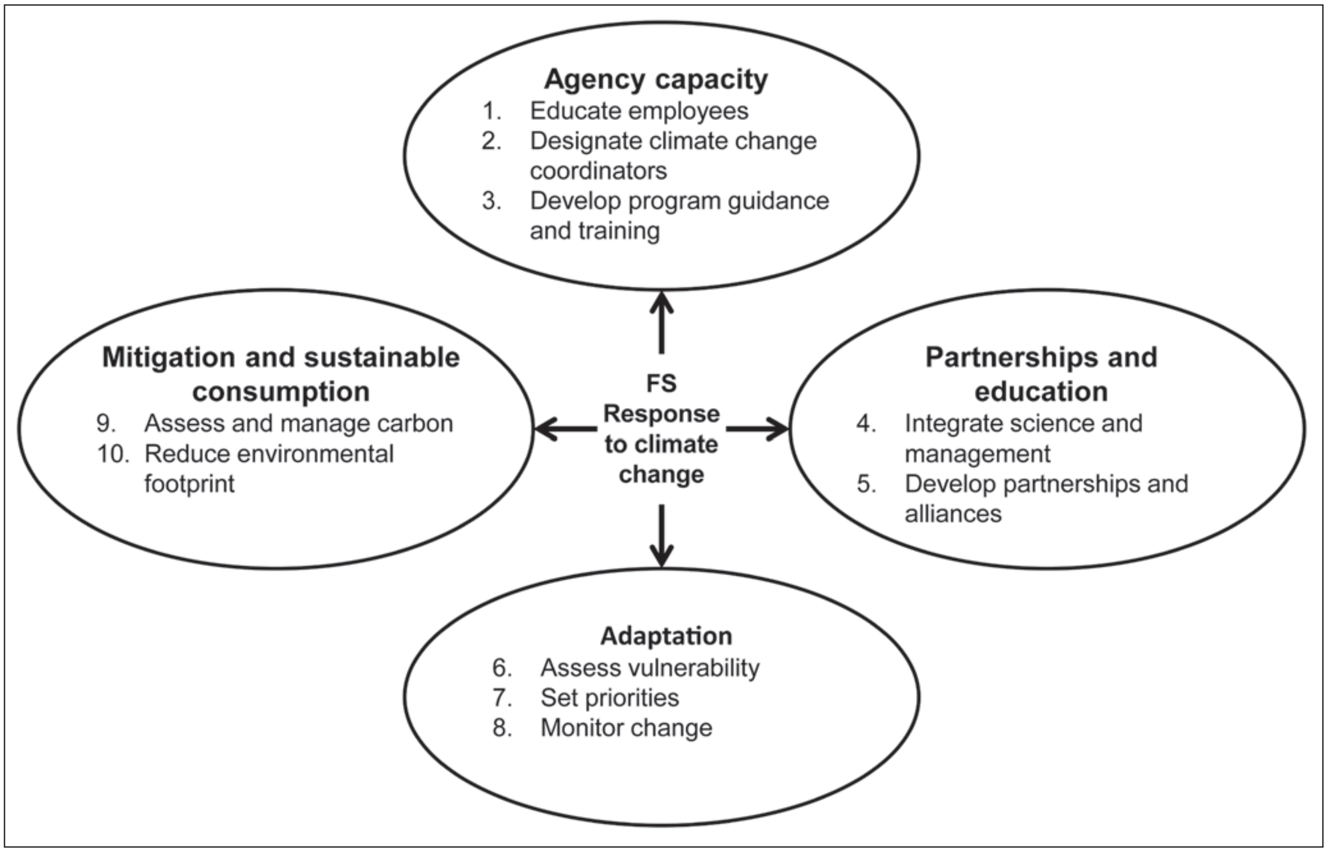


Figure 4.3—Four dimensions of action outlined by the U.S. Forest Service roadmap for responding to climate change. (From USDA FS 2011b.)

climate change in planning and project implementation. Climate change coordinators are designated for each Forest Service region. Current initiatives from research and management branches of the agency provide climate science, develop vulnerability assessments, prepare adaptive monitoring plans, and align planning, policy, and regulations with climate challenges (box 4.3).

The Performance Scorecard (USDA FS 2011c) (table 4.5) is used annually to document progress of national forests, regions, and research stations on adaptation plans and "climate smart" actions. The scorecard also identifies areas of weakness, knowledge gaps, and budgetary limitations, which the climate change advisor's office can subsequently highlight for attention.

## U.S. Department of the Interior (DOI)

A U.S. Department of the Interior secretarial order (2009) provides a framework to coordinate climate change activities among DOI bureaus and to integrate science and management expertise with DOI partners. Climate Science Centers and Landscape Conservation Cooperatives form the cornerstones of the framework. Each has a distinct science and resource management role, but they share complementary capabilities in support of DOI resource managers and of integrated climate solutions with federal, state, local, tribal, and other stakeholders.

**Climate science centers (CSC)**—
Climate science centers are seven regional centers in development because of cooperative endeavors between DOI and universities to distill and make climate-adaptation information available to users. The CSCs fund the development of scientific information, tools, and techniques for resource

## Box 4.3

U.S. Forest Service initiatives to promote progress toward achieving goals of the national roadmap for responding to climate change. (From USDA FS 2011b.)

**Furnish predictive information on climate change and variability**, both immediate and longer term, building on current research capacity and partnerships with the National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, U.S. Geological Survey, and other scientific agencies.

- Develop, interpret, and deliver spatially explicit scientific information on recent shifts in temperature and moisture regimes, including incidence and frequency of extreme events.
- Provide readily interpretable forecasts at regional and subregional scales.

**Develop vulnerability assessments,** working through research and management partnerships and collaboratively with partners.

- Assess the vulnerability of species, ecosystems, communities, and infrastructure and identify potential adaptation strategies.
- Assess the impacts of climate change and associated policies on tribes, rural communities, and other resource-dependent communities.
- Collaborate with the U.S. Fish and Wildlife Service and National Marine Fisheries Service to assess the vulnerability of threatened and endangered species and to develop potential adaptation measures.

**Tailor monitoring** to facilitate adaptive responses.

- Expand observation networks, intensify sampling in some cases, and integrate monitoring systems across jurisdictions (see, for example, the national climate tower network on the experimental forests and ranges).
- Monitor the status and trends of key ecosystem characteristics, focusing on threats and stressors that may affect the diversity of plant and animal communities and ecological sustainability. Link the results to adaptation and genetic conservation efforts.

**Align Forest Service policy and direction** with the Forest Service strategic response to climate change.

- Revise National Forest System land management plans using guidance established in the new Planning Rule, which requires consideration of climate change and the need to maintain and restore ecosystem and watershed health and resilience.
- Review Forest Service Manuals and other policy documents to assess their support for the agency’s strategic climate change direction. Evaluate current policy direction for its ability to provide the flexibility and integration needed to deal with climate change.
- Develop proposals for addressing critical policy gaps.

**Table 4.5—Performance scorecard used by the U.S. Forest Service for annual review of progress and compliance, and to identify deficit areas in implementation of the national roadmap for responding to climate change**

| Scorecard element | Questions to be addressed | Yes/no |
|---|---|---|
| Organizational capacity: | | |
| Employee education | Are all employees provided with training on the basics of climate change, impacts on forests and grasslands, and the Forest Service response? | |
| | Are resource specialists made aware of the potential contribution of their own work to climate change response? | |
| Designated climate change coordinators | Is at least one employee assigned to coordinate climate change activities and be a resource for climate change questions and issues? | |
| | Is this employee provided with the time, training, and resources to make his/her assignment successful? | |
| Program guidance | Does the unit have written guidance for progressively integrating climate change considerations and activities into unit-level operations? | |
| Engagement: | | |
| Science and management partnerships | Does the unit actively engage with scientific organizations to improve its ability to respond to climate change? | |
| Other partnerships | Have climate change-related considerations and activities been incorporated into existing or new partnerships (other than science partnerships)? | |
| Adaptation: | | |
| Assessing vulnerability | Has the unit engaged in developing relevant information about the vulnerability of key resources, such as human communities and ecosystem elements, to the impacts of climate change? | |
| Adaptation actions | Does the unit conduct management actions that reduce the vulnerability of resources and places to climate change? | |
| Monitoring | Is monitoring being conducted to track climate change impacts and the effectiveness of adaptation activities? | |
| Mitigation and sustainable consumption: | | |
| Carbon assessment and stewardship | Does the unit have a baseline assessment of carbon stocks and an assessment of the influence of disturbance and management activities on these stocks? | |
| | Is the unit integrating carbon stewardship with the management of other benefits being provided by the unit? | |
| Sustainable operations | Is progress being made toward achieving sustainable operations requirements to reduce the environmental footprint of the agency? | |

Source: Adapted from USDA FS 2011b, 2011c.

managers to anticipate, monitor, and adapt to climate and to develop adaptation responses at multiple scales. Forest ecosystems are a primary focus of several CSCs.

**Landscape conservation cooperatives (LCC)**—
The LCCs complement existing science and conservation efforts of the CSCs and partners by leveraging resources and strategically targeting science topics to inform conservation decisions and actions (USDI FWS 2011). Each LCC operates within a specific landscape, with 21 geographic areas total (fig. 4.4). Partners include federal, state, and local governments, tribes, universities, and other stakeholders. The LCCs form a network of resource managers, scientists, and public and private organizations that share a common need for scientific information and interest in conservation. Land conservation cooperatives products include resource assessments, examples demonstrating the application of climate models, vulnerability assessments, inventory and monitoring protocols, and conservation plans and designs. Adaptation products include assessments of climate change effects and development of adaptation strategies for wildlife migration corridors, wildfire risk and fuel treatments, drought impacts and amelioration, detection and control of invasive species, and restoration of forest landscapes.

**National Park Service (NPS)**—
The NPS climate change response strategy (NPS 2010) provides direction for addressing effects of climate change in NPS-administered park units. The strategy directs NPS to adapt natural resources on its lands by using scenario exercises as a central approach, thereby creating flexible plans at park scales for dealing with climate effects. The broad goals of the strategy include developing effective natural-resource adaptation plans and promoting ecosystem resilience. Specifically the strategy requires that units (1) develop adaptive capacity for managing natural and cultural resources; (2) inventory resources at risk and conduct vulnerability assessments; (3) prioritize and implement actions and monitor the results; (4) explore scenarios, associated risks, and possible management options; and (5) integrate climate change effects in facilities management. The legacy dictum for NPS management has been to preserve and restore natural (usually interpreted as historical) conditions. Ecosystem dynamics associated with climate change have forced rethinking of this concept, and new paradigms are emerging in national park management for incorporating ecological change in adaptation philosophies and managing "beyond naturalness" (Cole and Yung 2010, Stephenson and Millar 2012). Emphasis on scenario exploration as a discussion focus is intended to promote solutions that address multiple feasible future outcomes.

**Bureau of Land Management (BLM)**—
The BLM focuses on a landscape approach to climate change adaptation, working within functional ecosystems at large scales and across agency boundaries, and assessing natural resource conditions and trends, natural and human influences, and opportunities for resource conservation and development. The landscape approach consists of (1) rapid ecoregional assessments (REA), which synthesize the information about resource conditions and trends within an ecoregion, with emphasis on areas of high ecological value (e.g., important wildlife habitats and corridors); (2) ecoregional direction, which uses the results of REAs to identify management priorities for public lands in an ecoregion and guide adaptation actions; (3) monitoring for adaptive management, which relies on monitoring and mapping programs to meet information needs and assessment, understand resource conditions and trends, and evaluate and refine implementation actions; and (4) science integration, which relies on participation with CSCs to provide science for management needs. To date, these have not yielded operational climate-change adaptation plans.

## Regional Integrated Sciences and Assessments (RISA)

Funded by National Oceanographic and Atmospheric Administration's Climate Program Office, the RISA program supports research and stakeholder interaction to improve understanding of how climate affects various regions of the United States, and to facilitate the use of climate information in decisionmaking. The RISA teams analyze climate data; apply, provide, and interpret climatic information for resource managers and policymakers in the United States; and are a good source of information on climate change and regional effects of climate change.

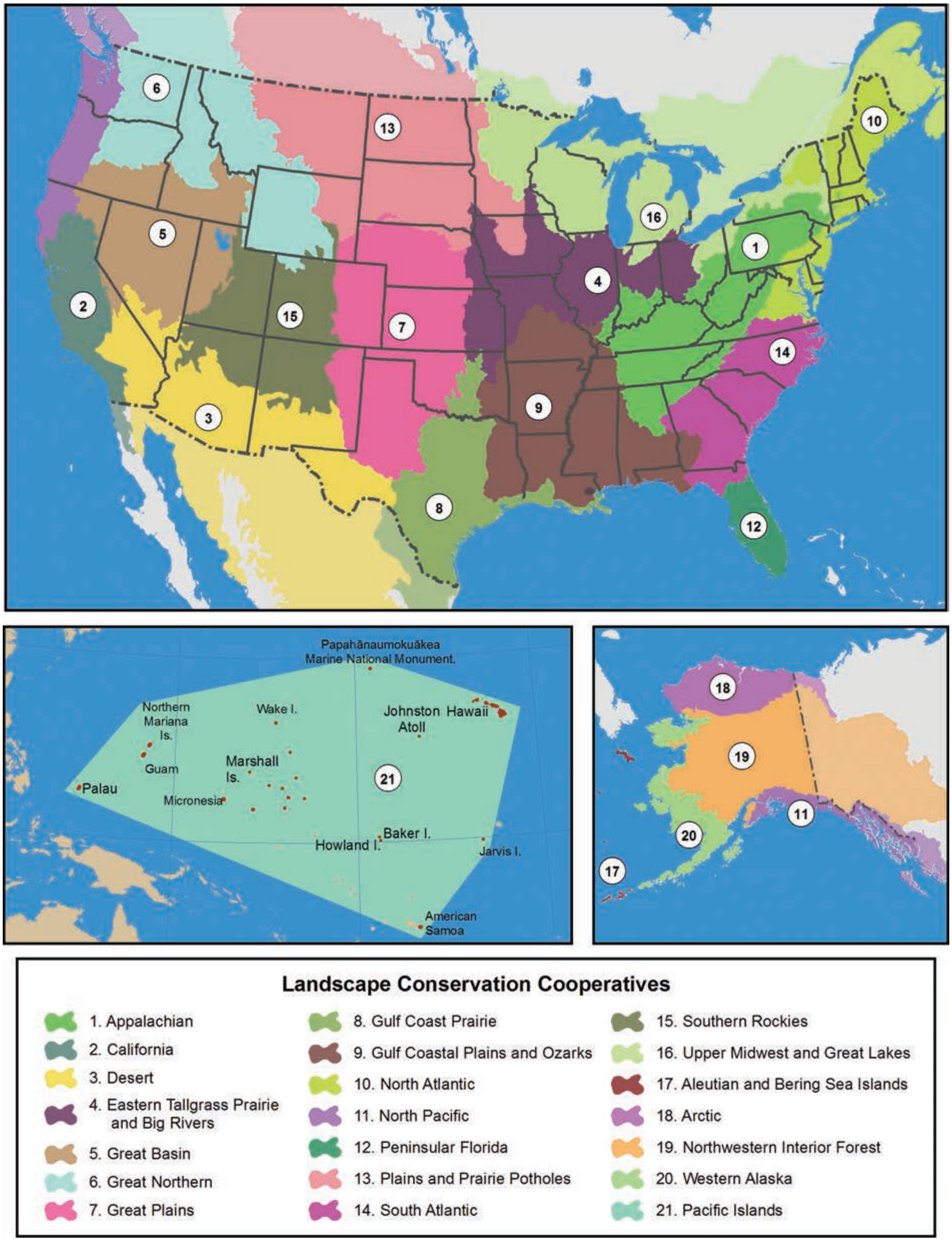


Figure 4.4—Twenty-one landscape conservation cooperatives of the U.S. Department of the Interior integrate climate-adaptation responses across federal, state, tribal, local, and private interests within geographically coherent regions. (From DOI FWS 2011.)

## State and Local Institutions

Climate-adaptation responses of state and local institutions are diverse, ranging from minimal action to fully developed and formal programs. State responses that focus on forest-sector issues include the following.

**Washington State climate response strategy**—
Beginning in 2009, the Washington Department of Ecology in partnership with the departments of Agriculture, Commerce, Fish and Wildlife, Natural Resouces, and Transportation, began developing a strategy to prepare for the effects of climate change outlined in the Washington State Climate Change Impacts Assessment (McGuire et al. 2009, Washington State Department of Ecology 2012). This collaborative effort involving a variety of public and private stakeholders sought to develop recommendations for addressing the effects of climate change. The working groups emphasized the priority of forest resources in the strategy, and recommendations for climate-adaptation efforts in major forest ecological systems have been developed (Helbrecht et al. 2011) (box 4.4), including for fire management and genetic preservation (Jamison et al. 2011). These options emphasize research, assessing vulnerabilities, developing pilot projects, improving forest health, avoiding forest conversion, using prescribed fire, and using adaptive management in decisionmaking. Strategies consistent with adaptation on forest lands include (1) preserve and protect Washington's existing working forest, (2) assess how land management decisions help or hinder adaptation, (3) foster interagency collaboration, (4) promote sociocultural and economic relations between eastern and western Washington to improve collaboration, (5) develop options that address major disturbance events, and (6) incorporate state decisions with global and local factors when adapting to climate change (Washington State Department of Ecology 2012).

**Western Governors' Association (WGA)**—
A nonpartisan organization of governors from 19 Western States, two Pacific territories, and one commonwealth, the WGA addresses the effects of climate on forest health, wildfire, water and watersheds, recreation, and forest products. The WGA supports integration of climate adaptation science in Western States (WGA 2009) and published a report on priorities for climate response in the West (WGA 2010), including sharing climate-smart practices for adaptation, developing science to be used in decisionmaking, and coordinating with federal entities and other climate adaptation initiatives. The WGA is focusing on developing training to help states incorporate new protocols and strategies relative to climate change (box 4.5), and improving coordination of state and federal climate adaptation initiatives. The WGA recommends that new state-level programs be designed that are relevant for on-the-ground climate change issues and also comply with federal regulations.

**Minnesota State climate response**—
The Minnesota Department of Natural Resources is building intellectual and funding capacity to implement policies that address climate change and renewable energy issues,

### Box 4.4

Interim recommendations of the Washington State Climate Change Response Strategy's topic advisory group on species, habitats, and ecosystems. (From Helbrecht et al. 2011.)

**Facilitate the resistance, resilience, and response of natural systems**

1. Provide for habitat connectivity across a range of environmental gradients.
2. For each habitat type, protect and restore areas most likely to be resistant to climate change.
3. Increase ecosystem resilience to large-scale disturbances, including pathogens, invasive species, wildfire, flooding, and drought.
4. Address stressors contributing to increased vulnerability to climate change.
5. Incorporate climate change projections in plans for protecting sensitive species.

**Build scientific and institutional readiness to support effective adaptation**

6. Fill critical information gaps and focus monitoring on climate change.
7. Build climate change into land use planning.
8. Develop applied tools to assist land managers.
9. Strengthen collaboration and partnerships.
10. Conduct outreach on the values provided by natural systems at risk from climate change.

**Box 4.5**

Goals of the Western Governors' Association (WGA) climate-adaptation initiative on training. (From WGA 2010.)

**The WGA seeks to provide training to its 19 member states and collaborators with goals to:**

1. Provide state resource planners with the tools, methods, and technical assistance needed to incorporate climate change into ongoing planning processes.
2. Create a forum to enhance communication and dialogue with climate adaptation researchers to help set priorities for investment in science and research that informs decisionmakers.
3. Identify multistate or cross-boundary climate adaptation needs, as well as regional data sharing needs, and consider how they may be addressed through regional collaboration.
4. Determine how state agencies can collaborate with federal and local governments and other partners.
5. Develop a clearinghouse of best practices that state agencies and managers may refer to when developing their state's adaptation efforts.

including vulnerability assessments that identify risks and adaptation strategies for forest ecosystems. These efforts complement climate adaptation efforts occurring in the state through the multi-institutional Northwoods climate change response framework (see "Regional Examples"). The Minnesota Forest Resources Council, which includes public and private stakeholders from the forestry sector, is developing recommendations to the governor and federal, state, county, and local governments on policies and practices that result in the sustainable management of forest resources. Regional landscape committees establish landscape plans that identify local issues, desired future forest conditions, and strategies to attain these goals (MFRC 2011). The regional landscape committees plan to integrate with the Northwoods climate change response framework to ensure that climate change is integrated in forest management and planning.

**North Carolina State climate response**—
The North Carolina Department of Environment and Natural Resources (DENR) is developing a comprehensive adaptation strategy to identify and address potential effects on natural resources, with emphasis on climate-sensitive ecosystems and land use planning and development. The North Carolina Natural Heritage Program is evaluating likely effects of climate change on state natural resources, including 14 forest ecosystems that are likely to respond to climate change in similar ways. The DENR co-hosted a statewide climate change adaptation workshop in 2010 and is now coordinating with other agencies on an integrated climate response and developing a climate change response plan and down-scaled climate assessments.

**State university and academic responses**—
In the Pacific Northwest, the University of Washington Climate Impacts Group (CIG) has a strong focus on climate science in the public interest. Besides conducting research and assessing climate effects on water, forests, salmon, and coasts, the CIG applies scientific information in regional decisions. The CIG works closely with stakeholders and has been a key coordinator for forest climate adaptation projects (e.g., Halofsky et al. 2011, Littell et al. 2011). An adaptation guidebook developed in collaboration with King County, Washington describes an approach for developing local, regional, and state action plans (Snover et al. 2007). In Alaska, the Alaska Coastal Rainforest Center, based at the University of Alaska Southeast, in partnership with the University of Alaska Fairbanks and other stakeholders, provides educational opportunities, facilitates research, and promotes learning about temperate rain forests. The center facilitates dialogue on interactions among forest ecosystems, communities, and social and economic systems and has developed a framework for integrating human and ecosystem adaptation. In Hawaii, the Center for Island Climate Adaptation and Policy, based at the University of Hawaii at Mānoa, promotes interdisciplinary research and solutions to public and private sectors, with a focus on science, planning, indigenous knowledge, and policy relative to climate adaptation. Recent projects focus on education, coordinating with state natural resource departments on adapting to climate change (CICAP 2009), and policy barriers and opportunities for adaptation. Forest-related climate issues include effects of invasive species, forest growth and decline, migration and loss of forest species, and threats to sustainability of water resources.

## Industrial Forestry

The response from forest industries in the United States to climate change has to date focused mostly on carbon sequestration, energy conservation, the role of biomass, and other climate-mitigation issues. Detailed assessments and efforts to develop adaptation strategies for the forest-industry sector have mostly been at the global to national scale (Sedjo 2010; Seppälä et al. 2009a, 2009b). Many forestry corporations promote stewardship forestry focused on adaptability of forest ecosystems to environmental challenges, but most ongoing adaptation projects are small scale and nascent. For example, Sierra Pacific Industries (SPI) in California is evaluating the potential for giant sequoia (*Sequoiadendron giganteum* [Lindl.] J. Buchholz) plantations to serve as a safeguard against changing climates. Giant sequoia currently grows in small groves scattered in the Sierra Nevada. Germplasm would be collected by SPI from the native groves and planted in riparian corridors on productive industry land, then managed as reserves that would benefit from the resilience of giant sequoia to climatic variability and its ability to regenerate after disturbance.

In Australia, the forest industry has been more assertive in addressing climate change. For example, the National Association of Forest Industries of Australia is working to improve the ability of forest industry to reduce the harmful effects of, and exploit opportunities from, changing climate. A short-term objective is to promote general awareness of the extent and range of likely climatic impacts and vulnerabilities specific to key forest regions, together with practical options for adaptation and mitigation given available scientific knowledge. The longer term objective is to provide tools and mechanisms to promote incorporation of adaptation options in forest-based industries. The Australian Commonwealth Scientific and Industrial Research Organization developed an initial assessment of climate risks and adaptation strategies for plantation forestry, with specific recommendations for planting, germplasm selection, and silvicultural actions (Pinkard et al. 2010).

## Native American Tribes and Nations

Many Native American tribes and nations have been actively developing detailed forest adaptation plans in response to climate change. Overall goals commonly relate to promoting ecosystem sustainability and resilience, restoration of forest ecosystems, and maintenance of biodiversity, especially of elements having historical and legacy significance to tribes. Maintenance of cultural tradition within the framework of changing times is also inherent in many projects.

An exceptional example of a tribal response is the climate change initiative of the Swinomish Tribe in Washington (SITC 2010) (box 4.6). The Swinomish Reservation (3900 ha) is located in northwestern Washington and includes 3000 ha of upland forest. The initiative focuses on building understanding among the tribal community about climate change effects, including support from tribal elders and external partners. A recent scientific assessment summarizes vulnerabilities of forest resources to climate change, and outlines potential adaptation options (Rose 2010). A report completed in 2009 provides a baseline for adaptation planning and states that the tribe's forest resources are at risk from wildfire, which will be addressed in an action plan on adaptive response (SITC 2010).

Tribes have been active partners in collaborative forest adaptation plans. An example is the Confederated Tribes and Bands of the Yakama Nation, whose reservation occupies 490 000 ha in south-central Washington. Tribal lands comprise forest, grazing, and farm lands in watersheds of the Cascade Range. The Yakama Nation has extensive experience in managing dry forest ecosystems and implementing forest action plans, and belongs to the Tapash Sustainable Forest Collaborative, in partnership with the U.S. Forest Service, Washington State Departments of Fish and Wildlife and of Natural Resources, and TNC. The collaborative encourages coordination among landowners to respond to common challenges to natural resources (Tapash Collaborative 2010). Climate change was ranked as a significant threat to forest productivity, leading to a proposal to incorporate specific adaptation strategies and tactics across the Tapash landscape, most of which relate to fire, fuels, and restoration in dry forest.

### Box 4.6

Adaptation framework of the Swinomish Tribe Washington) climate change initiative. (From SITC 2010).

**Phase 1 (2007–2009)**

- Tribal buy-in leads to issuance of the 2007 Climate Change Proclamation
- Secure funding
- Identification of partners, development of advisory committee, and identification of roles and responsibilities
- Development of the impact assessment
  - Data review and analysis
  - Risk zone mapping and inventory
  - Vulnerability assessment
  - Risk analysis
- Policy and strategy scoping (intergovernmental)
- Community outreach
  - Formed tribal outreach group
  - Held public meetings
  - Conducted personal interviews of tribal members and elders
  - Conducted storytelling workshop with tribal members

**Phase 2 (2010)**

Development of the action plan

- Adaptation goals
- Strategy evaluation and priorities
- Action recommendations
- Coordination of funding
- Other implementation issues

**Phase 3 (future work)**

- Action plan implementation
- Monitoring and adaptive management
- Update of the impact assessment

## Nongovernmental Organizations

Nongovernmental organizations and professional organizations serve a wide range of special interests, and thus respond to climate adaptation challenges in diverse ways.

**Pacific Forest Trust (PFT)**—
A nonprofit organization dedicated to conserving and sustaining America's productive forest landscapes, PFT provides support, knowledge, and coordination on private forest lands in the United States. Through its Working Forests, Winning Climate program, PFT has created policy and market frameworks to expand conservation stewardship of U.S. forests to help sustain ecosystem services (PFT 2011). The PFT also supports climate adaptation by working with private forest owners to promote stewardship forestry, whereby forests are managed to provide goods and services that society has come to expect. The PFT currently works with stakeholders on working forest lands to call on policymakers to safeguard U.S. forests for their value in adaptation and mitigation.

**The Nature Conservancy (TNC)**—
A science-based conservation organization, TNC has a mission to preserve plants, animals, and natural communities by protecting the lands and waters they need to survive. The TNC climate change adaptation program seeks to enhance the resilience of people and nature to climate change effects by protecting and maintaining ecosystems that support biodiversity and deliver ecosystem services. The program promotes ecosystem-based approaches for adaptation through partnerships, policy strategies for climate adaptation, tools to assist resource managers, and research. The Canyonlands Research Center (Monticello, Utah), a TNC initiative that conducts research and develops conservation applications for resource issues in the Colorado Plateau region, focuses on forest-climate concerns such as woodland ecosystem restoration, invasive species, and effects of drought on pinyon pine and juniper woodlands.

**Trust for Public Land (TPL)**—
A conservation organization that helps agencies and communities conserve land for public use and benefit, TPL uses vulnerability assessments, resilience and connectivity data, and other tools to realign its conservation planning at different spatial scales. The TPL is also designing and implementing restoration to enhance the climate resilience of protected tracts. As a member of the Northern Institute of Applied

Climate Science, TPL provides guidance to federal and nonfederal partners on strategic planning and on-the-ground management.

**The Wilderness Society (TWS)**—
The Wilderness Society leads efforts to fund natural resource adaptation and manage lands so they are more resilient under stresses of climate change, and is a leader in the Natural Resources Adaptation Coalition, which is focused on maintaining and restoring wildlands that include forest wilderness. Specific TWS goals relative to adaptation in forests include (1) restoring native landscapes to increase ecosystem resiliency, (2) protecting rural communities and providing flexibility in wildland fire management, (3) removing invasive species from ecosystems, and (4) repairing damaged watersheds.

### Ski Industry

Although not a direct member of the forest sector, the ski industry relies on mountainous terrain, usually forested land leased from federal landowners, and is concerned about reduced snow, rising temperatures, extreme weather events, and other consequences of climate change that may affect the profitability of ski areas. Adaptation options used by the ski industry (Scott and McBoyle 2007) include (1) snowmaking to increase the duration of the ski season (Scott et al. 2006), (2) optimizing snow retention (slope development and operational practices such as slope contouring, vegetation management, and glacier protection), and (3) cloud seeding. Forest vigor and stand conditions within and adjacent to ski area boundaries are important to ski areas, because forests burned by wildfire or killed by insect outbreaks affect snow retention, wind patterns, and aesthetic value.

## Examples of Regional and National Responses

Although general guidance and strategic plans about climate adaptation exist for many land management agencies, strategies for specific places and resource issues are in the early stages. Below we summarize examples for which the intent was to explore how forest adaptation strategies could be developed for specific locations.

### Western United States

**Olympic National Forest/Olympic National Park (ONFP), Washington**—
This case study in the Northwest was undertaken to represent a large landscape within a geographic mosaic of lands managed by federal and state agencies, tribal groups, and private landowners (Littell et al. 2011). The ONFP supports a diverse set of ecosystem services, including recreation, timber, water supply to municipal watersheds, pristine air quality, and abundant fish and wildlife. Management of Olympic National Forest focuses on "restoration forestry," which emphasizes facilitation of late-successional characteristics, biodiversity, and watershed values in second-growth forest. Collaboration with adjoining Olympic National Park, which has a forest protection and preservation mission, is strong.

Development of the ONFP adaptation approach employed a science-management partnership, including scientific expertise from the CIG, to implement education, analysis, and recommendations for action. Analysis focused on hydrology and roads, vegetation, wildlife, and fish, which were the resources most valued by agency resource managers and most likely to be influenced by climate change. A vulnerability assessment workshop for each resource area was paired with a workshop to develop adaptation options based on the assessment, resulting in adaptation options for management issues within each disciplinary topic. Emphasis in adaptation was on conserving biodiversity while working to restore late-successional forest structure through active management. The overall process used in the case study has been adopted by local resource managers to incorporate climate change issues in forest plans and projects (Halofsky et al. 2011) and is currently being used to catalyze climate-change education, vulnerability assessment, and adaptation planning across 2.5 million ha in Washington state (North Cascadia Adaptation Partnership 2011).

**Inyo National Forest and Devils Postpile National Monument, California**—
Inyo National Forest (INF) in eastern California contains Mediterranean and dry forest ecosystems, grading from alpine through forest to shrub-steppe vegetation. Much of the

national forest is wilderness with a high degree of biodiversity. Water on the national forest is scarce, fire and insects are important issues, and recreation is the dominant use of public lands. Devils Postpile National Monument (DEPO) is a small national park unit surrounded by INF lands, and collaboration with INF is strong. Ongoing near- and mid-term projects of highest concern focus on vulnerability of INF resources to climate effects that might affect DEPO, and climate adaptation is a high priority in the DEPO general management plan. A science-management partnership facilitated sharing of knowledge about climate change and effects through targeted workshops (Peterson et al. 2011), and assessment reports developed by scientists (Morelli et al. 2011a) assisted managers to consider climate effects relevant to specific resource responsibilities. A scientific technical committee (Peterson et al. 2011) helped to meet science needs for managers of these units. For INF, the Climate Project Screening Tool (Morelli et al. 2011b) was developed, providing a screening process to rapidly assess if climate change would affect resources in the queue for current-year management implementation. Questions about climate-mediated quaking aspen (*Populus tremuloides* Michx.) decline spurred a review of aspen responses to climate and an aspen screening tool for the INF (Morelli and Carr 2011).

For DEPO, where ecosystem protection is prioritized, managing the monument as a climate refugium (Joyce et al. 2008, Peterson et al. 2011) is being evaluated. Because DEPO is at the bottom of a large canyon with cold-air drain age, it contains high biodiversity, and the potential for cold-air drainage to increase in the future may ameliorate the effects of a warmer climate (Daly et al. 2009). In anticipation of this, a network of temperature sensors in multiple-elevation transects and a climate monitoring station were recently installed to measure ongoing changes in temperature.

**Shoshone National Forest, Wyoming**—
Resource managers in Shoshone National Forest worked with Forest Service scientists to write a synthesis on climate change effects and a vulnerability assessment of key water and vegetation resources. The synthesis (Rice et al. 2012) describes what is currently understood about local climate and the surrounding Greater Yellowstone Ecosystem, including paleoclimate, and how future climate change may affect plants, animals, and ecosystems. The assessment highlights components of local ecosystems considered most vulnerable to projected changes in climate and will be integrated in resource-related decisionmaking processes of forest management through collaborative workshops to train managers.

**The Strategic Framework for Science in Support of Management in the Southern Sierra Nevada, California (SFS)**—
The SFS addresses collaborative climate adaptation for the southern Sierra Nevada bioregion of California (Nydick and Sydoriak 2011), including the southern and western slopes of the Sierra Nevada, three national parks, a national monument, three national forests, tribal lands, state and local public lands, forest industry, and other private lands. This landscape spans ecosystems from alpine through diverse conifer and hardwood forests to woodland and chaparral. The effort is coordinated by a coalition of federal resource managers and academic and agency scientists, and was launched with a public symposium to review the state of science on climate issues and adaptation options. The framework document (Exline et al. 2009) guides adaptation by asking (1) Which ecosystem changes are happening, why are they happening, and what does it mean? (2) What is a range of plausible futures? (3) What can we do about it?, and (4) How can relevant information be made available? Interactions among climate change and habitat fragmentation, encroaching urbanization, shifting fire regimes, invasive species, and increasing air pollution are also being considered. To date the SFS collaborative has generated a list of ideas to provide knowledge and tools regarding agents of change and potential responses (box 4.7). An information clearinghouse will be established, including data for vulnerability assessments, decision-support tools, and reports.

## Southern United States

Uwharrie National Forest (UNF) represents a typical national forest context in the southeastern United States, containing 61 parcels mixed with private land and near

### Box 4.7

Initiatives begun and proposed by the strategic framework for science in support of management in the Southern Sierra Nevada cooperative and their alignment with the goals of the strategic framework. (From Nydick and Sydoriak 2011.)

**Goal 1: Detection and attribution**

- Coordinate regional monitoring strategies—tree population dynamics and fisher (*Martes pennanti* Erxleben) populations

**Goal 2: Forecasting future conditions**

- Alternative fire management futures
- Comparison and integration of climate adaptation projects

**Goal 3: Tools and actions**

- Both projects under goal 2 also address goal 3
- Kaweah Watershed coordinated restoration initiative
- Enabling forest restoration goals via ecologically managed biomass generation, including a cost-benefit analysis

**Goal 4: Communication**

- Information clearinghouse for shared learning
- Education and outreach initiative

**Integration across goals**

- Reevaluation of invasive plant programs and practices under alternative climate futures
- Investigation of the vulnerability of blue oak woodlands to climate change and development of adaptive management guidelines

metropolitan areas (Joyce et al. 2008). Providing a wide range of ecosystem services, the region is undergoing a rapid increase in recreational demand. The UNF identified drought-related forest mortality, wildfire, insect outbreaks, soil erosion, stream sedimentation, and water shortages as key issues relative to climate effects. Revision of the forest land management plan explicitly considers climate change effects. Opportunities for adaptation in UNF focus on reestablishing longleaf pine (*Pinus palustris* Mill.) through selective forest management (Joyce et al. 2008). Replanting of drought-tolerant species could provide increased resistance to potential future drought and intense wildfire. Selective harvest and prescribed burns also could target restoration of longleaf pine savannas, mitigating water stress, fuel loads, and wildfire risk anticipated under warming conditions. Concerns about soil erosion and stream sedimentation focus on increasing the size of stream buffer zones where trees are not harvested. Collaboration with surrounding landowners to remove fuels in wildland-urban interfaces is a high priority.

## Northern United States

The U.S. Forest Service in the northeast and upper Midwest is pursuing a comprehensive program of adaptation to climate change (fig. 4.5), including education and training, partnership building, vulnerability assessment and synthesis, planning and decision support, and implementation of demonstration projects. The Forest Service Northern Research Station, Northeastern Area State and Private Forestry, and Northern Institute of Applied Climate Science work collectively to respond to climate change needs. The Climate Change Response Framework (CCRF) developed by these entities augments the institutional capacity of national forests to adapt to climate change by providing a model for collaborative management and climate change response that can accommodate multiple locations, landscapes, and organizations (fig. 4.6). As of 2011, three projects were underway in the Northwoods, Central Hardwoods, and Central Appalachians (fig. 4.7).

The projects focus on building science-management partnerships, developing vulnerability assessments and synthesis of existing information, and establishing a

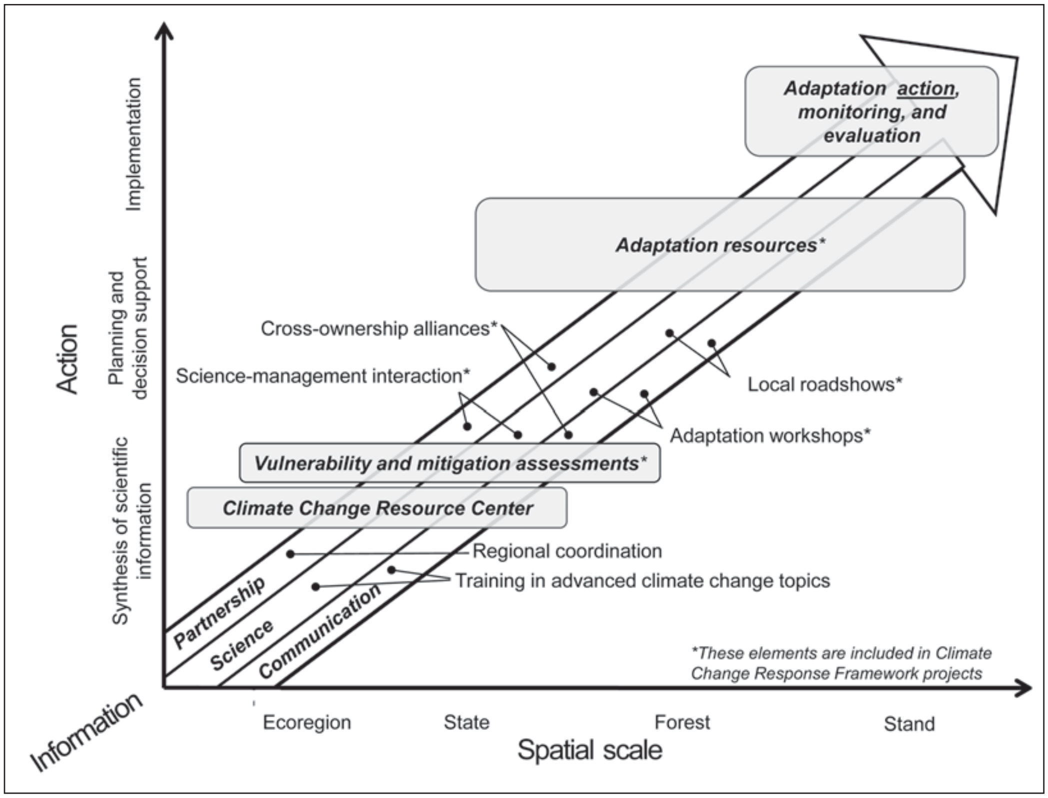


Figure 4.5—The U.S. Forest Service Eastern Region approach to climate change response works from ecoregional scales down to the stand scale by moving information to action through partnerships, science, and communication.

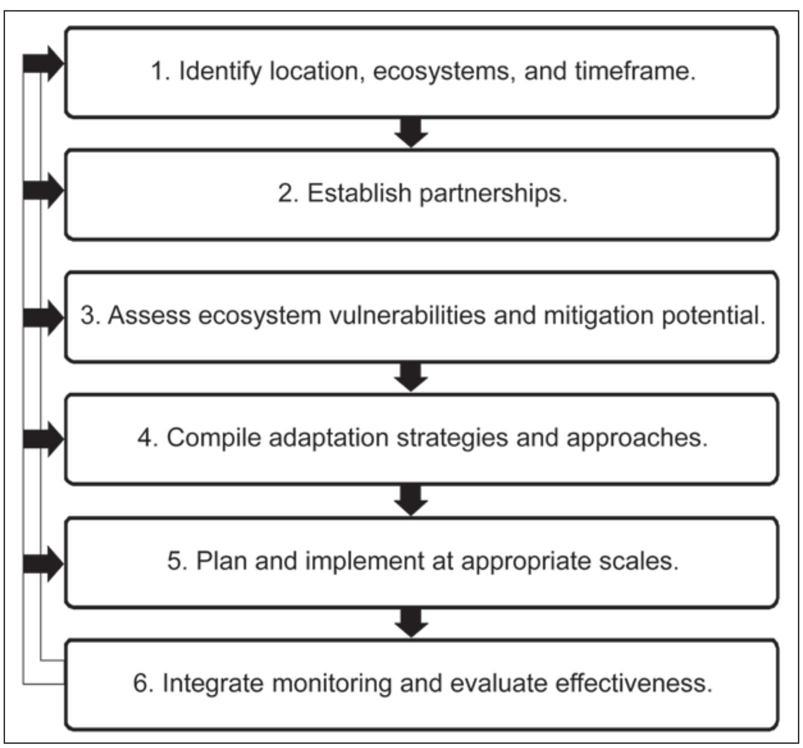


Figure 4.6—The Climate Change Response Framework uses an adaptive management approach to help land managers understand the potential effects of climate change on forest ecosystems and integrate climate change considerations into management. (From Swanston et al. 2012.)

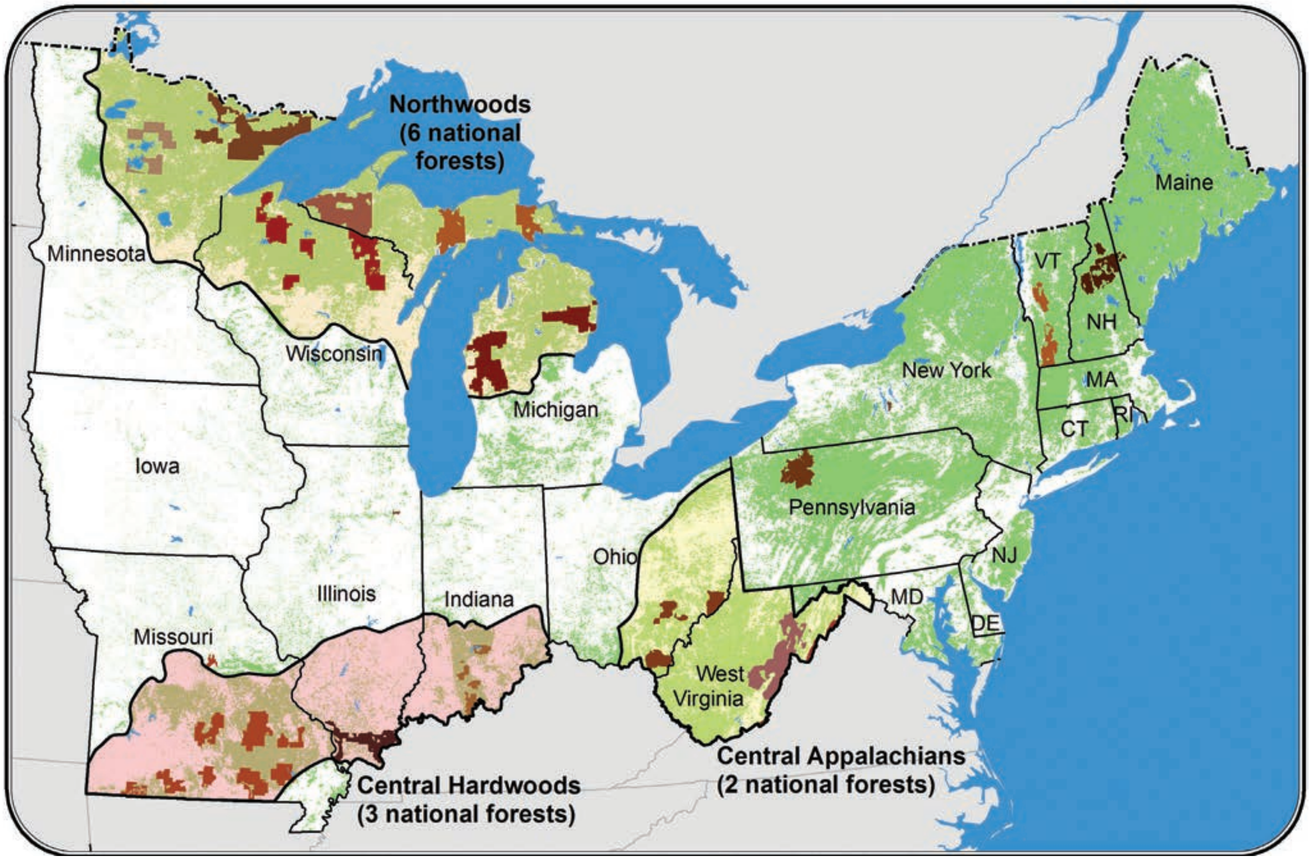


Figure 4.7—The U.S. Forest Service Eastern Region with Climate Change Response Framework (CCRF) projects, identified by shading. National forests are core partners in the CCRF projects, but the projects take an all-lands approach with numerous federal and nonfederal partners. The goal of the CCRF is to complement science-based management decisions made by multiple organizations, each with their own diverse goals, so that forest ecosystems managed by these organizations can become better adapted to a changing climate.

standardized process for considering management plans and activities in the context of the assessment. First, an ecosystem vulnerability assessment and synthesis evaluates ecosystem vulnerabilities and management implications under a range of plausible future climates. Second, a shared landscape initiative promotes dialogue among stakeholders and managers about climate change, ecosystem response, and management. Third, a science team encourages rapid dissemination of information. Fourth, an adaptation resources document includes relevant strategies and a process for managers to devise appropriate tactics. Fifth, demonstration projects incorporate project information and tools in adaptation activities. The CCRF emphasizes an all-lands approach, including national forests, other agencies, and other landowners and stakeholders.

The Northwoods CCRF Project covers 26 million ha of forest in Michigan, Minnesota, and Wisconsin, including six national forests, the Forest Service Northern Research Station, state resource agencies, universities, and other stakeholders. Products to date focus on northern Wisconsin, including a vulnerability assessment (Swanston et al. 2011), a forest adaptation resources document (Swanston and Janowiak 2012), and initiation of demonstration projects in Chequamegon-Nicolet National Forest, where each district was asked to integrate climate change considerations into forest activities. The Medford-Park Falls District identified two aspen stands where silvicultural prescriptions had already been written, but timber had not been marked for harvest, then used CCRF information to consider climate change effects and devised specific adaptation tactics.

A demonstration project started in 2011 convenes a variety of landowners, forest managers, and other stakeholders to discuss climate change effects on specific forest ecosystems, identify adaptation actions, and coordinate implementation of adaptation activities across multiple ownerships. Participants are using CCRF information and tools to devise adaptation tactics appropriate to their management goals. In addition, the Central Hardwoods CCRF, which covers 17 million ha of hardwood forest in Missouri, Illinois, and Indiana, has formed a regional coordinating team with partners from three national forests, the Northern Research Station, and other stakeholders. The Central Appalachians CCRF, which covers 11 million ha of central Appalachian forest in West Virginia and Ohio, includes partners from two national forests and state forestry agencies.

### National Example

**Watershed vulnerability assessment**—
In 2010, a draft watershed vulnerability assessment process was tested in 11 national forests (Furniss et al. 2010), with the goal of quantifying current and projected future condition of watersheds as affected by climate change. A principal objective was to develop a general process that could be tailored to local data availability and resource investment (box 4.8). National forests were asked to include infrastructure, aquatic species, and water uses in the assessments, with analysis areas including at least one "river basin" watershed (hydrologic unit code [HUC] 4). Design of useful strategies for reducing the effects of climate change on ecosystem services requires the ability to (1) identify watersheds of highest priority for protecting amenity values, (2) identify watersheds in which climate-related risk to those values is greatest and least, (3) detect evidence of the magnitudes of change as early as possible, and (4) select actions appropriate for reducing effects in particular watersheds (Peterson et al. 2011).

Hydrologic specialists from participating forests developed an approach for quantifying watershed vulnerability within a relatively short period, and four national forests completed the process within 8 months. Acquiring suitable climate exposure data (the degree, duration, or extent of deviation in climate that a system experiences), which had not been previously used by the participants, was challenging. Threshold values for species and water use differed across the forests. For example, brook trout (*Salvelinus fontinalis* Mitchill) was viewed as a stressor in one forest and a valued resource in another. These differences suggest that, whereas information on processes and resource conditions can be shared among forests, local (forest- and watershed-scale) assessments have the greatest value.

**Box 4.8**

Steps defining the watershed vulnerability assessment process and the types of questions to be addressed. (From Furniss et al. 2010.)

**Step 1—**Set up the analysis and establish the scope and water resource values that will drive the assessment
**Step 2—**Assess exposure
**Step 3—**Assess sensitivity
**Step 4—**Evaluate and categorize vulnerability
**Step 5—**Recommend responses
**Step 6—**Critique the vulnerability assessment

Typical questions to be addressed in a watershed vulnerability assessment:

- Which places are vulnerable?
- Which places are resilient?
- Where are the potential refugia?
- Where will conflicts arise first, and worst?
- Which factors can exacerbate or ameliorate local vulnerability to climate change?
- What are the priorities for adaptive efforts?
- How can context-sensitive adaptations be designed?
- What needs tracking and monitoring?

## Challenges and Opportunities

### Assessing Adaptation Response

In recent years, federal agencies responsible for administering forest ecosystems have produced national climate change response strategies that define adaptation goals and describe a framework for action in field units. These strategies, intended to inform and guide consistent agency-wide responses, emphasize (1) staff training and education in climate sciences, (2) science-management partnerships, (3) assessment of vulnerabilities and risks, (4) maintenance of ecosystem sustainability and biodiversity conservation, (5) integration of climate challenges with other forest disturbance agents and stressors, (6) integration of adaptation with greenhouse-gas mitigation, (7) all-lands and collaborative approaches (working with whole ecosystems and across jurisdictional borders), (8) recognition of short- and long-term planning perspectives, (9) setting priorities, and (10) monitoring and adaptive management.

Adaptation strategies have been advanced unevenly by federal agencies at their regional levels and across local units (e.g., national forests and national parks). Implementation of these strategies is assisted by the presence of local motivated leaders, the support and flexibility provided by regional directors and supervisors, and the understanding and concurrence of constituencies. Some units have worked with local scientists to analyze regional climate projections, develop ecosystem vulnerability assessments, and develop intellectual capacity through staff and constituency education. Collaborative partnerships that extend across ownerships and jurisdictions have been developed as a foundation for some adaptation projects and an aid to communication across ownerships with different resource objectives. A few progressive units have implemented climate adaptation projects on the ground. Only a few site-specific adaptation projects, as described in this chapter, have been implemented across a range of resource issues and tiered to local and regional strategies. Responses of state governments have also been variable, with major forest-sector states in the Western and Northern United States taking leading adaptation strategies. Similar to the federal situation, concepts and frameworks for adaptation are sometimes available, but site-specific project implementation is rare. Education, vulnerability assessments, collaborative partnerships, biodiversity protection, and adaptive management have been key features in adaptation responses by tribes and nongovernmental organizations.

Among the groups that actively address forest adaptation, they commonly address climate change as a metadisturbance agent with other ecosystem stressors. Frequently, climate adaptation is not identified as the primary reason for planning; rather, climate response strategies are subordinate to ecosystem sustainability, forest and watershed restoration, and biodiversity conservation. Adaptation goals are thus commonly met through projects that address high-priority management goals, such as management of fuels and fire, invasive species, insects and pathogens, and watershed condition.

Implementation of site- and issue-specific adaptation plans has been uneven and often superficial across the forest sector, and there appears to be a tendency to rely on quantitative climate- and ecosystem-response models without corroboration to local ecosystems (Millar et al. 2007). A subtle danger in using complex, downscaled, spatially rendered models is that users (e.g., forest managers and planners) may accept model output as the single and likely future, rather than one among many possible outcomes. Models are better used to understand processes and cautiously project future climates and ecosystem responses on specific landscapes and definitive timescales, allowing adaptation treatments to be developed for those outcomes. Better understanding by practitioners of how models are built, and what they can and cannot do, would improve effective application of model output to adaptation.

## Existing Constraints

Various organizations have made progress on adaptation in forest lands, but implementation has been slow, integration across the various sectors (e.g., multiple use, protected area, forest industry) unbalanced, awareness generally low, and site-specific projects few. Numerous barriers appear to impede development and implementation of plans that would promote widespread readiness for American forests to adapt to climate change.

**Education, awareness, and empowerment**—
Many natural resource science curricula now include courses on climate science, ecosystem responses to climate change, and implications for resource management. However, education on historical climatology is rare. Without a clear understanding of mechanisms of climatic dynamics,

use of concepts like "100-year floods" or "restoration to historic conditions," which rest on assumptions of stationary long-term conditions, may lead to inappropriate interpretations and management actions (Milly et al. 2008).

Lack of experience and understanding of climate science by resource managers can lead to low confidence in taking management action in response to climate threats; similar limitations through the chain of supervision and decisionmaking appear to constrain appropriate efforts. Inconsistent support for climate readiness and action extending from executive levels can impede regional planning, which in turn sets up barriers to local implementation. Even if resource managers are trained and competent in climate science, they may lack support from their superiors to implement adaptation strategies and projects.

Lack of public awareness of how climate change affects natural resources influences the level and nature of adaptation by public institutions. Despite widespread public engagement in land management over the past 30 years, pressure to act on climate change has not been as prominent as for other resource issues. On the one hand, little support exists for implementing projects directed to adaptation; on the other hand, there is often strong opposition to projects that address indirect effects of climate, such as forest thinning, postfire logging, herbicide treatments to encourage regeneration, and road improvements for watershed protection. Nonetheless, public pressure can result in climate issues being addressed in resource evaluations and plans.

In some cases, scientific expertise may be unavailable even when science-based strategies are recognized as essential. Scientific institutions have suffered budget reductions, and only some scientists have the interest and capacity to work in management contexts. Even experienced scientists may need to learn the culture, issues, expectations, and scientific focus of management organizations. The demand for scientific participation in on-the-ground adaptation will likely continue to exceed supply as more adaptation programs evolve.

**Policy, planning, and regulatory constraints**—
Both public and private lands are subject to policy, planning, and regulatory direction. Federal agencies are constrained by hierarchies of laws and internal policy and direction, whereas private forest landowners have greater flexibility to determine actions and timing on their land, but remain bound by local, state, and federal laws. In federal agencies, site-specific projects are tiered to levels of planning at higher levels in the organization.

In national forests, site-specific projects tier to each forest's land management plan. These plans guide resource management activities on a forest to ensure that sustainable management considers the broader landscape and values for various resources. The U.S. Forest Service has developed procedures through a new national Planning Rule (Federal Register vol. 76, no. 30; 36 CFR Part 219) to amend, revise, and develop land management plans for 176 units in the National Forest System (NFS). The Planning Rule gives the Forest Service the ability to complete plan revisions more quickly and reduce costs, while using current science, collaboration, and an all-lands approach to produce better outcomes for federal lands and local communities. The Planning Rule addresses management in the context of climate change and changing environmental conditions and stressors, requiring plans to include components that address maintenance and restoration of ecosystem and watershed health and resilience, protection of key resources (e.g., water, air, and soil), and protection and restoration of water quality and riparian areas.

All forest management agencies face the challenge of working at spatial and temporal scales compatible with climate change. This demands integration of goals and projects from small to large scales, a reality that often clashes with the mix of ownerships and regulations, making collaboration across multiple organizations essential. As noted above, progress has been made by recent collaborative efforts that recognized that different regulatory and policy environments (e.g., federal versus private) were not necessarily a barrier. Even at small scales, such as a single national forest or national park, traditional planning approaches dissect lands into discrete units. Thus, harvest units, wilderness areas, developed recreation zones, and endangered species reserves are delimited, subject to standards and guidelines developed for the management zone. This area-constrained approach is static and inflexible, incompatible with the dynamism of climate and climate-related changes and responses.

Environmental laws developed over the past four decades were conceived primarily with an assumption of climatic stationarity, and thus many lack capacity (or legal authorization) to accommodate dynamics of climate-related changes. For example, endangered species laws are often interpreted as indicating native species ranges as they were in presettlement times (e.g., before 1900). Climate changes since then are catalyzing range shifts that sometimes define new native ranges. Enforced maintenance of species in the prior range could prove to be counter adaptive. The National Forest Management Act (NFMA) of 1976 implies maintenance of the status quo based on historical conditions, usually defined, like above, as presettlement ($19^{th}$-century) ranges. For example, the NFMA "diversity clause" requires that a similar mix of species be reforested on national forest lands after harvest as was present before. Because regeneration is the most effective period for changing forest trajectories, planting nontraditional mixes of similar species or introducing new species might be a defensible adaptation response (Joyce et al. 2008).

**Monitoring and adaptive management**—
Future climates and environmental conditions will likely be nonanalog relative to the past. Compounding this situation is the imprint of human land use that has fragmented, restructured, and altered forest ecosystems over the past century. Forest adaptation practices must meet this challenge of novelty and surprise with equally innovative approaches informed by monitoring and adaptive management ("learn as you go"). However, adaptive management in public agencies and other institutions has had minimal success and been implemented slowly, owing in part to lack of funding commitment and lack of analyst capacity. Reorientation of programs, expectations, and interactions with public constituents will be required for monitoring and adaptive management to become a successful partner to adaptation.

**Budget and fiscal barriers**—
Significant additional funding will be needed for a full national response to forest climate adaptation. Education and training, development of science-management partnerships, vulnerability assessments, and development of adaptation strategies are critical components of the adaptation process and can be integrated with other aspects of management, but effective consideration of climate requires additional time and effort. Collaboration across management units and organizations, leveraging of institutional capacities, and other innovative solutions will be needed to address this budget challenge.

## Vision for the Future

**Vision**—
Facilitating long-term sustainability of ecosystem function is the foundation of climate change adaptation. Just as there is no single approach to sustainable forestry, effective climate change adaptation will differ by ecosystem, management goals, human community, and regional climate. If adaptation is addressed in a piecemeal fashion (ecological, geographic, and social), large areas and numerous communities within the forest sector may suffer the consequences of poor preparation, slow response, and inefficiencies. The preceding sections describe principles, policies, approaches, and examples of addressing the challenges of climate adaptation. Here we offer a vision of successful adaptation across U.S. forests within the next 20 years: "A proactive forest sector makes the necessary investments to work across institutional and ownership boundaries to sustain ecosystem services by developing, sharing, and implementing effective adaptation approaches." This broad vision incorporates several critical concepts, each embodied by its own vision.

**Investment**—
Sufficient investment is allocated to successfully achieve visions of development, sharing, and implementation. This includes (1) investment in basic and applied research; (2) support of adequate staffing to accommodate increased planning, monitoring complexity, and interaction with partners; and (3) concerted effort to communicate to the general public the dynamic nature of climate and forests. Monitoring and data sharing are critical to adaptation and adaptive management, and are jointly supported across multiple agencies and land ownerships. Climate change resource centers, instructional courses, and professional meetings are supported to encourage rapid communication and amplify learning in

adaptation management and science. Planning, decisionmaking, and contracting processes that support implementation of ground-level activities are adequately funded so that lands in need of adaptive treatments can be reached before ecosystem function is jeopardized.

**Development**—

***Research***—Research into all aspects of forest ecosystem sciences continues to provide valuable insights into forest responses to climate change. Research into effectiveness of climate-adaptation strategies guides adaptive policy responses.

***Assessment***—Credible information is regularly produced and updated at scales relevant to management decisions that (1) assess vulnerability of ecosystem components, (2) incorporate a range of climate projections, (3) use multiple modeling approaches to project ecosystem response, and (4) incorporate skills and experience of scientists and land managers.

***Learning***—Active learning occurs through traditional research and other pathways: (1) formal adaptive management trials continually produce information to evaluate adaptation techniques; (2) working forests, especially national forests, serve as "living laboratories" with adequate support to pursue adaptive management including adaptation techniques; and (3) management on federal lands is sufficiently documented and monitored to identify broad landscape trends and efficacy of adaptation efforts.

**Sharing**—

***Transparency***—Management goals are clearly stated in forest planning documents, and explicit options for sustaining ecosystem function under a range of plausible future climates provide a preview of potential choices in meeting those goals.

***Communication***—Vulnerable ecosystems and ecosystem components are identified in vulnerability assessments and noted in management plans. Existing or conditional decisions to pursue different adaptation options are explicit in management plans, and associated risks to ecosystem services are addressed. This information is proactively shared and discussed with the general public.

***Ownerships***—Increased investment in local programs that facilitate forest stewardship assists small landowners in managing sustainably. Outreach to consulting foresters and professional associations creates an informed base of private landowners. Information about management activities is shared across boundaries of all public and private lands to enable the forest sector to take advantage of biological and management diversity across large landscapes. Collaboration to manage across administrative and ownership boundaries is commonplace.

***Partnerships***—Adaptation across landscapes is addressed by engaging in productive partnerships, spanning boundaries of agency, ownership, and discipline. Science-management partnerships provide critical information and perspective to members of each discipline and form strong communities of practice.

**Implementation**—

***Planning***—Climate change is incorporated in all planning activities, and on-the-ground prescriptions are adjusted to include adaptation where necessary. Planning is developed for explicit locations with attention to appropriate scale. Public land managers and forestry consultants are well versed in finding and interpreting climate and vegetation projections, and in adjusting plans to accommodate a range of plausible future climates. Open avenues of discussion provide the scientific community with feedback on the relevance and clarity of tools, information, and research directions.

***Monitoring***—Monitoring is integrated across multiple scales and coordinated across institutions. Monitored indicators are sensitive to changes in key ecosystem components. Monitoring data and summaries are freely available. Monitoring data, clear thresholds, and transparent processes for interpretation of data are incorporated in processes for decision-making and changes in management practices (the adaptive management cycle).

***Flexibility***—Management plans acknowledge the increased potential of extreme events, novel climates, and unanticipated ecosystem responses. Decisionmaking structures have adequate flexibility to accommodate multiple potential futures, and to adopt alternative goals if prior goals are no longer feasible in vulnerable systems. Likewise, if adaptation approaches are ineffective, they are redirected. Lessons are shared with the management and scientific communities to encourage transparency and flexibility.

***Implementation***—New information and lessons are rapidly incorporated in management activities. Active management is used to promote resistance in short terms and long-term resilience where appropriate, and the backlog from previous decades of lands in need of treatment is diminishing. Some forests are managed to "soften the landing" as they transition to new species assemblages and forest structures, such that ecosystem processes and ecosystem services are maintained. Forests affected by extreme events are rapidly restored, with due consideration of future climatic effects on species composition and the long-term function of the recovering forest.

### Path to the Vision

The U.S. forest sector can make significant progress toward a vision of sustained forest ecosystem function in the face of climate change by doing the following:

- **Embrace education**. Widespread understanding of the central role of climatic dynamics in ecosystem processes and services is fundamental; therefore, training and educational programs need to be deployed for resource professionals in agencies and for other organizations and the general public. Partnerships with universities can enhance scientific support to science-management partnerships for both adaptation and education.
- **Ensure accountability and infuse climate into all organizational efforts.** The responsibility for ensuring that resource management plans, projects, and decisions are "climate smart" rests on every professional within agencies and other organizations. Knowledge about climate is not an independent staff area but a context through which resource issues can be evaluated. Implementation of this knowledge is the responsibility of personnel across all resource disciplines.
- **Live the all-lands approach and make collaboration the norm.** Effective collaboration across administrative, political, and ownership boundaries, and across diverse cultural and social perspectives is difficult but necessary, often requiring focused effort over an extended period. "Early adapter" collaborations show how regulations, traditions, cultures, and organizational legacies can be navigated successfully. These collaborations need cross-agency and cross-sector support to catalyze effective partnerships.
- **Streamline planning and put projects on the ground.** Nimbleness and flexibility to implement changes are essential ingredients for successful adaptive responses to climatic challenges. Much of the current planning and project implementation process in public agencies contains bureaucratic requirements that detract from actual resource work. Planning processes that prioritize project implementation, including uncertainty, risk, and provisions for experimentation will have the most success. For resource managers, emphasizing education and resource projects rather than administrative tasks will expedite timely adaptation accomplishments.

The challenge of climate change adaptation will require creativity by future generations of forest resource managers. No one agency or organization can fully meet the challenge, but this task is within reach of the forest sector if willing partners work collaboratively toward sustainable management grounded in knowledge of climate science and dynamic ecosystems.

## Carbon Management

Sequestering more carbon (C) in forests and offsetting C emissions with use of wood for energy and products are two of a range of objectives in managing forests. Increasing C storage and C offsets across a range of C pools and emission sources contributes to stabilizing atmospheric concentrations of carbon dioxide ($CO_2$). One time period of interest for the effect of an increase in C emissions on radiative forcing is 100 years (Pachauri and Reisinger 2007). Another, although less well defined, is the time period required to achieve "… stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations 1992). In addition, management activities that would be most desirable would contribute co-benefits, avoid adverse impacts, and sustainably provide needed goods, services, and values.

The historical and current conditions of U.S. forests, forest management practices, and use of forest products have resulted in net C additions to forests and to harvested wood products stocks (tables 4.6, 4.7). However, recent forest sector projection scenarios for the 2010 Resource Planning Act assessment (USDA FS 2012a) suggest that annual C additions could decline more rapidly and U.S. forests could become a net C emitter of 10s to 100s of $Tg \cdot C \cdot yr^{-1}$ within a few decades. This possibility highlights the urgency in identifying the most effective C management strategies given the complexity of factors that drive broader trends on the forest C cycle, and the broad variety of goods, services, and values forests provide.

Understanding biophysical and social influences on the forest C cycle is critical to developing management strategies that can be used to effectively manage forest C stocks and offset C emissions with minimal risks of failure and adverse environmental effects (tradeoffs). With sufficient knowledge of social processes (e.g., landowner or wood-user response to incentives and markets), policies and incentives may be chosen to support strategies with maximum effect. For example, if forest C stocks are expected to decline owing to decreasing land area caused by land use change (e.g., exurban development), policies or incentives to avoid deforestation in those areas may be especially effective. Also, if forest C stocks are expected to decline owing to the effects of changing climate (e.g., prolonged periods of drought), thinning might be especially effective in those areas by protecting C stocks or ensuring some level of continued productivity. Thinning might also reduce impacts on water availability (mainly in arid and semiarid environments) and help increase forest resilience to various stressors (Jackson et al. 2005, Millar et al. 2007, Reinhardt et al. 2008). Protecting old-growth forests and other forests containing high C stocks may be more effective than strategies that would seek to attain C offsets associated with wood use, especially if those forests would recover C very slowly or would not recover in an altered climate.

Sometimes, even if harvest treatment strategies are effective, there may be tradeoffs (losses) judged to be greater than the offset benefits, such as loss of biodiversity in sensitive areas. Alternately, if climate change is expected to increase potential productivity on a given area over a long period of time, increasing forest C stocks through intensive management and forest products, including biomass energy, may be especially effective. Equally important, knowing which strategies to avoid for specific areas will prevent excessive risks and tradeoffs that could make strategies unsustainable. No widely accepted evaluation framework exists to aid decisionmaking on alternative C management strategies designed to maximize C storage while minimizing risks and tradeoffs.

This section discusses (1) current details and trends on where forest C is stored in the United States, (2) issues concerning how to measure progress and effectiveness in averting emissions, (3) current knowledge on the effectiveness of various management strategies in reducing atmospheric GHGs, and (4) effects of incentives, regulations, and institutional arrangements in implementing C management strategies.

## Status and Trends in Forest-Related Carbon

Net annual C additions to forests and harvested wood products account for the vast majority of total annual GHG sequestration among all land uses in the United States (fig. 4.8). Within forests, the two largest C components are aboveground biomass and soil organic C (fig. 4.9). Because aboveground biomass accumulates, then shifts to dead wood, litter, or wood products in a matter of decades, there is an opportunity for forest management and land use activities to affect aboveground biomass accumulation and its disposition over decadal time (i.e., management modifications can result in higher C accumulation and emission offsets).

The change in forest C stocks over time is determined by change in forest area and the change in forest C per unit

**Table 4.6—Net annual changes in carbon stocks in forest and harvested wood pools, 1990–2009**

| Carbon pool | 1990 | 2000 | 2005 | 2009 |
|---|---|---|---|---|
| | *– – Teragrams of carbon per year – –* | | | |
| Forest: | | | | |
| Live, aboveground | -98.2 | -78.3 | -122.1 | -122.1 |
| Live, belowground | -19.3 | -15.7 | -24.1 | -24.1 |
| Dead wood | -8.6 | -3.5 | -8.4 | -9.1 |
| Litter | -8.8 | 7.5 | -11.4 | -11.4 |
| Soil organic carbon | -14.9 | 17.6 | -53.8 | -53.8 |
| Total forest | -149.8 | -72.4 | -219.9 | -220.6 |
| Harvested wood products: | | | | |
| Products in use | -17.7 | -12.8 | -12.4 | 1.9 |
| Products in solid waste disposal sites | -18.3 | -18.0 | -16.3 | -16.7 |
| Total harvested wood products: | -35.9 | -30.8 | -28.7 | -14.8 |
| Total net flux | -185.7 | -103.2 | -248.6 | -235.4 |

Source: USEPA 2011.

**Table 4.7—Carbon stocks in forest and harvested wood pools, 1990–2010**

| Carbon pool | 1990 | 2000 | 2005 | 2010 |
|---|---|---|---|---|
| | *– – – – Teragrams of carbon – – – –* | | | |
| Forest: | | | | |
| Live, aboveground | 15,072 | 16,024 | 16,536 | 17,147 |
| Live, belowground | 2,995 | 3,183 | 3,285 | 3,405 |
| Dead wood | 2,960 | 3,031 | 3,060 | 3,105 |
| Litter | 4,791 | 4,845 | 4,862 | 4,919 |
| Soil organic carbon | 16,965 | 17,025 | 17,143 | 17,412 |
| Total forest | 42,783 | 44,108 | 44,886 | 45,988 |
| Harvested wood products: | | | | |
| Products in use | 1,231 | 1,382 | 1,436 | 1,474 |
| Products in solid waste disposal sites | 628 | 805 | 890 | 974 |
| Total harvested wood products: | 1,859 | 2,187 | 2,325 | 2,449 |
| Total carbon stock | 44,643 | 46,296 | 47,211 | 48,437 |

Source: USEPA 2011.

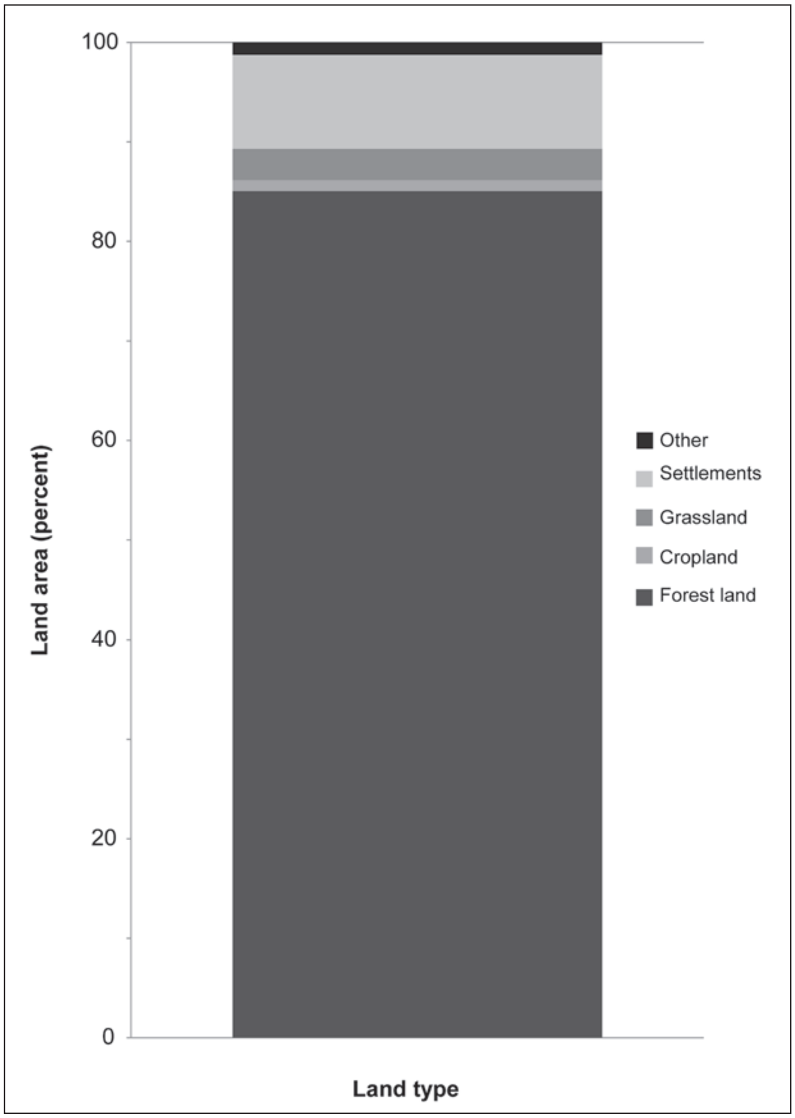


Figure 4.8—Contribution of land areas to net annual carbon sequestration, percentage by land type, 2009.

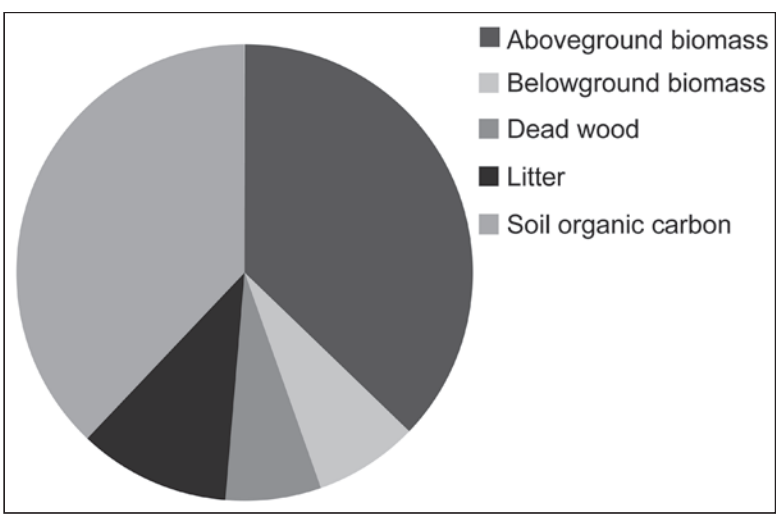


Figure 4.9—Forest carbon pools, share of carbon stored in 2009.

area (C density). Since the 1950s, timberland area nationwide has been stable (fig. 4.10) while the C per unit area has been increasing (i.e., increasing C density). In recent years, the annual increase per unit area has been increasing. The slow accumulation of forests is primarily the result of large-scale reforestation of the United States since the early 1900s. The increasing rate of annual sequestration is a result of gross growth per year continuing to increase, while mortality has increased slowly and harvest removals have stablized (fig. 4.10). Although there are national trends of stable forest area and increasing annual additions of C to forests, it is likely that there are local areas where mortality plus harvest exceeds growth.

Aboveground biomass C stocks are largely found in the Pacific coastal region, Appalachian Mountains, Rocky Mountains, Lake States, and central hardwoods (fig. 4.11). Despite the gradual net increase in forest land area and increased C stocks per unit area, there can be higher variation in net annual C sequestration at smaller spatial scales. A forest can easily become a net emitter of C on account of local disturbances such as wildfire. For most counties, it is estimated that C stocks have been increasing in recent years (fig. 4.12), although uncertainty in annual net sequestration estimates increase greatly as the scale decreases. Given the low density of forest plots that are remeasured each year, estimates of interannual variation in forest C stocks for a local area may only be detectable after major changes such as those occurring after large disturbance events (e.g., large wildfire).

## Monitoring and Evaluating Effects of Carbon Management

Figure 4.13 shows C storage and emission processes that can be affected by management of C in forests and wood products. Carbon changes are evaluated by tracking C flows across the system boundaries over time. The boundary around the "forest sector" includes forest, wood products, and wood energy processes. The system boundary includes a defined forest area. A system can be defined to include only C fluxes to and from forests or wood products, or it may include C fluxes from equipment used to manage forests and make and transport wood products, nonwood products, and fossil fuel feedstocks. The effectiveness of C management activities for mitigating GHG emissions is based on forest removal (and retention) of $CO_2$ from the atmosphere.

Forest management can also affect GHG emissions beyond the "forest sector." System boundaries can be expanded to include processes to make energy from fossil fuels where wood energy can substitute, or to include GHG emitting processes to make nonwood products where wood products can substitute. System boundaries can also be expanded beyond the defined forest area to nonforest areas where actions may cause indirect land use change and associated GHG emissions. System boundaries also include a definition of the time period over which C storage or emissions are evaluated. The choice of system boundaries affects the overall assessment, and defining an objective to alter C management strategy, store C, or alter emissions cannot be done without clearly defining boundaries, processes, and time period. Currently, no standard approach exists for doing this to evaluate forest biomass as a replacement for fossil fuels.

Evaluation of C management strategies associated with forests requires (at a minimum) (1) monitoring C stock changes and emissions over time, and (2) evaluating the effects of altered activities that affect in-forest C (in situ) and associated C storage or emissions outside forests (ex situ). The first accounting framework (type A) determines how C fluxes in terrestrial systems and harvested wood products have actually changed for a current or past period because of management actions and other factors such as natural disturbances. The second accounting framework (type B) determines the degree to which a change in management under various mitigation strategies could increase C storage and decrease emissions.

This accounting compares mitigation activities to a baseline to determine the magnitude of additional C offsets compared to the baseline. A baseline is the level of C stock, C stock change, level of emissions or emissions change as the result of a given set of land conditions and activities (e.g., forest management, timber harvest, and disturbances) and off-land activities (e.g., substitution for fossil emissions, as defined by the accounting system and boundaries at a point in time or over a period of time). A baseline can be defined by a past set of conditions or an envisioned future set

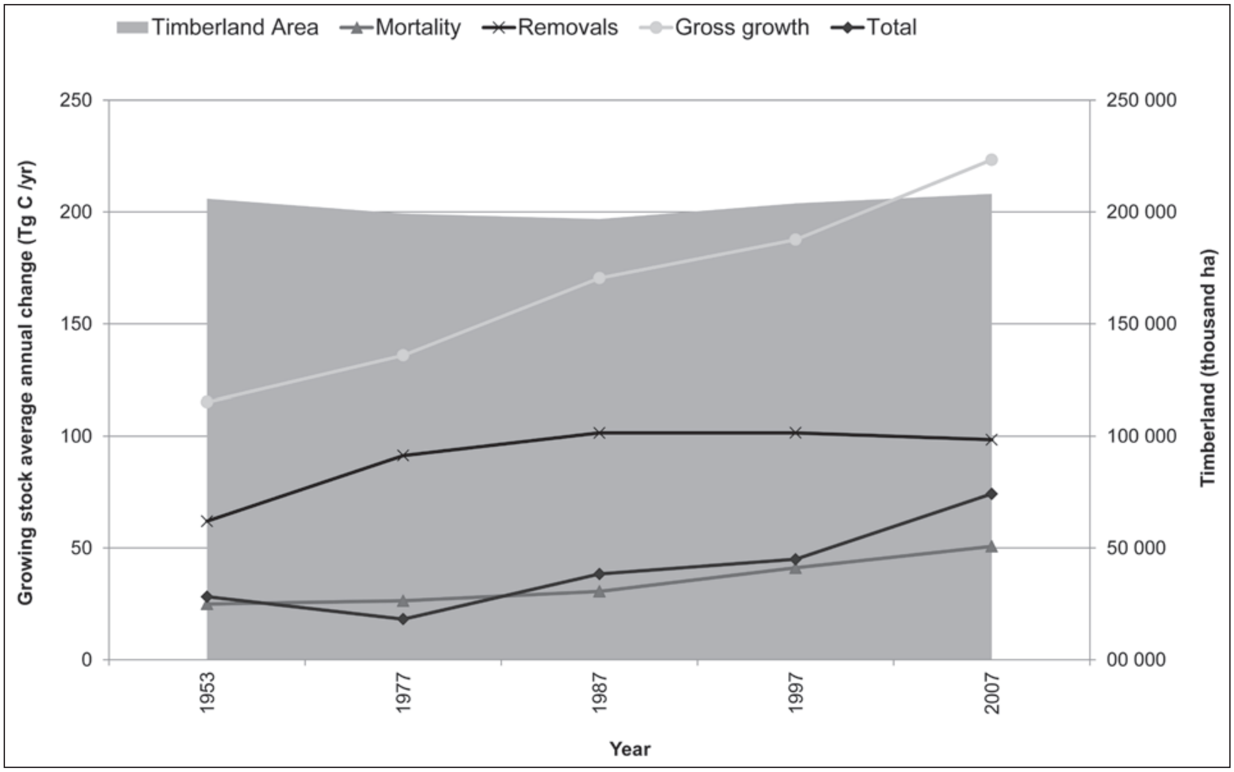


Figure 4.10—Growing stock carbon change owing to growth, mortality, and removals, along with timberland area, 1953–2007.

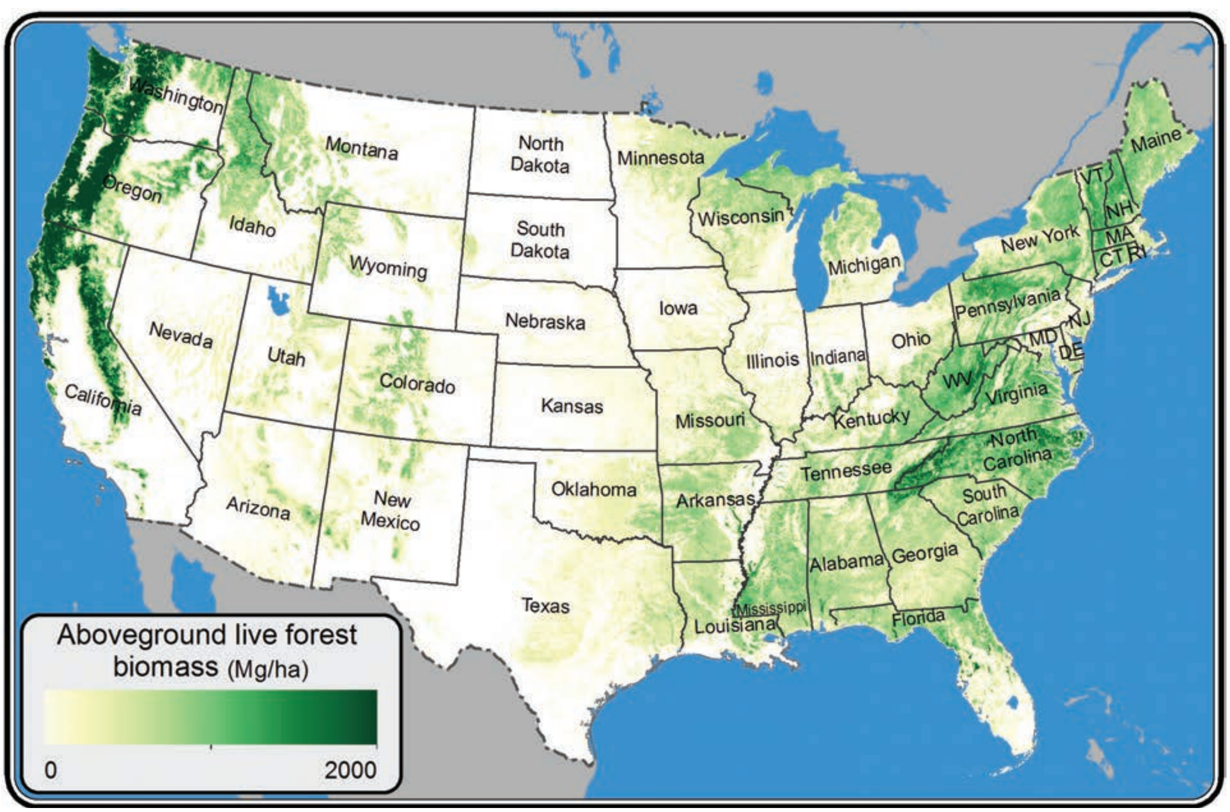


Figure 4.11—Aboveground live biomass in forests.

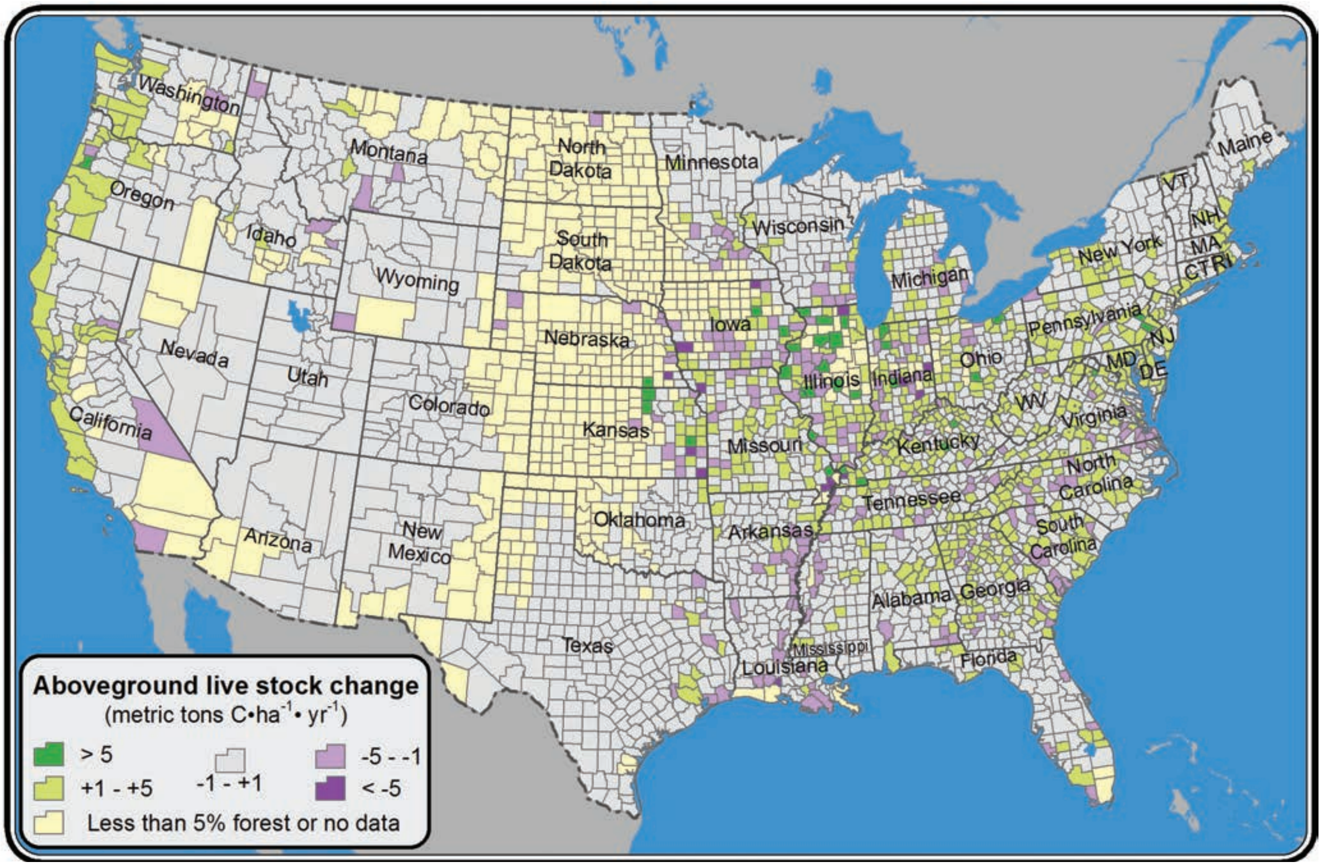


Figure 4.12—Aboveground live forest carbon (C) change.

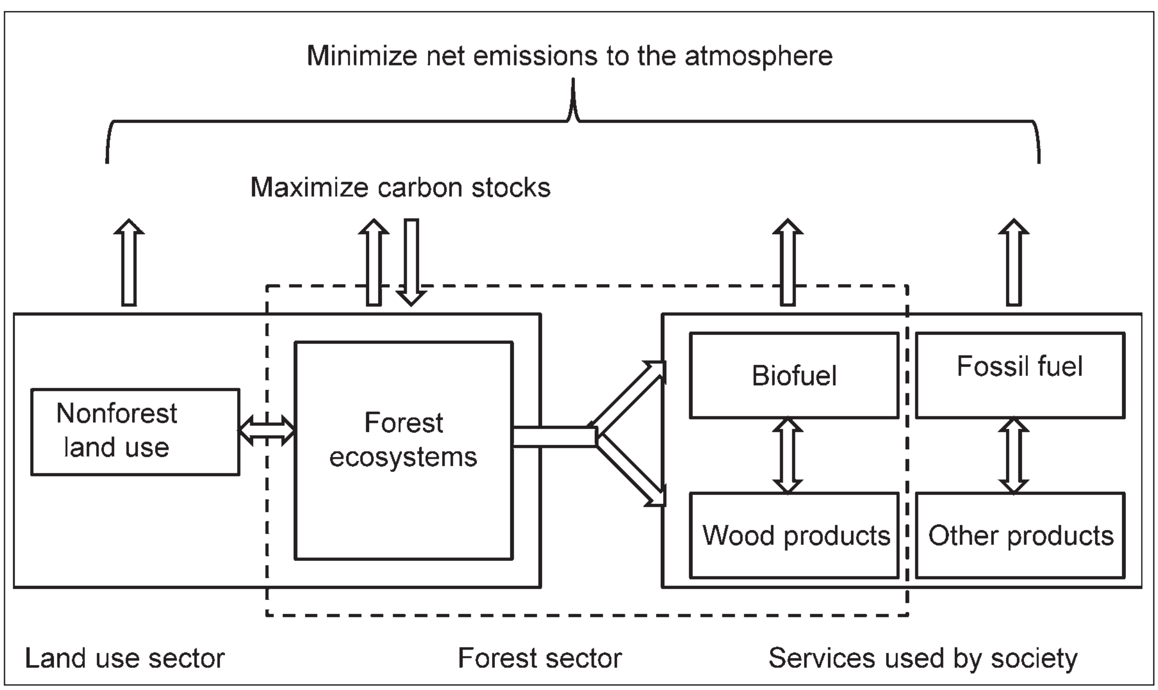


Figure 4.13—Forest sector and nonforest sector greenhouse gas emissions and stock changes that are influenced by forest management.

of conditions. The effectiveness of a new strategy, such as an incentive to increase wood use for energy, is determined by changes in landowner behavior. For example, with high energy use (high price) some landowners may convert non-forest land to wood plantations and accumulate more C as well as gain benefit from substituting wood for fossil fuel. In addition, an increase in wood prices could cause pulpwood to be used for energy and decrease oriented strandboard panel production and resultant C storage in panels.

A specific accounting framework for evaluating C management must include, explicitly or implicitly, a specification of the type of accounting framework (A or B) and of the system boundaries for the processes included (e.g., forest sector, service sector, nonforest land use, specific forest area, time period, wood C only, and other GHG emissions from processes).

A "common" type A accounting framework for monitoring is to define system boundaries to include current annual C exchange with the atmosphere from forest ecosystems at a given geographic scale, plus C additions and emissions for harvested wood products from those forests (fig. 4.13). This framework can be used to answer this management question for a given forest area: "Are forests and forest products continuing to (collectively) withdraw and store C from the atmosphere?" The framework is also the basis for reporting GHG emissions and sinks in many accounting systems such as that used in annual reports to the United Nations Framework Convention on Climate Change.

This framework is not intended for evaluating the full effects on atmospheric $CO_2$ of a change in strategy, which would require a system boundary that includes changes in nonwood C emissions and C emissions or storage outside the forest. Some excluded changes may include altered fossil fuel use, other land use emissions, and altered nonwood product emissions (fig. 4.13). Evaluating strategy changes requires a framework that includes all processes that significantly change atmospheric $CO_2$. If changes in emissions occur over many years, the framework must evaluate $CO_2$ fluxes over many years. For example, a strategy to increase use of wood for heat, electric power, or biofuels via incentives at a national level would change $CO_2$ flux estimates compared to a given baseline over an extended time from (1) wood for energy, (2) fossil fuels for energy, (3) land use change (crops to plantation, or forest to intensive plantation), and (4) flux from forests where wood is removed (including regrowth after removal). The accounting system needs to include all processes noted in fig 4.13.

"Leakage" is a term used to recognize certain C effects when evaluating the effects of a policy or management change by using a type B accounting framework. Leakage is the C effects of a program change that are outside the system boundaries defined by a limited set of processes, (e,g., C changes for a specific forest area). Leakage, which includes C changes on land outside of a system boundary (e.g., caused by changes in harvest or land use) (Gan and McCarl 2007, Murray et al. 2004, Pachauri and Reisinger 2007, Schwarze et al. 2002, Sohngen et al. 1999), differs depending on the mitigation activity and can be quite high (Gan and McCarl 2007, Murray et al. 2004). In the United States, leakage estimates associated with activities on a given land area range from less than 10 percent to greater than 90 percent (proportion of C benefit lost), depending on the activity and region (Murray et al. 2004). Globally, leakage estimates range between 42 and 95 percent (Gan and McCarl 2007).

Leakage tends to be highest where programs constrain the supply of forest products (e.g., no harvest is allowed) or constrain land use change (e.g., forest land conversion to agriculture) (Aukland et al. 2003; Depro et al. 2008; Murray et al. 2004; Sohngen et al. 1999, 2008; Sohngen and Brown 2008). In contrast, the indirect effects of a program can increase C benefits outside of a system boundary, a phenomenon termed "spillover" (Magnani et al. 2009). For example, spillover can occur if an increase in plantation forestry reduces C losses from established forests by increasing C flows in cheaper forest products (Magnani et al. 2009). Defining system boundaries to include indirect effects on C (e.g., multinational programs) or otherwise accounting for leakage ensures program integrity.

Carbon storage strategies may be ineffective because of flaws in incentive structures or policies, and not caused by the biophysical attributes of the strategy itself. For example, an incentive program might favor harvesting large trees that produce lumber, assuming that lumber would replace building materials that emit more C in manufacturing. If this incentive strategy were implemented, the lumber could go to nonbuilding uses, or an increase in harvest by one landowner could be offset by a decrease by another. This is a flaw of the incentive system, not of the underlying wood substitution strategy. If there were incentives for builders to use wood in structures rather than alternate materials, the strategy could be effective in reducing overall emissions from manufacturing; however, the effectiveness depends on the assumed changes in forest management.

As described above, the focus of evaluating C management strategies was on understanding how altered management influenced C on a given land area. It is also possible to evaluate strategies by focusing on the change in C storage or emissions associated with producing one unit of wood energy or one unit of wood product, by using life cycle assessment (LCA). An "attributional LCA" is similar to a type A accounting framework and includes specification of processes that include forest growth, harvest, manufacturing, end use, disposal, and reuse, with the objective of estimating storage and emissions over the life cycle of one unit of product. Attributional LCAs are used to monitor inputs and emissions associated with production and do not include all process that would be affected by a change in production or in processes. A "consequential LCA" also specifies a unit of product and system boundary, but is similar to the type B framework noted above because the objective is to estimate the change in emissions associated with a one-unit change in product production or some change in processes over the life cycle. Consequential LCAs are typically used to analyze the potential response of a change to a system, such as a change in policy, and can include the effect of changing demand levels for products on production and emissions from other products across many sectors.

Different C management strategies are often evaluated by using different system boundaries, accounting frameworks, models, assumptions, functional units (land area vs. product units), and assumed incentives. Therefore, it can be difficult to compare the effectiveness of different strategies. However, it is possible to describe the effects of strategies on changing particular processes, uncertainty in attaining the effects, and timing of the effects.

## Carbon Mitigation Strategies

Carbon mitigation through forest management focuses on (1) land use change to increase forest area (afforestation) or to avoid deforestation, or both; (2) C management in existing forests; and (3) use of wood as biomass energy, in place of fossil fuel or in wood products for C storage and in place of other building materials. Estimates of the amount of the Nation's $CO_2$ emissions offset by forests and forest products (using the type A framework) vary with assumptions and accounting methods (e.g., from 10 to 20 percent) (McKinley et al. 2011), with 13 percent (about 221 $Tg \cdot C \cdot yr^{-1}$) being the most recent estimate for the United States (USEPA 2011). The first two strategies aim to maintain or increase forest C stocks (using the type B framework with a boundary around forest area and other land capable of growing forests). The last strategy focuses on increasing C storage or reducing fossil fuel emissions, including C fluxes associated with forests and products removed from the forest (using the type B framework with a boundary around the forest sector, services, and nonforest land processes [fig. 4.13]. The mitigation potential of these strategies differs in timing and magnitude (table 4.8).

**Land use change: afforestation, avoiding deforestation, and urban forestry**–

**Afforestation**—In the United States, estimates of the potential for afforestation (active establishment or planting of forests) to sequester C vary from 1 to 225 $Tg \cdot C \cdot yr^{-1}$ for 2010 to 2110 (U.S. Climate Change Science Program 2007, USEPA 2005). Afforestation can be done on land that has not been forested for some time (usually more than 20 years), such as some agricultural lands, or on lands than have not historically supported forests, such as grasslands. Reforestation refers to establishing forests on land that has been in nonforest use for less than the specified time period. Mitigation potentials, cobenefits, and environmental tradeoffs depend on where afforestation and reforestation efforts are implemented (table 4.8).

The mitigation potential of afforestation and reforestation on former forest land is significant and generally has the greatest cobenefits, lowest risk, and fewest tradeoffs. Forest regrowth on abandoned cropland comprises about half of the

## Table 4.8—Mitigation strategies, timing of impacts, uncertainty in attaining carbon (C) effects, cobenefits and tradeoffs[a]

| Mitigation strategy | Timing of maximum impact | Uncertainty about strategy (biophysical risks) | Uncertainty about strategy (structural risks)[b] | Cobenefits | Tradeoffs |
|---|---|---|---|---|---|
| Land use change: | | | | | |
| Afforestation (on former forest land) | Delayed | Low | Leakage | Erosion control; improved water quality; increased biodiversity and wildlife habitat | Lost revenue from agriculture |
| Afforestation (on nonforest land) | Delayed | Moderate | Leakage | Biodiversity | Erosion; lower streamflow; decreased biodiversity and wildlife habitat; increased nitrous oxide emissions; competition for agricultural water; local warming from lower albedo |
| Avoided deforestation | Immediate | Low | Leakage | Watershed protection; maintain biodiversity and wildlife habitat, some recreational activities | Lost economic opportunities affecting farmers or developer directly |
| Urban forestry | Delayed | High | | Reduced energy use for cooling; increased wildlife habitat; possible recreational opportunities | High maintenance might be required in terms of water, energy, and nutrients; possible damage to infrastructure |
| In situ forest C management: | | | | | |
| Decreasing C outputs | Immediate | Moderate | Leakage | Increased old-growth seral stage; increased structural and species diversity, and wildlife habitat; effects on benefit depend on landscape condition | Displaced economic opportunities affecting forest owners, forest industry, and employees |
| Increasing forest growth | Delayed | Low | Leakage | Higher wood production, potential for quicker adaptation to climate change | Lower streamflow, loss of biodiversity, release of nitrous oxide, greater impact of disturbance on C storage |
| Fuel treatments | Delayed | High | | Lower risk from fire and insects; increased economic activity; possible additional offsets from use of wood; climate change adaptation tool | Lost economic opportunities to firefighting business and employees; lower C on site; site damage caused by treatment |
| Ex situ forest C management: | | | | | |
| Product substitution | Part immediate, part delayed | Moderate | Leakage | Increased economic activity in forest product industries | Active forest management on larger area; low C storage in forests |
| Biomass energy | Immediate to delayed depending on source | Moderate/high | Leakage | Increased economic activity in forest product industries; could reduce cost of forest restoration efforts | Intensive management on large area; lower C storage in forests |

[a] Uncertainty as defined here is the extent to which an outcome is not known. All mitigation strategies have a risk of leakage and reversal, which could compromise C benefits. Timing of maximum impact is adapted from IPCC (2007) and uncertainty, cobenefits, and tradeoffs from McKinley et al. (2011).

[b] The potential degree of leakage or other structural risk for a strategy depends on the incentives, regulations, or policy used to implement it. For example, if an incentive program to increase forest growth is in only one region, then growth may be decreased in other regions. If the incentive is nationwide, there is little leakage within the United States, but may be leakage to other countries. Other structural risks can come from improper selection of locations to implement the strategy. For example, fire hazard reduction treatments could be done on land areas where fire-risk offsets are insufficiently long lasting or emission mitigating in comparison to expected avoided emissions from fire. There can also be risk in selecting wood for fuel (e.g., from older forests) where C recovery will be very slow.

U.S. C sink (Pacala et al. 2001). One study estimated that sequestering the equivalent of 10 percent of U.S. fossil fuel emissions (160 Tg of C) would require that 44 million ha, or one-third of U.S. croplands, be converted to tree plantations (Jackson and Schlesinger 2004). Another report estimates that 262 000 to 1 133 000 ha are needed to sequester 1 Tg of C annually (USEPA 2005). Given potential global food shortages and high value of many crops, forest establishment on productive croplands is not likely tenable and may cause project leakage (Murray et al. 2004). However, establishing forest plantations on marginal agricultural land or abandoned agricultural land is more feasible, because potential interference with food production is lower. Where climatic and soil conditions favor forest growth (over crops), irrigation and fertilization inputs would be low relative to gains in C storage. Cobenefits may include erosion control, improved water quality, higher species diversity, and wildlife habitat. The cobenefits of afforestation are enhanced where native species comprise a substantial proportion of the regenerated forest. Monocultures of nonnative or native improved-growth species may yield high C storage rates and have a low risk for unintended results, but may also provide fewer cobenefits.

Afforestation on lands that do not naturally support forests may require more human intervention and environmental tradeoffs. Carbon storage in tree and shrub encroachment into grasslands, rangelands, and savannas is estimated to be 120 $Tg{\cdot}C{\cdot}yr^{-1}$, a C sink that could be equivalent to more than half of what existing U.S. forests sequester annually, although this estimate is highly uncertain (U.S. Climate Change Science Program 2007). This C sequestration shows the potential (unintentional) effects of land use change and other human activities (Van Auken 2000). Planting trees where they were not present historically can sometimes alter species diversity, lower the water table, cause soil erosion on hill slopes, and absorb more solar energy compared with the native ecosystem (Farley et al. 2008, Jackson et al. 2008, Jobbagy and Jackson 2004, McKinley and Blair 2008, Schwaiger and Bird 2010). Irrigation and fertilization would likely be needed in many areas, particularly in arid and semiarid regions, which might compete with agricultural water supply and other uses. Afforestation also has the potential to reduce streamflow because some species of trees use more water than grasses or crops (Farley et al. 2005, Jackson et al. 2005). Use of nitrogen (N) fertilizers may increase nitrous oxide emissions, a GHG with roughly 300 times more global warming potential than $CO_2$. This type of afforestation has more risks compared with afforestation on lands that naturally support forests.

***Avoiding deforestation***—Avoiding the loss of forested land can prevent a significant loss of C to the atmosphere. Currently, global deforestation results in the gross annual loss of nearly 90 000 $km^2$, or 0.2 percent of all forests (FAO 2007, Pachauri and Reisinger 2007), which is estimated to release 1400 to 2000 $Tg{\cdot}C{\cdot}yr^{-1}$, with about two-thirds of the deforestation occurring in tropical forests in South America, Africa, and Southeast Asia (Houghton 2005, Pachauri and Reisinger 2007). Over a recent 150-year period, global land use change released 156 000 Tg of C to the atmosphere, mostly from deforestation (Houghton 2005). In contrast, forested area in the United States increased at a net rate of about 340 000 $ha{\cdot}yr^{-1}$ in a recent 5-year period (2002 to 2007). Increases in forested area and forest regrowth are largely responsible for the current U.S. forest C sink of 211 $Tg{\cdot}C{\cdot}yr^{-1}$ (USEPA 2011). However, these dynamics will change, with future land use expected to decrease total forested area by more than 9 million ha by 2050 (Alig et al. 2003). Development and conversion of forest to pasture or agricultural land are responsible for much of the current and expected loss of forests. In addition, increased area burned by fire may result in the conversion of some forests to shrublands and meadows (Westerling et al. 2011), or a permanent reduction in C stocks on existing forests if fire-return intervals are reduced (Balshi et al. 2009, Harden et al. 2000). Potential C mitigation estimates through avoided deforestation are not available for the United States.

Avoided deforestation protects existing forest C stocks and has many cobenefits and low risk (table 4.8). Cobenefits include maintaining ecosystem properties and processes, such as watersheds, biodiversity, wildlife habitat, and some recreational activities (McKinley et al. 2011). Risks include incentives to avoid deforestation in one area that may increase removal of forest in other areas, with little net lowering of atmospheric $CO_2$. Avoided deforestation may decrease economic opportunities for timber, agriculture, pasture, or urban development (Meyfroidt et al. 2010). Leakage can be large for avoided deforestation, particularly if harvest is not allowed (Murray et al. 2004). Regenerating forests after severe wildfires may be important for avoiding conversion of forest to meadow or shrubland (Donato et al. 2009, Keyser et al. 2008).

***Urban forestry*—**Urban forestry, the planting and management of trees in and around human settlements, offers limited potential to store additional C, but urban trees provide some indirect ways to reduce fossil fuel emissions and have many cobenefits. Although U.S. urban C stocks are surprisingly large (Churkina et al. 2010), the potential for urban forestry to help offset GHG emissions is limited for two reasons: (1) urban areas make up only a small fraction of the U.S. landscape (3.5 percent) (Nowak and Crane 2002), and (2) urban trees generally require intensive management. Urban forests have important indirect effects on climate by cooling with shading and transpiration, potentially reducing fossil fuel emissions associated with air conditioning (Akbari 2002). When urban forests are planted over very large regions, the climate effects are less certain, because trees have both warming effects (low albedo) and cooling effects, and may result in complex patterns of convection that can alter air circulation and cloud formation (Jackson et al. 2008). However, urban trees can have high mortality rates in all regions (Nowak et al. 2004), and they require ongoing maintenance, particularly in cities that are in arid regions; risks increase when irrigation, fertilization, and other forms of maintenance are necessary (Pataki et al. 2006).

## In Situ Forest Carbon Management

Carbon mitigation through forest management focuses on efforts to increase forest C stock by either decreasing C outputs in the form of harvest and disturbance, or increasing C inputs through active management. Potential C mitigation for a combined effort including increased harvest intervals, increased growth, and preserved establishment could remove 105 Tg·C·yr $^{-1}$, although achieving these results would require large land areas. It is estimated that between 479 000 and 707 000 ha of manageable forest land is needed to store 1 Tg·C·yr $^{-1}$ (USEPA 2005).

**Increasing forest carbon by decreasing harvest and protecting large carbon stocks**—
Forest management can increase the average forest C stock by increasing the interval between harvests or decreasing harvest intensity (Balboa-Murias et al. 2006, Harmon and Marks 2002, Harmon et al. 2009, Jiang et al. 2002, Kaipainen et al. 2004, Liski et al. 2001, Schroeder 1992, Seely et al. 2002, Thornley and Cannell 2000). Increasing harvest intervals would have the biggest effect on forests harvested at ages before peak rates of growth begin to decline (culmination of mean annual increment [CMAI]), such as some Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests in the northwestern United States. Increasing rotation age for forests with low CMAI, such as southern pine species that are already harvested near CMAI, would yield a decreasing benefit per year of extended rotation.

Harvesting forests with high biomass and planting a new forest reduces overall C stocks more in the near term than if the forest were retained, even counting the C storage in harvested wood products (Harmon et al. 1996, 2009). For example, some old-growth forests in Oregon store as much as 0.0011 Tg·C·ha$^{-1}$ (Smithwick et al. 2002), which would require centuries to regain if these stocks were liquidated and replaced, even with fast-growing trees (McKinley et al. 2011). Low intensity or partial harvests, including leaving dead wood on site, maintain higher C stocks compared to clearcuts (Harmon et al. 2009), while possibly reducing the risk of disturbance, such as fire and damaging storms, and concurrently allowing forests to be used for wood products or biomass energy. However, although thinning increases the size and vigor of residual trees, it generally reduces net C storage rates and C storage at the stand scale (Dore et al. 2010, Schonau and Coetzee 1989). Studies evaluating the harvest effects on soil C provide mixed conclusions (Johnson and Curtis 2001, Nave et al. 2010). Decreasing removal of C from forests through longer harvest intervals or less intense harvests increases forest C stocks. Benefits of decreased outputs include an increase in structural and species diversity (table 4.8). Risks include C loss owing to disturbance and reduced substitution of wood for materials that emit more C in manufacturing.

**Managing forest carbon with fuel treatments**—
Since 1990, $CO_2$ emissions from wildland forest fires in the conterminous United States have averaged 67 $Tg{\cdot}C{\cdot}yr^{-1}$ (USEPA 2009a, 2010). The possibility that fuel treatments, although reducing onsite C stocks, may contribute to mitigation by providing a source for biomass energy and avoiding future wildfire emissions, is attractive, especially because fuel treatments may play an important role in climate change adaptation. Fuel treatments have other important benefits, including their potential to protect property and restore forest conditions more resilient to periodic wildfire. It is unlikely that fuel treatments would be implemented solely to manage C stocks.

Fuel treatments are a widespread forest management practice in the Western United States. (Battaglia et al. 2010), and are designed to alter fuel conditions to reduce wildfire intensity, crown fires, tree mortality, and suppression difficulty (Reinhardt et al. 2008, Scott and Reinhardt 2001). Fuel treatment to reduce crown fire hazard can be done by reducing surface fuels, ladder fuels (small trees), and canopy fuels (Peterson et al. 2005). All of these remove C from the site, whether through harvest or prescribed fire (Reinhardt et al. 2010, Stephens et al. 2009), and alter subsequent forest C dynamics by modifying the residual stand.

Crown fires often result in near-total tree mortality, whereas many trees can survive surface fires. This contrast in survival has led to the notion that fuel treatments may offer a C benefit by removing some C from the forest to protect the remaining C (Dore et al. 2010, Finkral and Evans 2008, Hurteau et al. 2008, Mitchell et al. 2009, Stephens et al. 2009). Thinned stands that burn in a surface fire typically have much higher tree survival and lower C losses than similar, unthinned stands that burn in a crown fire (e.g., Finkral and Evans 2008, Hurteau and North 2009, Hurteau et al. 2008, Stephens et al. 2009), although the net effect of fuel treatment C removal and surface fire emissions may exceed that from crown fire alone, even when materials from fuel treatments are used for wood products (Reinhardt et al. 2010). Because fuel treatment benefits are transient, they may lapse before a wildfire occurs, in which case the C removed by the fuel treatment is not offset by reduced wildfire emissions.

Modeling studies suggest that fuel treatments in most landscapes will result in a net decrease in landscape C over time (Ager et al. 2010, Harmon et al. 2009, Mitchell et al. 2009), because the savings in wildfire emissions is gained only on the small fraction of the landscape where fire occurs each year. For treatments to yield a substantial C benefit, the following conditions would be required: (1) relatively light C removal would substantially reduce emissions, (2) fire occurrence is high in the near term (while fuel treatments are still effective), and (3) thinnings can provide wood for energy or long-lived products that yield substitution benefits. If fuel treatments are implemented, it is advantageous from a C management standpoint to use removed fuels for energy production or wood products, rather than burning them onsite (Coleman et al. 2010, Jones et al. 2010). Feasibility and energy implications depend in part on hauling distance (Jones et al. 2010). An intriguing alternative to hauling bulky biomass to conversion facilities is in situ pyrolysis to produce energy-dense liquid fuel and biochar which can remain onsite to enhance soil productivity and sequester C (Coleman et al. 2010).

**Increasing forest carbon stocks by increasing forest growth**—
Increasing growth rates in existing or new forests could increase C storage on the landscape and increase the supply of forest products or biomass energy. Practices that increase forest growth include fertilization, irrigation, use of fast-growing planting stock, and control of weeds, pathogens, and insects (Albaugh et al. 1998, 2003, 2004; Allen 2008; Amishev and Fox 2006; Borders et al. 2004; Nilsson and Allen 2003). The potential associated with increasing forest growth differs by site and depends on the specific climate, soil, tree species, and management.

Increased yields from these practices can be impressive. In pine forests in the Southern United States, tree breeding has improved wood growth by 10 to 30 percent (Fox et al. 2007b), and has increased insect and stress resistance (McKeand et al. 2006.) In this region, pine plantations using improved seedlings, control of competing vegetation, and fertilization grow wood four times faster than naturally regenerated second-growth pine forests without competition control (Carter and Foster 2006). Tree breeding and intensive management could also provide an opportunity to plant species and genotypes that are better adapted to future climates.

Many U.S. forests are N limited and would likely respond to fertilization (Reich et al. 1997). Nitrogen and phosphorus fertilizers have been used in about 6.5 million ha of managed forests in the southeast to increase wood production (Albaugh et al. 2007, Fox et al. 2007a, Liski et al. 2001, Seely et al. 2002). Fertilization can produce 100 percent gains for wood growth (Albaugh et al. 1998, 2004), although the benefits of fertilization for growth and C increase would need to be balanced by the high emissions associated with fertilizer production and potential emissions from eutrophication in aquatic systems (Carpenter et al. 1998) (table 4.8). Other risks include reduced water yield (faster growth uses more water), which is more pronounced in arid and semiarid forests, and a loss of biodiversity if faster growth is done by replacing multispecies forests with monocultures (limited diversity can make some forests vulnerable to insects and pathogens). In some areas, increasing the genetic and species diversity of trees and increasing C stocks could be compatible goals (Woodall et al. 2011).

Markets for current or new forest products can provide revenue to invest in growth-enhancing forest management. For example, expectation of revenue from the eventual sale of high-value timber products would support investment in treatments or tree planting to increase growth rate. Taxation or other government incentives may also support growth-enhancing management. To the extent that incentives to alter growth also alter timber harvest and wood product use, evaluation will require type B accounting with system boundaries that include forest sector, services sector, and possibly nonforest land.

## Ex Situ Forest Carbon Management

Carbon is removed from the forest for a variety of uses, and those uses can have different effects on C balances. Depending on the forest product stream, C can be stored in wood products for a variable length of time, oxidized to produce heat or electrical energy, or converted to liquid transportation fuels and chemicals that would otherwise come from fossil fuels (fig. 4.14). In addition, there can be a substitution effect when wood products are used in place of other products that emit more GHG in manufacturing (Lippke et al. 2011).

Strategies that would add to storage in long-lived wood products, increase use life, and increase use of wood products in place of higher emitting alternate products can complement strategies aimed at increasing forest C stocks. Risk and uncertainty in attaining benefits need to be considered when comparing strategies for increasing forest C with strategies for attaining wood product C offsets. Strategies need to ensure energy offsets are attained in an acceptable period of time and that substitution effects are attained.

**Carbon in forest products**—
Wood and paper continue to store C when in use and also in landfills (fig. 4.14). Rates of net C accumulation depend on rates of additions, disposal, combustion, and landfill decay. The half-life for single-family homes made of wood built after 1920 is about 80 years (Skog 2008, USEPA 2008), whereas the half-life of paper and paperboard products is less than 3 years (Skog 2008). About two-thirds of discarded wood and one-third of discarded paper go into landfills (Skog 2008). Decay in landfills is typically anaerobic and very slow (Barlaz 1998), and 77 percent of the C in solid wood products and 44 percent in paper products remain in landfills for decades (Chen et al. 2008, Skog 2008). However, current rates of methane release and capture can eliminate this C storage benefit for certain low lignin paper products (Skog 2008). About 2,500 Tg of C was accumulated in wood products and landfills in the United States from 1910 to 2005 (Skog 2008), with about 700 Tg of C (in 2001) in single- and multifamily homes (Skog 2008). In 2007, net additions to products in use and those in landfills combined were 27 $Tg{\cdot}C{\cdot}yr^{-1}$ (USEPA 2009b), with about 19 $Tg{\cdot}C{\cdot}yr^{-1}$ from products in use (Skog 2008).

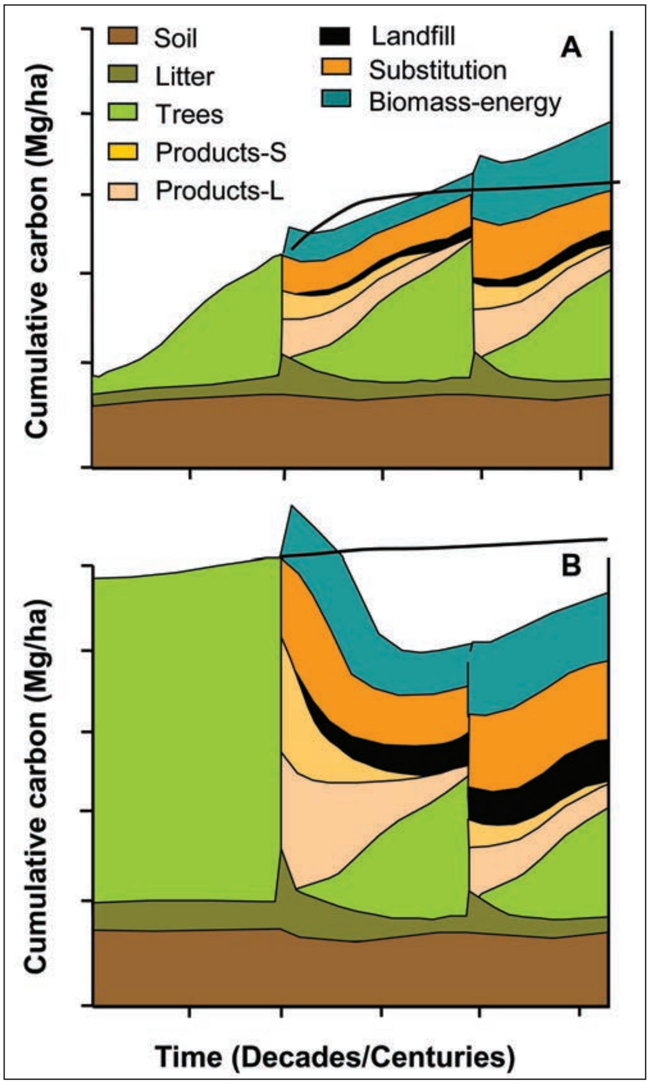


Figure 4.14—Carbon (C) balance from two hypothetical management projects with different initial ecosystem C stocks and growth rates. Cumulative C stocks in forest, C removed from forest for use in wood projects (long [L]- and short-lived [S]), substitution, and biomass energy are shown on land that (A) has been replanted or afforested, or (B) has an established forest with high C stocks. The heavy black line represents the trajectory of forest C stocks if no harvest occurred. Actual C pathways vary by project. Carbon stocks for trees, litter, and soils are net C stocks only. The scenario is harvested in x-year intervals, which in the United States could be as short as 15 years or longer than 100 years. This diagram assumes that all harvested biomass will be used and does not account for logging emissions. Carbon is sequestered by (1) increasing the average ecosystem C stock (tree biomass) by afforestation, or (2) accounting for C stored in wood products in use and in landfills, as well as preventing the release of fossil fuel C through product substitution or biomass energy. The product-substitution effect is assumed to be 2:1 on average. Biomass is assumed to be a 1:1 substitute for fossil fuels in terms of C, but this is not likely for many wood-to-energy options. This scenario represents a theoretical maximum C benefit, given this composition of forest products and management practices. Carbon "debt" is any period of time at which the composition of forest products and remaining forest C stocks after harvest is lower than estimated C stocks under a no-harvest scenario. (Adapted from McKinley et al. [2011], Pachauri and Reisinger [2007], and Solomon et al. [2007]).

**Product substitution**—

Net C emissions associated with production and use of forest products can be substantially less than those associated with steel and concrete. Use of 1 Mg of C in wood materials in construction in place of steel or concrete can result in 2 Mg of lower C emission (Sathre and O'Connor 2008, Schlamadinger and Marland 1996). Sometimes, using wood from faster-growing forests for substitution can be more effective in lowering atmospheric $CO_2$ than storing C in the forest where increased wood production is sustainable (Baral and Guha 2004, Marland and Marland 1992, Marland et al. 1997) (fig. 4.14a). On the other hand, harvesting forests with very high C stocks that have accumulated over many decades may result in a large deficit of biological C storage that could take many decades to more than a century to restore (McKinley et al. 2011) (fig. 4.14b). Opportunities for substitution in the United States are largely in nonresidential buildings (McKeever et al. 2006, Upton et al. 2008) because most houses are already built with wood, although opportunities to increase the substitution effect in residential buildings exist, for example, by using wood for walls in houses (Lippke and Edmonds 2006). Attaining the substitution effect requires incentives that avoid or reduce type 1 risks by encouraging increased use of wood (box 4.9). Incentives focused on landowners to harvest wood for products may not provide as many substitution effects because of leakage. In

**Box 4.9**

Each strategy has risks and uncertainties in attaining carbon (C) impacts as well as non-C impacts—cobenefits and tradeoffs. In this section, we describe two general sources of risk that may prevent a strategy from attaining its C mitigating potential in terms of magnitude or timing, or both, or possibly resulting in reversal. Type 1 risk refers to the failure of incentives or regulations. This risk stems from the constructs of the policy or incentive structure, which might not have the intended effect on human behaviors. This might include, for example, lower than expected participation in markets or unintended negative economic distortions, such as supply-side diversions, that alter forest management or forest product use.

Type 1 risks are "structural risk." One "structural risk" if not accounted for is, for example, "leakage" in the form of shifting of harvest or land use. Type 2 risk or "biophysical risk" refers to failures caused by unpredictable or greater than expected biophysical events, such as natural disturbance (e.g., wildfire, insects). Disturbance can be a cause of "risk of reversal" or failure to attain "permanence." Type 3 risk or "tradeoffs" is the intensification of negative non-C impacts. Uncertainty may also result in greater than expected mitigation. For example, changing climate and atmospheric chemistry (e.g., increasing carbon dioxide or nitrogen deposition) may result in faster accumulation of C in forests than expected for some period of time.

addition, incentives would help avoid type 1 risks in which wood may come from forest conditions where C recovery is slow (fig. 4.14a) and instead comes from forest conditions where C recovery is fast (e.g., fig. 4.14b).

**Biomass energy**—

Biomass energy could prevent the release of an estimated 130 to 190 $Tg \cdot C \cdot yr^{-1}$ from fossil fuels (Perlack et al. 2005, Zerbe 2006). Biomass energy comprises 28 percent of renewable energy supply and 2 percent of total energy use in the United States; the latter amount has the potential to increase to 10 percent (Zerbe 2006). Currently, wood is used in the form of chips, pellets, and briquettes to produce heat or combined heat and generation of electricity (Saracoglu and Gunduz 2009). These basic energy carriers can be further transformed, using advanced conversion technologies, into liquid transportation fuels, and gases (e.g., methane and hydrogen) (Bessou et al. 2011, Demirbas 2007). Conversion processes for these fuels are still largely experimental and require further development to improve efficiency and commercial viability. The GHG balances for simple energy carriers (e.g., wood chips and pellets) for producing heat and electricity are more certain than for advanced energy carriers. In addition, the potential exists to create high-value chemicals and other bioproducts from wood that would otherwise be made from fossil fuels, resulting in reduced emissions compared to use of fossil fuels (Hajny 1981, USDOE 2004).

Most biomass for energy is a byproduct of conventional forest product streams, such as milling residues (Gan and Smith 2006a), with some use of trees killed by insects, disease, and natural disturbance (Peng et al. 2010, Tumuluru et al. 2010). However, most of these residues, mainly sawdust and bark, are already used for direct heating in milling operations or used for other wood products, such as particle board (Ackom et al. 2010, Mälkki and Virtanen 2003, Nilsson et al. 2011); obtaining higher quantities of biomass feedstock would require using other residues. A number of currently unused residues have been identified, including residues from logging, hazardous fuel reduction treatments, precommercial thinning, urban areas, insect kill, and other sources (Ackom et al. 2010; Gan 2007, Gan and Smith 2006b; Mälkki and Virtanen 2003; Perlack et al. 2005, 2011; Repo et al. 2011; Smeets and Faaij 2007).

If forest harvesting is expanded to meet the demand for biomass energy, roundwood from standing trees will increasingly be used for energy. For example, short-rotation plantations devoted to biomass feedstock production have been proposed (Fantozzi and Buratti 2010, Tuskan 1998). If prices for biomass energy increase, short-rotation forest crops such as poplars could become a significant feedstock source (Solomon et al. 2007). Carbon emissions from increased use of roundwood for energy may be offset over time by a subsequent increase in forest C. This can be done through increased forest growth on land where the roundwood is harvested. The amount and speed of the offset are influenced by the time period considered, forest growth rate, initial stand C density, and the efficiency with which wood offsets fossil fuel emissions (Schlamadinger et al. 1995). The offset can also be done through increased landowner investment in forestry. The investment can include converting nonforest land to forest, retaining land in forest that would otherwise be converted to nonforest, or planting land in faster growing pulpwood or short-rotation plantations. Forest inventory and C projections for the United States indicate that for scenarios with higher wood energy use (versus those with lower wood energy use) there will be more land retained in forest and more land in plantations for the Southern United States (USDA FS 2012b). The effect on forest C of retaining land in forest is greater than the effect of increasing plantation area. Landowner investment in revenue for biomass is expected to be low for most of the United States.

Reductions in GHG emissions from wood-to-energy pathways depend, in part, on how efficiently wood substitutes for fossil fuels. The energy value of wood (energy content per unit mass) is lower than for fossil fuels (Demirbas 2005, Patzek and Pimentel 2005), a difference that is most pronounced when wood substitutes for fossil fuels with high energy values (e.g., natural gas). The risk of not attaining various levels of offset from use of wood for energy differs, depending on whether biomass is from residues or from greater use of roundwood (Schlamadinger et al. 1995, Zanchi et al. 2010). Risks for using residues are relatively small, especially if forests and supply chains are well managed. Risks associated with using roundwood differ by forest conditions, treatments, and degree of landowner response by investment in more intensive forest management. Large increases in demand could cause loss of C if natural forest with high C density were converted to forest plantations or agricultural biomass plantations with lower C density.

Recent research has provided contrasting conclusions regarding the potential C mitigation benefits from using wood for energy. A number of studies report that using biomass instead of fossil fuels can significantly reduce net C emissions (Boman and Turnbull 1997, Cherubini et al. 2009, Jones et al. 2010, Malmsheimer et al. 2011, Mann and Spath 2001, Spath and Mann 2000). Other studies report that the postharvest regrowth period during which forest C is initially low negates the benefits of wood energy (Bracmort 2011, Cardellichio and Walker 2010, Fargione et al. 2008, Manomet Center for Conservation Sciences 2010, Mathews and Tan 2009, McKechnie et al. 2011, Melamu and von Blottnitz 2011, Melillo et al. 2009, Pimentel et al. 2008, Repo et al. 2011, Schlamadinger et al. 1995, Searchinger et al. 2009). Studies that used life cycle assessments (LCAs) with both biomass pathways and forest C dynamics over time calculated lower reductions in $CO_2$ emissions than similar LCAs without forest C dynamics. For some cases and time periods, LCAs with biomass pathways and forest C dynamics indicate biomass emissions can be higher than fossil emissions (Johnson 2009, Manomet Center for Conservation Sciences 2010, McKechnie et al. 2011, Pimentel et al. 2008, Searchinger et al. 2008).

These conflicting conclusions are caused by differing assumptions and methods used in the LCAs (Cherubini et al. 2009, 2012; Matthews and Tan 2009). Emerging C accounting methods are increasingly focused on the effect of emissions on the atmosphere and climate over an extended time period, rather than assuming C neutrality (Cherubini et al. 2012). Continuing efforts are needed to provide evaluation frameworks that are adequate to evaluate the overall C and climate effects of specific combinations of forest management and wood energy use.

## Mitigation Strategies: Markets, Regulations, Taxes, and Incentives

Forests currently comprise about a third of the land area in the United States, but fragmentation and conversion of forest to other land uses is increasing, especially in the East (Drummond and Loveland 2010). Various mechanisms exist at national, regional, and local scales that can enhance mitigation efforts while providing incentives to keep forests intact. National forests are not eligible for incentive programs or market-based payments for C sequestration or other ecosystem services, but markets and incentive programs can potentially play a role in ecosystem-enhancing mitigation on private and nonfederally owned land. Markets and incentive programs can provide a means for landowners to be financially compensated for voluntary restoration activities that improve ecosystem services. Some of these mechanisms, such as C markets, are designed to encourage mitigation, while other mechanisms help maintain or augment C stores as an ancillary benefit.

**Markets, registries, and protocols for forest-based carbon projects**—

Carbon markets are an emissions trading mechanism and are typically designed to create a multisector approach that encourages reductions and often (but not always) enhances sequestration of GHG emissions (measured in megagrams of $CO_2$ equivalent, or $CO_2e$) in an economically efficient manner. Registries exist to track and account for the C, and protocols outline the specific methodologies that are a prerequisite to creating legitimate C offsets.

The United States does not have a national-level regulatory market, but several mandatory regional efforts and voluntary over-the-counter markets provide limited opportunities for mitigation through forest-based C projects. Offsets generated from these projects can compensate for emissions generated elsewhere. Forest C projects generally take the following form:

**Avoided emissions**

- Avoided deforestation (or avoided conversion): projects that avoid emissions by keeping forests threatened with conversion to nonforest intact.

**Enhanced sequestration**

- Afforestation/reforestation: projects that reforest areas that are currently nonforested, but may have been forested historically.
- Improved forest management: projects that offer enhanced C mitigation through better or more sustainable management techniques. These projects are compatible with sustainable levels of timber harvest.
- Urban forestry: projects that plant trees in urban areas. Only sequestered C is eligible (avoided C emissions that result from energy savings are not eligible for credit).

The Regional Greenhouse Gas Initiative (RGGI) is a mandatory multistate effort in New England and the Mid-Atlantic that allows offset credits to be generated through afforestation projects within RGGI member states. The Climate Action Reserve is another mandatory initiative that is based in California but accepts forest projects from throughout the country. In addition, protocols created by the American Carbon Registry, Verified Carbon Standard provide quality assurance to domestic and international forest C projects that may be sold on the voluntary market (Kollmuss et al. 2010, Peters-Stanley et al. 2011). In 2009, 5.1 Mg of $CO_2e$, or 38 percent of the global share of forest-based C offsets, was generated in North America (Hamilton et al. 2010). However, factors such as substantial startup and transaction costs and restrictions on the long-term use and stewardship of forest land enrolled in C projects often serve as barriers to engagement for many private forest landowners in the United States (Diaz et al. 2009).

**Tax and incentive programs**—

Some states offer reduced taxes on forest land, as long as certain requirements are met. These tax incentives may be crafted to maintain a viable timber industry and achieve open space objectives, but have the added benefit of helping to maintain or enhance forest C stores. For example, private forest landowners enrolled in Wisconsin's Managed Forest Law Program receive an 80 to 95 percent tax reduction on land that is at least 80 percent forested and is managed for the sustainable production of timber resources. Vermont's Use Value Appraisal Program is similar. Carbon benefits from these programs must be evaluated based on specific circumstances; younger, rapidly growing forests have higher rates of C uptake, whereas older stands may have lower C uptake but higher overall storage (Harmon 2001, Malmsheimer et al. 2008). A "no harvest" unmanaged forest scenario may produce more or less C benefit than a sustainably managed forest, but much depends on current C stocks, the likelihood of disturbance, and whether and how the harvested timber products are used (Ingerson 2007, Nunnery and Keeton 2010). The timeframe of expected C benefits therefore depends on both forest management regimes and forest product pathways (long-term vs. short-term products) (McKinley et al. 2011).

Several federal programs administered by the USDA Natural Resources Conservation Service, Forest Service, and Farm Service Agency provide cost-share and rental payment incentives for good farm, forest, watershed, and wildlife habitat stewardship. As an ancillary benefit, these programs may also help maintain or enhance C stores, but this is currently not an explicit goal of any of these programs. The area enrolled in each program fluctuates annually and depends on commodity prices, program funding, and authorization levels, as sanctioned in the Farm Bill. In 2010, 13 million ha of United States farmland were enrolled in the Conservation Reserve Program, down from 15 million ha in 2005 (Claassen et al. 2008, USDA Farm Service Agency 2010). A brief description of relevant programs is shown in table 4.9.

If policy favored land management that would decrease the buildup of atmospheric $CO_2$, it might be possible to either fine tune existing incentive programs to more explicitly support C mitigation strategies, and develop an alternative incentive program that prioritizes C management. In the case of the former, the explicit objective of the program could remain as is (to determine general eligibility), but the financial incentives for enrollment could be related to estimated average C benefit per hectare, rather than being calculated based only on hectares enrolled. Carbon benefit per hectare could be estimated at a county or regional scale based on a combination of factors, including geographic location, land use, species planted, and overall landscape connectivity. This may help to ensure that priority lands for C management receive the highest potential benefits. Alternatively, a specific forest C incentive program could complement current incentive programs by targeting small family forest owners and providing financial incentives that may be sufficient to ensure that forests remain as forests. Best management practices could be made available (e.g., for artificial regeneration, thinning, and insect control) (table 4.10), and financial incentives could be based on estimated C benefits (Pinchot Institute for Conservation 2011). These estimated

**Table 4.9—Programs that influence carbon mitigation**

| Program | Agency | Land area | Purpose |
|---|---|---|---|
| | | *Millions of hectares* | |
| Conservation Reserve Program and Continuous Conservation Reserve Program | Farm Service Agency | ~13 | Reduce erosion, increase wildlife habitat, improve water quality, and increase forested acres |
| Environmental Quality Incentives Program (EQIP) | Natural Resources Conservation Service (NRCS) | ~6.9 | Forest management practices including timber stand improvement, site preparation for planting, culverts, stream crossings, water bars, planting, prescribed burns, hazard reduction, fire breaks, silvopasture, fence, grade stabilization, plan preparation |
| Conservation Stewardship Program (CSP) | NRCS | n/a | Incentives for sustainable forest management and conservation activities |
| Wildlife Habitat Incentive Program (WHIP) | NRCS | 0.26 | Assistance/incentives to develop or improve fish and wildlife habitat, including prairie and savanna restoration, in-stream fish structures, livestock exclusion, and tree planting |
| Forest Legacy Program | Forest Service (FS) | ~0.8 | Incentives to preserve privately-owned working forest land through conservation easements and fee acquisitions |
| Stewardship Program | FS | ~14 | Encourages private landowners to create and implement stewardship plans on their land |

n/a = not applicable.

**Table 4.10—Tools and processes to inform forest management**

| Organization | Relevant content | Internet site |
|---|---|---|
| U.S. Forest Service Forest Inventory and Analysis | Forest statistics by state, including carbon (C) estimates | http://fia.fs.fed.us |
| | Sample plot and tree data | |
| | Forest inventory methods and basic definitions | |
| U.S. Forest Service Forest Health Monitoring | Forest health status | http://www.fhm.fs.fed.us |
| | Regional data on soils, dead wood stocks | |
| | Forest health monitoring methods | |
| U.S. Department of Agriculture (USDA) Greenhouse Gas Inventory | State-by-state forest C estimates | http://www.usda.gov/oce/global_change/gg_inventory.htm |
| United Nations Framework Convention on Climate Change and Intergovernmental Panel on Climate Change | International guidance on C accounting and estimation | http://unfccc.int<br>http://www.ipcc.ch |
| USDA Natural Resources Conservation Service | Soil Data Mart—access to a variety of soil data | http://soildatamart.nrcs.usda.gov |
| U.S. Forest Service, Northern Research Station | Accounting, reporting procedures, and software tools for C estimation | http://www.nrs.fs.fed.us/carbon/tools |
| U.S. Energy Information Administration, Voluntary GHG Reporting | Methods and information for calculating sequestration and emissions from forestry | http://www.eia.gov/oiaf/1605/gdlins.html |
| U.S. Environmental Protection Agency | Methods and estimates for GHG emissions and sequestration | http://www.epa.gov/climatechange/emissions/usinventoryreport.html |

benefits would require only a statistically robust verification of practices rather than annual site monitoring.

## The Role of Public Lands in Mitigation

Public lands encompass large areas of forests and rangelands, about 37 percent of the land area of the United States, with federally managed lands occupying 76 percent of the total area managed by all public entities. A decision to manage these lands for C benefits would involve a complex set of interacting forces and multiple jurisdictions, and would be governed by laws mandating multiple uses of land in the public domain. The Council on Environmental Quality (CEQ) has the responsibility of overseeing environmental policy across the federal government. The CEQ has developed draft guidelines for all agencies describing how federal agencies can improve their consideration of the effects of GHG emissions and climate change when evaluating proposals for federal actions under NEPA (Sutley 2010). Another recent policy that affects all federal agencies is Executive Order 13,514 (2009), which requires agencies to set targets that focus on sustainability, energy efficiency, reduced fossil fuel use, and increased water efficiency. In addition, the order requires agencies to measure, report, and reduce GHG emissions from direct and indirect activities, including federal land management practices. The CEQ guidance and these orders are being considered by land management agencies, but it is unclear how effective they will be in reducing GHGs, given the many other uses of federal lands. It should be noted that large areas of forest land protected by conservation organizations (e.g., The Nature Conservancy) across the United States are being managed for public benefits but may not be subject to some of the regulatory issues cited above.

## Managing Forests in Response to Climate Change

Managing forests in response to climate change is just one component of the broad and complex task of sustainable natural resource management. Climatic variability (year to year, and decade to decade differences in climate) has always been a factor in forest management, but now resource managers must begin to address directional trends in human-caused climate change in the context of increased variability and movement away from historical averages. Climate change provides a context to be considered in management, but it is rarely appropriate to focus on climate change exclusive of other issues that affect forest resources. An increasing number of potential strategies and forest management options are now available for addressing climate change. However, these strategies and options are rarely institutionalized. Implementing these approaches, or at least a thorough consideration thereof, through planning and management processes on public and private lands is a major organizational and social challenge.

If projected changes in temperature, precipitation, and extreme weather events are realized, management activities that facilitate adaptation to climate change can be realistically viewed as providing additional time until biological and social systems adjust to a new climate. The sooner action is implemented, the more options will be available to prepare forest systems for a new climate. Two major institutional shifts are needed for successful adaptation in U.S. forests. First, scientists and resource managers need to agree that static and equilibrium concepts relative to ecosystem function and management (historical range of variation, restoration of "presettlement" conditions, climax vegetation, etc.) will be less relevant in the future. Ecosystems that exist in nonanalog climates with increased disturbance, new species, and invasive species will rarely be in equilibrium with climate or other environmental factors, and it will not be possible to preserve them intact in a specific location over time. Second, natural resource management organizations will need to consider climate effects as part of normal business operations. If ongoing management protocols and projects include the role of climatic variability and change, then accomplishment targets and on-the-ground practices can be adjusted as needed. This will minimize surprises and lead to realistic long-term planning objectives. If climate effects are not considered, rapid changes in ecosystem dynamics will challenge their ability to manage forest resources sustainably.

As noted in the adaptation section above, adapting to climate change is a viable option for most natural resource management organizations if viewed as adaptive management in the context of climatic variability and change. Currently, most public and private institutions need considerable input from the scientific community to help interpret climate science and model output, and to project the effects of climate change on natural resources at different spatial and temporal scales. Successful science-management partnerships have typically required 2 to 5 years to make substantial progress on science-based solutions to climate challenges. To sustainably manage the Nation's forests, natural resource management organizations will need to make climate change a mainstream issue (much as "ecosystem management," and "ecological restoration" did previously) that can be addressed without continuous high-level, external scientific input.

Multi-institutional collaboration is required, both now and in the future, to apply consistent strategies and tactics across large landscapes. Cooperation among agencies and other organizations in addressing natural resource issues has often been challenging. However, recent efforts between the U.S. Forest Service and National Park Service to collaborate on climate change adaptation, and nascent efforts by U.S. Fish and Wildlife Service Landscape Conservation Cooperatives to instill an all-lands approach in conservation issues, including climate change, provide hope that collaboration will become more common. Perhaps more challenging are the barriers of "paralysis by analysis" within agencies, external litigation, and appeals, which delay timely implementation of projects that can facilitate adaptation. It will be difficult to break the gridlock that seems to envelop public land management in some regions until engagement of stakeholders and consistent, open communication of climate science with the public, policymakers, and land managers becomes commonplace. Climate change is at the forefront of many policy and management discussions on private lands as well (e.g., the Southern Forest Futures Project, http://www.srs.fs.usda.gov/futures), with similar concerns about the effects of climate change on forest lands and potential management options for adaptation and mitigation. In regions dominated by private lands such as the southeast and northeast, dealing with complex ownership patterns and a wide range of management objectives will be critical for successful climate-smart management across large landscapes. Given multiple management objectives and limited funding and staff for implementation, it will be necessary to optimize long-term strategies on a regional to subregional basis by considering where the most benefit can be gained.

Projections of climate change effects are relatively certain for some components of forest ecosystems, and less certain for others, especially beyond the mid-21$^{st}$ century. Developing effective management options to address uncertain, dynamic, and novel conditions will require ongoing monitoring to identify ecosystems at risk, detect change, and evaluate the success or failure of management activities. Now more than ever, land managers will need detailed information on forest conditions to inform management decisions and help adapt to changing conditions. The U.S. Forest Service Forest Inventory and Analysis program and Forest Service Forest Health Monitoring network provide information on changes in forest growth and condition over most of the Nation. In addition, the Forest Service operates 80 experimental forests and ranges that are critical assets for change detection, climate-change experiments, and management demonstrations. Combined with other large networks such as the National Ecological Observatory Network (20 core sites to be established in representative ecoclimate domains), the National Science Foundation Long-Term Ecological Research Program (27 sites located across the United States, Puerto Rico, and Antarctica), National Weather Service weather stations, and numerous U.S. Geological Survey gauging stations, many variables are monitored across a broad geographic area. In most cases, these networks operate independently, and although some lack central data storage, data management protocols, and easy access, efforts are underway to increase data access for many core data sets. These monitoring networks can help detect changes in climate and forest condition, but they are not a substitute for on-the-ground monitoring that will be required to assess the effectiveness of specific management activities. This will require a larger investment by land management agencies, although improved efficiency and coordination can, in some cases, compensate for insufficient funding.

In the near term, it is logical to pursue management strategies that are relatively low cost, have few barriers, and will produce near-term results. For adaptation, this would include reducing co-occurring stressors in forests (e.g., air pollution, exotic pathogens), implementing fuel reduction where feasible and effective, and reducing stand densities where feasible and appropriate (resistance and resilience strategies). For C management, this would include reducing deforestation, increasing afforestation, reducing wildfire severity where feasible, increasing growth, and increasing use of wood-based bioenergy where economically justified.

In the long term, specific adaptation strategies will need to be considered in light of emerging scientific evidence on climate change effects and assessments of the effectiveness of various management actions on the ground. Resilience strategies in the face of increasing large-scale disturbances often include standard management practices (e.g., forest thinning). Specific strategies for C management will need to be guided by emerging scientific evidence on how to concurrently manage forests in situ for products, energy, and other ecosystem services. Strategies will differ by location, inherent forest productivity, and local management objectives. The mandate for productivity on commercial private lands contrasts with objectives on public lands, but both private and public perspectives need to be accommodated in order to manage C across broad spatial scales, meet multiple management objectives, and benefit local economies.

It will also be important to consider how adaptation and mitigation can be coordinated to optimize implementation across specific landscapes. For example, fuel reduction treatments can reduce the prevalence of crown fires in dry forests, while also providing material for local bioenergy use (the long-term effect on C dynamics is site-specific based on current evidence). The interaction of adaptation and mitigation has been poorly assessed to date, and successful models of both strategic and tactical approaches to this interaction are needed. This topic may provide opportunities for coalitions among partners who would not normally collaborate on other natural resource issues. In the near term, we anticipate that federal land management agencies will continue to lead the development of science-management partnerships and collaborative approaches to adaptation and C management across public lands. Successful adaptation and C management will accelerate across larger landscapes if and when community-based partnerships become more engaged with climate change as a component of sustainable resource stewardship.

## Literature Cited

**Ackom, E.K.; Mabee, W.E.; Saddler, J.N. 2010**. Industrial sustainability of competing wood energy options in Canada. Applied Biochemistry and Biotechnology. 162: 2259–2272.

**Ager, A.A.; Finney, M.A.; McMahan, A.; Cathcart, J. 2010**. Measuring the effect of fuel treatments on forest carbon using landscape risk analysis. Natural Hazards and Earth System Sciences. 10: 2515–2526.

**Akbari, H. 2002**. Shade trees reduce building energy use and $CO_2$ emissions from power plants. Environmental Pollution. 116: S119–S1260.

**Albaugh, T.J.; Allen, H.L.; Dougherty, P.M. [et al.]. 1998**. Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions. Forest Science. 44: 317–328.

**Albaugh, T.J.; Allen, H.L.; Fox, T.R. 2007.** Historical patterns of forest fertilization in the southeastern United States from 1969 to 2004. Southern Journal of Applied Forestry. 31: 129–137.

**Albaugh, T.J.; Allen, H.L.; Dougherty, P.M.; Johnsen, K.H. 2004** Long term growth responses of loblolly pine to optimal nutrient and water resource availability. Forest Ecology and Management. 192: 3–19.

**Albaugh, T.J.; Allen, H.L.; Zutter, B.R.; Quicke, H.E. 2003**. Vegetation control and fertilization in midrotation *Pinus taeda* stands in the southeastern United States. Annals of Forest Science. 60: 619–624.

**Alig, R.J.; Plantinga, A.J.; Ahn, S.; Kline, J.D. 2003.** Land use changes involving forestry in the United States: 1952 to 1997, with projections to 2050. Gen. Tech. Rep. PNW-GTR-587. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 92 p.

**Allen, H.L. 2008**. Silvicultural treatments to enhance productivity. In: Evans, J., ed. The forests handbook, volume 2: applying forest science for sustainable management. Oxford, United Kingdom; Malden, MA: Blackwell Science Ltd.: 129–139. Chapter 6.

**Amishev, D.Y.; Fox, T.R. 2006.** The effect of weed control and fertilization on survival and growth of four pine species in the Virginia Piedmont. Forest Ecology and Management. 236: 93–101.

**Aubry, C.; Devine, W.; Shoal, R. [et al.]. 2011**. Climate change and forest biodiversity: a vulnerability assessment and action plan for national forests in western Washington. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 310 p. http://ecoshare.info/wp-content/uploads/2011/05/CCFB.pdf. (27 December 211).

**Aukland, L.; Costa, P.M.; Brown, S. 2003**. A conceptual framework and its application for addressing leakage: the case of avoided deforestation. Climate Policy. 3: 123–136.

**Bagne, K.E.; Friggens, M.M.; Finch, D.M. 2011.** A system for assessing vulnerability of species (SAVS) to climate change. Gen. Tech. Rep. RMRS-GTR-257. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 28 p. http://www.treesearch.fs.fed.us/pubs/37850. (27 December 2011).

**Balboa-Murias, M.A.; Rodriguez-Soalleíro, R.; Merino, A.; Álvarez-González, J.G. 2006.** Temporal variations and distribution of carbon stocks in aboveground biomass of radiata pine and maritime pine pure stands under different silvicultural alternatives. Forest Ecology and Management. 237: 29–38.

**Balshi, M.S.; McGuire, A.D.; Duffy, P. [et al.]. 2009**. Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century. Global Change Biology. 15: 1491–1510.

**Baral, A.; Guha, G.S. 2004**. Trees for carbon sequestration or fossil fuel substitution: the issue of cost vs. carbon benefit. Biomass and Bioenergy. 27: 41–55.

**Barlaz, M.A. 1998**. Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills. Global Biogeochemical Cycles. 12: 373–380.

**Baron, J.S.; Allen, C.D.; Fleishman, E. [et al.]. 2008.** National parks. In: Julius, S.H.; West, J.M., eds. Preliminary review of adaptation options for climate-sensitive ecosystems and resources: a report by the U.S. Climate Change Science Program and the Subcommittee on Climate Change Research. Washington, DC: U.S. Environmental Protection Agency: 4-1 to 4-68.

**Baron, J.S.; Gunderson, L.; Allen, C.D. [et al.]. 2009**. Options for national parks and reserves for adapting to climate change. Environmental Management. 44: 1033–1042.

**Battaglia, M.A.; Rocca, M.E.; Rhoades, C.C.; Ryan, M.G. 2010**. Surface fuel loadings within mulching treatments in Colorado coniferous forests. Forest Ecology and Management. 260: 1557–1566.

**Bessou, C.; Ferchaud, F.; Gabrielle, B.; Mary, B. 2011**. Biofuels, greenhouse gases and climate change. A review. Agronomy for Sustainable Development. 31: 1–79.

**Birdsey, R.; Pregitzer, K.; Lucier, A. 2006.** Forest carbon management in the United States: 1600-2100. Journal of Environmental Quality. 35: 1461–1469.

**Birdsey, R.A.; Plantinga, A.J.; Health, L.S. 1993.** Past and prospective carbon storage in United States forests. Forest Ecology and Management. 58: 33–40.

**Boman, U.R.; Turnbull, J.H. 1997.** Integrated biomass energy systems and emissions of carbon dioxide. Biomass and Bioenergy. 13: 333–343.

**Borders, B.E.; Will, R.E.; Markewitz, D. [et al.]. 2004.** Effect of complete competition control and annual fertilization on stem growth and canopy relations for a chronosequence of loblolly pine plantations in the lower coastal plain of Georgia. Forest Ecology and Management. 192: 21–37.

**Bracmort, K. 2011.** Is biopower carbon neutral? 7-5700. Washington, DC: Congressional Research Service. 14 p.

**Butler, P.R.; Swanston, C.W.; Janowiak, M.K. [et al.]. 2012**. Adaptation strategies and approaches. In: Swanston, C.W.; Janowiak, M.K., eds. Forest adaptation resources: climate change tools and approaches for land managers. Gen. Tech. Rep. NRS-87. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 15–34.

**Cardellichio, P.; Walker, T. 2010.** Why the Manomet study got the biomass carbon accounting right. The Forestry Source. 15: 4.

**Carpenter, S.R.; Caraco, N.F.; Correll, D.L. [et al.]. 1998**. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications. 8: 559–568.

**Carter, M.C.; Foster, C.D. 2006**. Milestones and millstones: a retrospective on 50 years of research to improve productivity in loblolly pine plantations. Forest Ecology and Management. 227: 137–144.

**Carter, T.R.; Parry, M.L.; Harasawa, H.; Nishioka, S. 1994.** IPCC technical guidelines for assessing climate change impacts and adaptation. Working group 2 of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press: 1–72.

**Cayan, D.R.; Maurer, E.P.; Dettinger, M.D. [et al.]. 2008.** Climate change scenarios for the California region. Climatic Change. 87: S21–S42.

**Center for Island Climate Adaptation and Policy [CICAP]. 2009.** A framework for climate change adaptation in Hawaii. Honolulu, HI: State of Hawaii, Ocean Resources Management Plan Working Group; University of Hawaii, Center for Island Climate Adaptation and Policy. 30 p.

**Chen, J.; Colombo, S.J.; Ter-Mikaelian, M.T.; Heath, L.S. 2008.** Future carbon storage in harvested wood products from Ontario's Crown forests. Canadian Journal of Forest Research. 38: 1947–1958.

**Cherubini, F.; Bird, N.D.; Cowie, A. [et al.]. 2009.** Energy- and green-house gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. Resource Conservation and Recycling. 53: 434–447.

**Cherubini, F.; Guest, G.; Stømman, A.H. 2012.** Application of probability distributions to the modeling of biogenic $CO_2$ fluxes in life cycle assessment. GCB Bioenergy, DOI: 10.1111/j.1757-1707.2011.01156.x.

**Churkina, G.; Brown, D.G.; Keoleian, G. 2010**. Carbon stored in human settlements: the conterminous United States. Global Change Biology. 16: 135–143.

**Claassen, R.; Cattaneo, A.; Johansson, R. 2008**. Cost-effective design of agri-environmental payment program: U.S. experience in theory and practice. Ecological Economics. 65: 737–752.

**Clean Air Act of 1970;** 42 U.S.C. s/s 7401 et seq.

**Clean Water Act of 1977**; 33 U.S.C. s/s 1251 et seq.

**Climate Adaptation Knowledge Exchange [CAKE]. 2011.** CAKE: climate adaptation knowledge exchange. http://www.cakex.org. (28 December 2011).

**Cole, D.N.; Yung, L. 2010.** Beyond naturalness: rethinking park and wilderness stewardship in an era of rapid change. Washington, DC: Island Press. 304 p.

**Coleman, M.; Page-Dumroese, D.; Archuleta, J. [et al.]. 2010.** Can portable pyrolysis units make biomass utilization affordable while using bio-char to enhance soil productivity and sequester carbon. In: Jain, T.B.; Graham, R.T.; Sandquist, J., tech. eds. Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate. Proc. RMRS-P-61. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 159–168.

**Crook, J.A.; Forster, P.M. 2011.** A balance between radiative forcing and climate feedback in the modeled 20th century temperature response. Journal of Geophysical Research. 116: D17108.

**Daly, C.; Conklin, D.R.; Unsworth, M.H. 2009.** Local atmospheric decoupling in complex topography alters climate change impacts. International Journal of Climatology. 30: 1857–1864.

**Daniels, A.E.; Morrison, J.F.; Joyce, L.A. [et al.]. 2012.** Climate projections FAQ. Gen. Tech. Rep. RMRS-GTR-277WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 32 p.

**Demirbas, A. 2005**. Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. Progress in Energy and Combustion Science. 31: 171–192.

**Demirbas, A. 2007**. Progress and recent trends in biofuels. Progress in Energy and Combustion Science. 33: 1–18.

**Depro, B.M.; Murray, B.C.; Align, R.J.; Shanks, A. 2008**. Public land, timber harvests, and climate mitigation: quantifying carbon sequestration potential on U.S. public timberlands. Forest Ecology and Management. 255: 1122–1134.

**Diaz, S.; Hector, A.; Wardle, D.A. 2009.** Biodiversity in forest carbon sequestration initiatives: not just a side benefit. Current Opinion in Environmental Sustainability. 1: 55–60.

**Donato, D.C.; Fontaine, J.B.; Campbell, J.L. [et al.]. 2009.** Conifer regeneration in stand-replacement portions of a large mixed-severity wildfire in the Klamath-Siskiyou Mountains. Canadian Journal of Forest Research. 39: 823–838.

**Dore, S.; Kolb, T.E.; Montes-Helu, M. [et al.]. 2010.** Carbon and water fluxes from ponderosa pine forests disturbed by wildfire and thinning. Ecological Applications. 20: 663–683.

**Drummond, M.A.; Loveland T.R. 2010**. Land-use pressure and a transition to forest-cover loss in the eastern United States. Bioscience. 60: 286–298.

**Endangered Species Act of 1973 [ESA]**; 16 U.S.C. 1531-1536, 1538–1540.

**ESSA. 2011**. Vegetation dynamics development tool (VDDT). http://essa.com/tools/vddt. (28 December 2011).

**Exec. Order No. 13,514, 74 Fed. Reg. 194, 52117 (October 8, 2009).** Federal leadership in environmental, energy, and economic performance. http://www.whitehouse.gov/administration/eop/ceq/sustainability. (28 December 2011).

**Exline, J.; Graber, D.; Stephenson, N. [et al.]. 2009**. A strategic framework for science in support of management in the Southern Sierra Nevada ecoregion: a collaboratively developed approach. Three Rivers, CA: Southern Sierra Nevada Ecoregion. 24 p. http://www.nps.gov/seki/naturescience/upload/strategic-framework-2.pdf. (27 December 2011).

**Fantozzi, F.; Buratti, C. 2010.** Life cycle assessment of biomass chains: wood pellet from short rotation coppice using data measured on a real plant. Biomass and Bioenergy. 34: 1796–1804.

**Fargione, J.; Hill, J.; Tilman, D. [et al.]. 2008**. Land clearing and the biofuel carbon debt. Science. 319: 1235–1238.

**Farley, K.A.; Jobbágy, E.G.; Jackson, R.B. 2005**. Effects of afforestation on water yield: a global synthesis with implications for policy. Global Change Biology. 11: 1565–1576.

**Farley, K.A.; Piñeiro, G.; Palmer, S.M. [et al.]. 2008.** Stream acidification and base cation losses with grassland afforestation. Water Resources Research. 44: W00A03.

**Finkral, A.J.; Evans, A.M. 2008.** Effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. Forest Ecology and Management. 255: 2743–2750.

**Food and Agriculture Organization of the United Nations [FAO]. 2007**. State of the world's forests 2007. Rome, Italy: Food and Agriculture Organization of the United Nations, Communications Division, Electronic Publishing Policy and Support Branch. 144 p. http://www.fao.org/docrep/009/a0773e/a0773e00.htm. (November 2011).

**Fox, T.R.; Allen, H.L.; Albaugh, T.J. [et al.]. 2007a.** Tree nutrition and forest fertilization of pine plantations in the southern United States. Southern Journal of Applied Forestry. 31: 5–11.

**Fox, T.R.; Jokela, E.J.; Allen, H.L. 2007b.** The development of pine plantation silviculture in the southern United States. Journal of Forestry. 105: 337–347.

**Furniss, M.J.; Staab, B.P.; Hazelhurst, S. [et al.]. 2010.** Water, climate change, and forests: watershed stewardship for a changing climate. Gen. Tech. Rep. GTR-PNW-812. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 75 p.

**Gallopín, G.C. 2006.** Linkages between vulnerability, resilience, and adaptive capacity. Global Environmental Change. 16: 293–303.

**Gan, J. 2007**. Supply of biomass, bioenergy, and carbon mitigation: method and application. Energy Policy. 35: 6003–6009.

**Gan, J.; McCarl, B.A. 2007**. Measuring transnational leakage of forest conservation. Ecological Economics. 64: 423–432.

**Gan, J.B.; Smith, C.T. 2006a**. A comparative analysis of woody biomass and coal for electricity generation under various $CO_2$ emission reductions and taxes. Biomass and Bioenergy. 30: 296–303.

**Gan, J.; Smith, C.T. 2006b.** Availability of logging residues and potential for electricity production and carbon displacement in the USA. Biomass and Bioenergy. 30: 1011–1020.

**Glick, P.; Stein, B.A.; Edelson, N.A., eds. 2011.** Scanning the conservation horizon: a guide to climate change vulnerability assessment. Washington, DC: National Wildlife Federation. 176 p. http://www.nwf.org/vulnerabilityguide. (27 December 2011).

**Hajny, G.J. 1981.** Biological utilization of wood production for production of chemicals and foodstuffs. Res. Pap. FPL-RP-385. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 65 p.

**Halofsky, J.E.; Peterson, D.L.; O'Halloran, K.A.; Hawkins Hoffman, C. 2011.** Adapting to climate change at Olympic National Forest and Olympic National Park. Gen. Tech. Rep. PNW-GTR-844. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 130 p.

**Hamilton, K.; Sjardin, M.; Peters-Stanley, M.; Marcello, T. 2010**. Building bridges: state of the voluntary carbon markets 2010: a report by Ecosystem Marketplace and Bloomberg New Energy Finance. New York: Bloomberg New Energy Finance; Washington, DC: Ecosystem Marketplace. 108 p.

**Harden, J.W.; Trumbore, S.E.; Stocks, B.J. [et al.]. 2000.** The role of fire in the boreal carbon budget. Global Change Biology. 6: 174–184.

**Harmon, M. 2001**. Carbon sequestration in forests—addressing the scale question. Journal of Forestry. 99: 24–29.

**Harmon, M.E.; Harmon, J.M.; Ferrell, W.K.; Brooks, D. 1996**. Modeling carbon stores in Oregon and Washington forest products: 1900–1992. Climatic Change. 33: 521–550.

**Harmon, M.E.; Marks, B. 2002**. Effects of silvicultural practices on carbon stores in Douglas-fir–western hemlock forests in the Pacific Northwest, U.S.A.: results from a simulation model. Canadian Journal of Forest Research. 877: 863–877.

**Harmon, M.E.; Moreno, A.; Domingo, J.B. 2009.** Effects of partial harvest on the carbon stores in Douglas-fir/western hemlock forests: a simulation study. Ecosystems. 12: 777–791.

**Harris, J.A.; Hobbs, R.J.; Higgs, E.; Aronson, J. 2006.** Ecological restoration and global climate change. Restoration Ecology. 14: 170–176.

**Helbrecht, L.; Jackson, A.; Speaks, P., co-chairs. 2011**. Washington State climate change response strategy: interim recommendations from Topic Advisory Group 3 on species, habitats and ecosystems. Topic Advisory Group 3 interim report, February 2011. Olympia, WA: State of Washington, Department of Ecology. 95 p.

**Houghton, R.A. 2005.** Aboveground forest biomass and the global carbon balance. Global Change Biology. 11: 945–958.

**Hurteau, M.; North, M. 2009.** Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wildfire scenarios. Frontiers in Ecology and the Environment. 7: 409–414.

**Hurteau, M.D.; Koch, G.W.; Hungate, B.A. 2008.** Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets. Frontiers in Ecology and the Environment. 6: 493–498.

**Ingerson, A. 2007.** U.S. forest carbon and climate change: controversies and win-win policy approaches. Washington, DC: The Wilderness Society. 18 p.

**Intergovernmental Panel on Climate Change [IPCC]. 2001.** Climate change 2001: mitigation. Third assessment report of the Intergovernmental Panel on Climate Change, Working Group III. Cambridge, United Kingdom: Cambridge University Press. 753 p.

**Jackson, R.B.; Jobbágy, E.G.; Avissar, R. [et al.]. 2005**. Trading water for carbon with biological carbon sequestration. Science. 310: 1944–1947.

**Jackson, R.B.; Randerson, J.T.; Canadell, J.G. [et al.]. 2008**. Protecting climate with forests. Environmental Research Letters. 3: 044006.

**Jackson, R.B.; Schlesinger, W.H. 2004.** Curbing the U.S. carbon deficit. Proceedings of the National Academy of Sciences, USA. 101: 15827–15829.

**Jackson, S.T. 2012**. Conservation and resource management in a changing world: extending historical range of variation beyond the baseline. In: Wiens, J.; Regan, C.; Hayward, G.; Safford, H., eds. Historical environmental variation in conservation and natural resource management. New York: Springer: 92–110.

**Jamison, R.; Cook, K.; Sandison, D., co-chairs. 2011.** Washington state integrated climate change response strategy: interim recommendations of the natural resources: working lands and water topic advisory group. http://www.ecy.wa.gov/climatechange/2011TAGdocs/R2011_interimreport.pdf. (27 December 2011).

**Janowiak, M.K.; Butler, P.R.; Swanston, C.W. [et al.]. 2011a.** Adaptation workbook. In: Swanston, C.W.; Janowiak, M.K., eds. Forest adaptation resources: climate change tools and approaches for land managers. Gen. Tech. Rep. NRS-87. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 35–56. Chapter 3.

**Janowiak, M.K.; Swanston, C.W.; Nagel, L.M. [et al.]. 2011b.** Silvicultural decision-making in an uncertain climate future: a workshop-based exploration of considerations, strategies, and approaches. Gen. Tech. Rep. NRS-81. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 14 p.

**Jiang, H.; Apps, M.J.; Peng, C. [et al.]. 2002**. Modeling the influence of harvesting on Chinese boreal forest carbon dynamics. Forest Ecology and Management. 169: 65–82.

**Jobbágy, E.G.; Jackson, R.B. 2004.** Groundwater use and salinization with grassland afforestation. Global Change Biology. 10: 1299–1312.

**Johnson, D.W.; Curtis, P.S. 2001.** Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management. 140: 227–238.

**Johnson, E. 2009.** Good-bye to carbon neutral: getting biomass footprints right. Environmental Impact Assessment Review. 29: 165–168.

**Johnstone, M.; Williamson, T. 2007**. A framework for assessing climate change vulnerability of the Canadian forest sector. The Forestry Chronicle. 83: 358–361.

**Jones, G.; Loeffler, D.; Butler, E. [et al.]. 2010.** Emissions, energy return and economics from utilizing forest residues for thermal energy compared to onsite pile burning. In: Jain, T.B.; Graham, R.T.; Sandquist, J., tech. eds. Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate. Proc. RMRS-P-61. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 145–158.

**Joyce, L.A.; Blate, G.M.; McNulty, S.G. [et al.]. 2009.** Managing for multiple resources under climate change. Environmental Management. 44: 1022–1032.

**Joyce, L.A.; Blate, G.M.; Littell, J.S. [et al.]. 2008**. National forests. In: Julius, S.H.; West, J.M., eds. Preliminary review of adaptation options for climate-sensitive ecosystems and resources: a report by the U.S. Climate Change Science Program and the Subcommittee on Climate Change Research. Washington, DC: U.S. Environmental Protection Agency: 3-1–3-127. Chapter 3.

**Kaipainen, T.; Liski, J.; Pussinen, A.; Karjalainen, T. 2004.** Managing carbon sinks by changing rotation length in European forests. Environmental Science and Policy. 7: 205–219.

**Keyser, T.L.; Lentile, L.B.; Smith, F.W.; Shepperd, W.D. 2008.** Changes in forest structure after a large, mixed-severity wildfire in ponderosa pine forests of the Black Hills, South Dakota, USA. Forest Science. 54: 328–338.

**Kohm, K.A.; Franklin, J.F., eds. 1997.** Creating a forestry for the 21st century: the science of ecosystem management. Washington, DC: Island Press. 475 p.

**Kollmuss, A.; Lee, C.; Lazaru, M. 2010.** How offset programs assess and approve projects and credits. Carbon Management. 1: 119–134.

**Lackey, R.T. 1995.** Seven pillars of ecosystem management. Landscape and Urban Planning. 40: 21–30.

**Lindner, M.; Maroschek, M.; Netherer, S. [et al.]. 2010.** Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management. 259: 698–709.

**Lippke, B.; Oneil, E.; Harrison, R. [et al.]. 2011.** Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. Carbon Management. 2: 303–333.

**Lippke, B.; Edmonds, L. 2006.** Environmental performance improvement in residential construction: the impact of products, biofuels, and processes. Forest Products Journal. 56: 58–63.

**Liski, J.; Pussinen, A.; Pingoud, K. [et al.]. 2001**. Which rotation length is favourable to carbon sequestration? Canadian Journal of Forest Research. 31: 2004–2013.

**Littell, J.S.; Oneil, E.E.; McKenzie, D. [et al.]. 2010.** Forest ecosystems, disturbance, and climatic change in Washington State, USA. Climatic Change. 102: 129–158.

**Littell, J.S.; Peterson, D.L. 2005.** A method for estimating vulnerability of Douglas-fir growth to climate change in the northwestern U.S. The Forestry Chronicle. 81: 369–374.

**Littell, J.S.; Peterson, D.L.; Millar, C.I.; O'Halloran, K.A. 2011**. U.S. national forests adapt to climate change through science-management partnerships. Climatic Change. 110: 269–296.

**Magnani, F.; Dewar, R.C.; Borghetti, M. 2009.** Leakage and spillover effects of forest management on carbon storage: theoretical insights from a simple model. Tellus Series B: Chemical and Physical Meteorology. 61: 385–393.

**Mälkki, H.; Virtanen, Y. 2003**. Selected emissions and efficiencies of energy systems based on logging and sawmill residues. Biomass and Bioenergy. 24: 321–327.

**Malmsheimer, R.W.; Bower, J.L.; Fried, J.S. [et al.]. 2011.** Managing forest because carbon matters: integrating energy, products, and land management policy. Journal of Forestry. 109: S7–S50.

**Malmsheimer, R.W.; Heffernan, P.; Brink, S. [et al.]. 2008**. Forest management solutions for mitigating climate change in the United States. Journal of Forestry 106: 115–173.

**Mann, M.K.; Spath, P.L. 2001.** A life-cycle assessment of biomass cofiring in a coal-fired power plant. Clean Products and Processes. 3: 81–91.

**Manomet Center for Conservation Sciences. 2010**. Massachusetts biomass sustainability and carbon policy study: report to the Commonwealth of Massachusetts Department of Energy Resources. Rep. NCI-201003. Brunswick, ME: Manomet Center for Conservation Sciences. 182 p.

**Margoluis, R.; Salafsky, N. 1998.** Measures of success: designing, managing, and monitoring conservation and development projects. Washington, DC: Island Press. 384 p.

**Marland, G.; Marland, S. 1992.** Should we store carbon in trees? Water, Air, and Soil Pollution. 64: 181–195.

**Marland, G.; Schlamadinger, B. 1997.** Forest for carbon sequestration of fossil fuel substitution? A sensitivity analysis. Biomass and Bioenergy. 13: 389–397.

**Marland, G.; Schlamadinger, B.; Leiby, P. 1997.** Forest/biomass based mitigation strategies: does the timing of carbon reductions matter? Critical Reviews in Environmental Science and Technology. 27: S213–S226.

**Mathews, J.A.; Tan, H. 2009**. Biofuels and indirect land use change effects: the debate continues. Biofuels, Bioproducts and Biorefining. 3: 305–317.

**McGuire, E.M.; Littell, J.; Whitely Binder, L., eds. 2009.** The Washington climate change impacts assessment. Seattle, WA: University of Washington, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, Climate Impacts Group. 414 p.

**McKeand, S.E.; Jokela, E.J.; Huber, D.A. [et al.]. 2006.** Performance of improved genotypes of loblolly pine across different soils, climates, and silvicultural inputs. Forest Ecology and Management. 227: 178–184.

**McKechnie, J.; Colombo, S.; Chen, J. [et al.]. 2011**. Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. Environmental Science and Technology. 45: 789–795.

**McKeever, D.B.; Adair, C.; O'Connor, J. 2006.** Wood products used in the construction of low-rise nonresidential buildings in the United States, 2003. Tacoma, WA: Wood Products Council. 68 p.

**McKenney, D.; Pedlar, J.; O'Neill, G. 2009.** Climate change and forest seed zones: past trends, future prospects and challenges to ponder. The Forestry Chronicle. 85: 258–266.

**McKinley, D.C.; Blair, J.M. 2008.** Woody plant encroachment by *Juniperus virginiana* in a mesic native grassland promotes rapid carbon and nitrogen accrual. Ecosystems. 11: 454–468.

**McKinley, D.C.; Ryan, M.G.; Birdsey, R.A. [et al.]. 2011.** A synthesis of current knowledge on forests and carbon storage in the United States. Ecological Applications. 21: 1902–1924.

**McLachlan, J.S.; Hellmann, J.J.; Schwart, M.W. 2007.** A framework for debate of assisted migration in an era of climate change. Conservation Biology. 21: 297–302.

**Melamu, R.; von Blottnitz, H. 2011.** 2nd generation biofuels a sure bet? A life cycle assessment of how things could go wrong. Journal of Cleaner Production. 19: 138–144.

**Melillo, J.M.; Reilly, J.M.; Kicklighter, D.W. [et al.]. 2009**. Indirect emissions from biofuels: how important? Science. 326: 1397–1399.

**Metz, B.; Davidson, O.; Swart, R.; Pan, J., eds. 2001.** Climate change 2001: mitigation. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press. 700 p.

**Meyfroidt, P.; Rudel, T.K.; Lambin, E.F. 2010.** Forest transitions, trade, and the global displacement of land use. Proceedings of the National Academy of Sciences, USA. 107: 20917–20922.

**Millar, C.I.; Stephenson, N.L.; Stephens, S.L. 2007.** Climate change and forests of the future: managing in the face of uncertainty. Ecological Applications. 17: 2145–2151.

**Milly, P.C.D.; Betancourt, J.; Falkenmark, M. [et al.]. 2008**. Stationarity is dead: whither water management? Science. 319: 573–574.

**Minnesota Forest Resources Council [MFRC]. 2011**. Landscape management documents. http://www.frc.state.mn.us/resources_documents_landscape.html. (28 December 2011).

**Mitchell, S.R.; Harmon, M.E.; O'Connell, K.E.B. 2009.** Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecological Applications. 19: 643–655.

**Morelli, T.L.; Carr, S.C. 2011**. A review of the potential effects of climate change on quaking aspen (*Populus tremuloides*) in the western United States and a new tool for surveying sudden aspen decline. Res. Pap. PSW-RP-235. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 31 p.

**Morelli, T.L.; McGlinchy, M.C.; Neilson R.P. 2011a.** A climate change primer for land managers: an example from the Sierra Nevada. Res. Pap. PSW-RP-262. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 44 p.

**Morelli, T.L.; Yeh, S.; Smith, N. [et al.]. 2011b.** Climate project screening tool: an aid for climate change adaptation. Res. Pap. PSW-RP-263. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 29 p.

**Moser, S.C.; Luers, A.L. 2008**. Managing climate risks in California: the need to engage resource managers for successful adaptation to change. Climatic Change. 87: S309–S322.

**Murray, B.C.; McCarl, B.A.; Lee, H.-C. 2004.** Estimating leakage from forest carbon sequestration programs. Land Economics. 80: 109–124.

**National Environmental Policy Act of 1969 [NEPA]**; 42 U.S.C. 4321 et seq.

**National Forest Management Act of 1976 [NFMA]**; Act of October 22, 1976; 16 U.S.C. 1600.

**National Park Service [NPS]. 2010**. Climate change response strategy: science, adaptation, mitigation, communication. Fort Collins, CO: U.S. Department of the Interior, National Park Service, Climate Change Response Program; Washington, DC: U.S. Department of the Interior, National Park Service. 26 p.

**National Research Council**, **Committee on Abrupt Climate Change. 2002**. Abrupt climate change: inevitable surprises. Washington, DC: National Academy Press. 230 p.

**Nave, L.E.; Vance, E.D.; Swanston, C.W.; Curtis, P.S. 2010.** Harvest impacts on soil carbon storage in temperate forests. Forest Ecology and Management. 259: 857–866.

**Nilsson, D.; Bernesson, S.; Hansson, P.A. 2011.** Pellet production from agricultural raw materials—a systems study. Biomass and Bioenergy. 35: 679–689.

**Nilsson, U.; Allen, H.L. 2003.** Short- and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. Forest Ecology and Management. 175: 367–377.

**Nitschke, C.R.; Innes, J.L. 2008.** Integrating climate change into forest management in south-central British Columbia: an assessment of landscape vulnerability and development of a climate-smart framework. Forest Ecology and Management. 256: 313–327.

**North Carolina State University [NCSU]. 2011**. TACCIMO: template for assessing climate change impacts and management options. http://www.sgcp.ncsu.edu:8090. (28 December 2011).

**North Cascadia Adaptation Partnership. 2011.** North Cascadia Adaptation Partnership: preparing for climate change through science-management collaboration. http://northcascadia.org. (20 June 2012).

**Northern Arizona University [NAU]. 2011**. Tribes and climate change. http://www4.nau.edu/tribalclimatechange. (28 December 2011).

**Nowak, D.J.; Crane, D.E. 2002.** Carbon storage and sequestration by urban trees in the USA. Environmental Pollution. 116: 381–389.

**Nowak, D.J.; Kuroda, M.; Crane, D.E. 2004.** Tree mortality rates and tree population projections in Baltimore, Maryland, USA. Urban Forestry and Urban Greening. 2: 139–147.

**Nunnery, J.S.; Keeton, W.S. 2010**. Forest carbon storage in the northeastern United States: net effects of harvesting frequency, post-harvest retention, and wood products. Ecological Applications. 259: 1363–1375.

**Nydick, K.; Sydoriak, C. 2011**. The strategic framework for science in support of management in the Southern Sierra Nevada, California. Park Science. 28: 41–43.

**Overpeck, J.; Udall, B. 2010.** Dry times ahead. Science. 328: 1642–1643.

**Pacala, S.W.; Hurtt, G.C.; Baker, D. [et al.]. 2001.** Consistent land- and atmosphere-based U.S. carbon sink estimates. Science. 292: 2316–2320.

**Pachauri, R.D.; Reisinger, A., eds. 2007.** Climate change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: Intergovernmental Panel on Climate Change. 104 p.

**Pacific Forest Trust [PFT]. 2011.** Working forests, winning climate. http://www.pacificforest.org/Working-Forests-Winning-Climate.html. (27 December 2011).

**Pataki, D.E.; Alig, R.J.; Fung, A.S. [et al.]. 2006.** Urban ecosystems and the North American carbon cycle. Global Change Biology. 12: 2092–2102.

**Patzek, T.W.; Pimentel, D. 2005.** Thermodynamics of energy production from biomass. Critical Reviews in Plant Sciences. 24: 327–364.

**Peng, J.H.; Bi, H.T.; Sokhansanj, S. [et al.]. 2010.** An economical and market analysis of Canadian wood pellets. International Journal of Green Energy. 7: 128–142.

**Perlack, R.D.; Wright, L.L.; Turhollow, A.F. [et al.]. 2005.** Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge, TN: U.S. Department of Energy, Oak Ridge National Laboratory. 60 p.

**Peters-Stanley, M.; Hamilton, K.; Marcello, T.; Sjardin, M. 2011**. Back to the future: state of the voluntary carbon markets 2011. Washington, DC: Ecosystem Marketplace. 78 p.

**Peterson, D.L.; Johnson, M.C.; Agee, J.K. [et al.]. 2005.** Forest structure and fire hazard in dry forests of the western United States. Gen. Tech. Rep. PNW-GTR-628. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 30 p.

**Peterson, D.L.; Millar, C.I.; Joyce, L.A. [et al.]. 2011.** Responding to climate change on national forests: a guidebook for developing adaptation options. Gen. Tech. Rep. PNW-GTR-855. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 109 p.

**Peterson, D.L.; Parker, V.T., eds. 1998.** Ecological scale: theory and applications**.** New York: Columbia University Press. 608 p.

**Pimentel, D.; Marklein, A.; Toth, M.A. [et al.]. 2008**. Biofuel impacts on world food supply: use of fossil fuel, land and water resources. Energies. 1: 41–78.

**Pinchot Institute for Conservation. 2011.** The Pinchot letter. 16(1). Available at http://www.pinchot.org/pubs/c34.

**Pinkard, L.; Battaglia, M.; Howden, M. [et al.]. 2010.** Adaptation to climate change in Australia's plantation industry. Canberra, Australia: Commonwealth Scientific and Industrial Research Organisation of Australia. 78 p.

**Potter, K.M.; Crane, B.S. 2010.** Assessing forest tree genetic risk across the southern Appalachians: a tool for conservation decision-making in changing times. http://www.forestthreats.org/current-projects/project-summaries/genetic-risk-assessment-system. (27 December 2011).

**Reich, P.B.; Grigal, D.F.; Aber, J.D.; Gower, S.T. 1997.** Nitrogen mineralization and productivity in 50 hardwood and conifer stands on diverse soils. Ecology. 78: 335–347.

**Reinhardt, E.D.; Holsinger, L.; Keane, R. 2010.** Effects of biomass removal treatments on stand-level fire characteristics in major forest types of the Northern Rocky Mountains. Western Journal of Applied Forestry. 25: 34–41.

**Reinhardt, E.D.; Keane, R.E.; Calkin, D.E.; Cohen, J.D. 2008.** Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecology and Management. 256: 1997–2006.

**Repo, A.; Tuomi, M.; Liski, J. 2011.** Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. GCB Bioenergy. 3: 107–115.

**Riccardi, A; Simberloff, D. 2009.** Assisted colonization is not a viable conservation strategy. Trends in Ecology and Evolution. 24: 248–253.

**Rice, J.; Tredennick, A.; Joyce, L.A. 2012.** Climate change on the Shoshone National Forest, Wyoming: a synthesis of past climate, climate projections, and ecosystem implications. Gen. Tech. Rep. RMRS-GTR-264. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 60 p.

**Rose, K.A. 2010.** Tribal climate change adaptation options: a review of the scientific literature. Seattle, WA: U.S. Environmental Protection Agency, Region 10, Office of Air, Waste and Toxics. 86 p.

**Saracoglu, N.; Gunduz, G. 2009.** Wood pellets—tomorrow's fuel for Europe. Energy Sources: Part A: Recovery Utilization and Environmental Effects. 31: 1708–1718.

**Sathre, R.; O'Connor, J. 2008.** A synthesis of research on wood products and greenhouse gas impacts. Tech. Rep. TR-19. Vancouver, BC, Canada: FPInnovations, Forintek Division.

**Schlamadinger, B.; Marland, G. 1996.** The role of forest and bioenergy strategies in the global carbon cycle. Biomass and Bioenergy. 10: 275–300.

**Schlamadinger, B.; Spitzer, J.; Kohlmaier, G.H.; Lüdeke, M. 1995.** Carbon balance of bioenergy from logging residues. Biomass and Bioenergy. 8: 221–234.

**Schönau, A.P.G.; Coetzee, J. 1989.** Initial spacing, stand density and thinning in eucalpt plantations. Forest Ecology and Management. 29: 245–266.

**Schroeder, P. 1992.** Carbon storage potential of short rotation tropical tree plantations. Forest Ecology and Management. 50: 31–41.

**Schwaiger, H.P.; Bird, D.N. 2010.** Integration of albedo effects caused by land use change into the climate balance: should we still account in greenhouse gas units? Forest Ecology and Management. 260: 278–286.

**Schwarze, R.; Niles, J.O.; Olander, J. 2002.** Understanding and managing leakage in forest-based greenhouse-gas-mitigation projects. Philosophical Transactions of the Royal Society of London Series A: Mathematical, Physical, and Engineering Sciences. 360: 1685–1703.

**Scott, D.; McBoyle, G. 2007.** Climate change adaptation in the ski industry. Mitigation and Adaptation Strategies for Global Change. 12: 1411–1431.

**Scott, D.; McBoyle, G.; Minogue, A.; Mills, B. 2006.** Climate change and the sustainability of ski-based tourism in Eastern North America: a reassessment. Journal of Sustainable Tourism. 14: 376–398.

**Scott, J.H.; Reinhardt, E.D. 2001.** Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p.

**Searchinger, T.; Heimlich, R.; Houghton, R.A. [et al.]. 2008.** Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science. 319: 1238–1240.

**Searchinger, T.D.; Hamburg, S.P.; Melillo, J. [et al.]. 2009.** Fixing a critical climate accounting error. Science. 326: 527–528.

**Sedjo, R. 2010.** Adaptation of forests to climate change; some estimates. Discussion Paper RFF DP 10-06. Washington, DC: Resources for the Future. 51 p.

**Seely, B.; Welham, C.; Kimmins, H. 2002.** Carbon sequestration in a boreal forest ecosystem: results from the ecosystem simulation model, FORECAST. Forest Ecology and Management. 169: 123–135.

**Seppälä, R.; Buck, A.; Katila, P., eds. 2009a.** Adaptation of forests and people to climate change: a global assessment report. IUFRO World Series volume 22. Vienna, Austria: International Union of Forest Research Organizations. 224 p.

**Seppälä, R.; Buck, A.; Katila, P., eds. 2009b.** Making forest lands fit for climate change: a global view of climate-change impacts on forests and people and options for adaptation. Policy Brief. Helsinki, Finland; Ministry of Foreign Affairs of Finland: International Union of Forest Research Organizations. 39 p.

**Skog, K.E. 2008**. Sequestration of carbon in harvested wood products for the United States. Forest Products Journal. 58: 56–72.

**Smeets, E.M.W.; Faaij, A.P.C. 2007**. Bioenergy potentials from forestry in 2050: an assessment of the drivers that determine the potentials. Climatic Change. 81: 353–390.

**Smithwick, E.A.H.; Harmon, M.E.; Remillard, S.M. [et al.]. 2002**. Potential upper bounds of carbon stores in forests of the Pacific Northwest. Ecological Applications. 12: 1303–1317.

**Snover, A.; Whitley Binder, L.; Lopez, J.; Willmott, E.; Kay, J.; Howell, D.; Simmonds, J. 2007**. Preparing for climate change: a guidebook for local, regional, and state governments. Oakland, CA: In association with and published by ICLEI—Local Governments for Sustainability. 172 p.

**Sohngen, B.; Beach, R.H.; Andrasko, K. 2008.** Avoided deforestation as a greenhouse gas mitigation tool: economic issues. Journal of Environmental Quality. 37: 1368–1375.

**Sohngen, B.; Brown, S. 2008**. Extending timber rotations: carbon and cost implications. Climate Policy. 8: 435–451.

**Sohngen, B.; Mendelsohn, R.; Sedjo, R. 1999**. Forest management, conservation, and global timber markets. American Journal of Agricultural Economics. 81: 1–13.

**Solomon, A.; Birdsey, R.; Joyce, R.; Hayes, J. 2009**. Forest Service global change research strategy overview, 2009–2019. FS-917a. Washington, DC: U.S. Department of Agriculture, Forest Service, Research and Development. 18 p. http://www.fs.fed.us/climatechange/documents/global-change-strategy.pdf. (27 December 2011).

**Solomon, B.D.; Barnes, J.R.; Halvorsen, K.E. 2007**. Grain and cellulosic ethanol: history, economics, and energy policy. Biomass and Bioenergy. 31: 416–425.

**Solomon, S.; Quin, D.; Manning, M. [et al.], eds**. **2007**. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press. 996 p.

**Spath, P.L.; Mann, M.K. 2000.** Life cycle assessment of a natural gas combined-cycle power generation system. NREL/TP-570-27715. Golden, CO: National Renewable Energy Laboratory. 55 p.

**Spittlehouse, D.L. 2005.** Integrating climate change adaptation into forest management. The Forestry Chronicle. 81: 691–695.

**State Agency Climate Leadership Act of 2009.** Revised Code of Washington.

**Stephens, S.L.; Moghaddas, J.J.; Hartsough, B.R. [et al.]. 2009**. Fuel treatment effects on stand-level carbon pools, treatment-related emissions, and fire risk in a Sierra Nevada mixed-conifer forest. Canadian Journal of Forest Research. 39: 1538–1547.

**Stephenson, N.L.; Millar, C.I. 2012.** Climate change: wilderness' greatest challenge. Park Science. 28: 34–38.

**Sutley, N.H. 2010.** Draft NEPA guidance on consideration of the effects of climate change and greenhouse gas emissions. Washington, DC: Council on Environmental Quality. 12 p. http://ceq.hss.doe.gov/nepa/regs/Consideration_of_Effects_of_GHG_Draft_NEPA_Guidance_FINAL_02182010.pdf.

**Swanston, C.W.; Janowiak, M.; Iverson, L. [et al.]. 2011.** Ecosystem vulnerability assessment and synthesis: a report from the climate change response framework project in northern Wisconsin. Gen. Tech. Rep. NRS-82. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 142 p.

**Swanston, C.W.; Janowiak, M.K. 2012.** Forest adaptation resources: climate change tools and approaches for land managers. Gen. Tech. Rep. NRS-87. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 121 p.

**Swanston, C.W.; Janowiak, M.K.; Butler, P.R. 2012.** Climate change response framework overview. In: Swanston, C.W.; Janowiak, M.K., eds. Forest adaptation resources: climate change tools and approaches for land managers. Gen. Tech. Rep. NRS-87. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 8–14.

**Swinomish Indian Tribal Community [SITC]. 2010**. Swinomish climate change initiative: climate adaptation action plan. La Conner, WA: Swinomish Tribal Community, Office of Planning and Community Development. 144 p.

**Tapash Sustainable Forest Collaborative. 2010.** The Tapash sustainable forest collaborative: collaborative forest landscape restoration program. http://www.tapash.org/cflra.htm. (27 December 2011).

**The Nature Conservancy [TNC]. 2011a**. ClimateWizard. http://www.climatewizard.org. (28 December 2011).

**The Nature Conservancy [TNC]. 2011b.** NaturePeopleFuture.org: TNC's knowledge base for climate change adaptation. http://www.naturepeoplefuture.org. (28 December 2011).

**Thornley, J.H.M.; Cannell, M.G.R. 2000**. Managing forests for wood yield and carbon storage: a theoretical study. Tree Physiology. 20: 477–484.

**Tumuluru, J.S.; Sokhansanj, S.; Lim, C.J. [et al.]. 2010**. Quality of wood pellets produced in British Columbia for export. Applied Engineering in Agriculture. 26: 1013–1020.

**Tuskan, G.A. 1998.** Short-rotation woody crop supply systems in the United States: what do we know and what do we need to know? Biomass and Bioenergy. 14: 307–315.

**United Nations. 1992**. United Nations Framework Convention on Climate Change. FCCC/INFORMAL/84, GE.05-62220 (E) 200705. http://unfccc.int/resource/docs/convkp/conveng.pdf. (20 September 2012).

**U.S. Climate Change Science Program. 2007.** The first state of the carbon cycle report (SOCCR): the North American carbon budget and implications for the global carbon cycle: a report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Asheville, NC: National Oceanic and Atmospheric Administration, National Climatic Data Center. 242 p.

**U.S. Department of Agriculture, Farm Service Agency. 2010.** Conservation reserve program: annual summary and enrollment statistics. https://www.fsa.usda.gov/Internet/FSA_File/annual2010summary.pdf. (2 October 2012).

**U.S. Department of Agriculture, Forest Service [USDA FS]. 2008.** Forest Service strategic framework for responding to climate change. Version 1. Washington, DC: U.S. Department of Agriculture, Forest Service. http://www.fs.fed.us/climatechange/documents/strategic-framework-climate-change-1-0.pdf. (27 December 2011).

**U.S. Department of Agriculture, Forest Service [USDA FS]. 2011a**. Climate change resource center (CCRC). http://www.fs.fed.us/ccrc. (28 December 2011).

**U.S. Department of Agriculture, Forest Service [USDA FS]. 2011b**. National roadmap for responding to climate change. FS-957B. Washington, DC: U.S. Department of Agriculture, Forest Service. 32 p. http://www.fs.fed.us/climatechange/pdf/roadmapfinal.pdf. (27 December 2011).

**U.S. Department of Agriculture, Forest Service [USDA FS]. 2011c.** Navigating the performance scorecard: a guide for national forests and grasslands. Version 2, August 2011. Washington, DC: U.S. Department of Agriculture, Forest Service. 104 p. http://www.fs.fed.us/climatechange/advisor/scorecard/scorecard-guidance-08-2011.pdf. (27 December 2011).

**U.S. Department of Agriculture, Forest Service [USDA FS]. 2012**. Future of America's forest and rangelands: Forest Service 2010 Resources Planning Act assessment. Gen. Tech. Rep. WO-87. Washington, DC. 198 p.

**U.S. Department of Agriculture, Forest Service. [USDA FS]. 2012b**. Southern forest futures project. http://www.srs.fs.usda.gov/futures. (20 June 2012).

**U.S. Department of Energy [USDOE]. 2009.** Annual energy review 2008. Washington, DC: Energy Information Administration. 407 p.

**U.S. Department of the Interior [DOI]. 2009.** Secretarial order no. 3289. Addressing the impacts of climate change on America's water, land, and other natural and cultural resources.

**U.S. Department of the Interior, Fish and Wildlife Service [DOI FWS]. 2011.** Landscape conservation cooperatives: shared science for a sustainable future. Fact sheet. March 2011. http://www.fws.gov/science/shc/pdf/LCC_Fact_Sheet.pdf. (27 December 2011).

**U.S. Environmental Protection Agency [USEPA]. 2005.** Greenhouse gas mitigation potential in U.S. forestry and agriculture. EPA 430-R-05-006. Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs. 157 p.

**U.S. Environmental Protection Agency [USEPA]. 2008**. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2006. 430-R-08-005. Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs.

**U.S. Environmental Protection Agency [USEPA]. 2009a.** Land use, land use change and forestry. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2007. Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs.

**U.S. Environmental Protection Agency [USEPA]. 2009b.** Waste. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2007. Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs.

**U.S. Environmental Protection Agency [USEPA]. 2010**. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2008. EPA 430-R-09-006. Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs.

**U.S. Environmental Protection Agency [USEPA]. 2011.** Draft inventory of U.S. greenhouse gas emissions and sinks: 1990–2009. EPA 430-R-11-005. Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs. http://epa.gov/climatechange/emissions/usinventoryreport.html. (12 March 2011).

**U.S. Global Change Research Program [USGCRP]. 2011.** The United States national climate assessment: uses of vulnerability assessments for the national climate assessment. NCA Report Series, volume 9. http://downloads.globalchange.gov/nca/workshop-reports/vulnerability-assessments-workshop-report.pdf. (20 June 2012).

**Upton, B.; Miner, R.; Spinney, M.; Heath, L.S. 2008.** The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. Biomass and Bioenergy. 32: 1–10.

**Van Auken, O.W. 2000**. Shrub invasions of North American semiarid grasslands. Annual Review of Ecology and Systematics. 31: 197–215.

**Walters, C. 1986.** Adaptive management of renewable resources. New York: Macmillan. 374 p.

**Weeks, D.; Malone, P.; Welling, L. 2011.** Climate change scenario planning: a tool for managing parks into uncertain futures. Park Science. 28: 26–33.

**Washington State Department of Ecology. 2012.** Preparing for a changing climate: Washington state's integrated climate response strategy. Olympia, WA: Washington State Department of Ecology, Climate Policy Group. http://www.ecy.wa.gov/climatechange/ipa_responsestrategy.htm. (26 Sepember 2012).

**Westerling, A.L.; Turner, M.G.; Smithwick, E.A.H. [et al.]. 2011.** Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proceedings of the National Academy of Sciences of the United States of America. 108: 13165–13170.

**Western Governors' Association [WGA]. 2009**. Supporting the integration of climate change adaptation science in the West. Policy Resolution 09-2. Denver, CO: Western Governors' Association. 3 p.

**Western Governors' Association [WGA]. 2010.** Climate adaptation priorities for the western states: scoping report. Denver, CO: Western Governors' Association. 20 p.

**Woodall, C.W.; D'Amato, A.W.; Bradford, J.B.; Finley, A.O. 2011**. Effects of stand and inter-specific stocking on maximizing standing tree carbon stocks in the eastern United States. Forest Science. 57: 365–378.

**Zanchi, G.; Pena, N.; Bird, N. 2010**. The upfront carbon debt of bioenergy. Graz, Austria: Joanneum Research. http://www.birdlife.org/eu/pdfs/Bioenergy_Joanneum_Research.pdf. (23 November 2011).

**Zerbe, J.I. 2006.** Thermal energy, electricity, and transportation fuels from wood. Forest Products Journal. 56: 6–14.