3 National Forests

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Chapter Contents

Chapter Structure

3.1 Background and History
Describes the origins of the National Forest System (NFS), its single-agency governance structure, and the formative factors that shaped its mission and goals

3.2 Current Status of Management System
Reviews existing system stressors, management practices currently used to address NFS' multiple use goals, and how those goals may be affected by climate change

3.3 Adapting to Climate Change
Discusses approaches to adaptation for planning and management in the context of climate change

3.4-3.6 Case Studies
Explores methods for and challenges to incorporating climate change into specific National Forest management activities and plans
- **Tahoe National Forest**
- **Olympic National Forest**
- **Uwharrie National Forest**

3.7 Conclusions

3.1 Background and History

3.1.1 Historical Context and Enabling Legislation

In the mid 1800s, the rapid western expansion of European-American settlement and the associated environmental impact of deforestation, human-caused wildfire, and soil erosion raised concerns about the sustainability of public lands (Rueth, Baron, and Joyce, 2002). At a meeting of the American Association for the Advancement of Science in 1873, Franklin Benjamin Hough described the environmental harm resulting from European forest practices and proposed that the United States take action to avoid such impacts. Congress directed the U.S. Department of Agriculture (USDA) to report on forest conditions, and in 1876 Hough—as the USDA special forestry agent—completed the first assessment of U.S. forests. In 1881, the Division of Forestry within USDA was created with the mission to provide information. Three years later, research was added to the mission.

With the passage of the Forest Reserve Act of 1891, President Harrison established the first timber land reserve (White River Plateau Timber Land Reserve, Colorado) under the control of the General Land Office (Fig. 3.1). Over the next two years, Harrison designated more than 13 million acres within 15 forest reserves in seven western states and Alaska (Rowley, 1985). The Forest Transfer Act of 1905 established the U.S. Forest Service, in USDA, and transferred the reserves from the General Land Office to USDA. With this legislation, the policy shifted from land privatization to federal forest protection and the organizational culture was established as one of production forestry and scientific management (Rowley, 1985; MacCleery, 2006). In 1907, the forest reserves were renamed to national forests (NFs). By 1909 when President Roosevelt left office, the national forests had expanded to 172 million acres (70 million hectares) on 150 NFs (USDA Forest Service, 2005).

Figure 3.1. Timeline of National Forest System formation and the legislative influences on the mission of the national forests.

3.1.2 Evolution of National Forest Mission

In the 1891 act, the mission was to "improve and protect the forest within the boundaries, or for the purposes of securing favorable conditions of water flows, and to furnish a continuous supply of timber." In 1905, Secretary of Agriculture James Wilson wrote that questions of use must be decided "from the standpoint of the greatest good for the greatest number in the long run." (USDA Forest Service, 1993). The 1936 Report of the Chief recognized a greater variety of purposes for NFs including "timber production, watershed production, forage production, and livestock grazing, wildlife production, recreational use, and whatever combination of these uses will yield the largest net total public benefits" (Williams and Liebhold, 2002; as cited in MacCleery, 2006). In 1960, the Multiple Use-Sustained Yield Act officially broadened the mission to give the agency "permissive and discretionary authority to administer the national forest for outdoor recreation, range, timber, watershed, and wildlife and fish purposes" (U.S. Congress, 1960).

Specific management goals for land within national forest boundaries were identified by legislation in the 1960s: Wilderness Act of 1964, National Trails System Act of 1968, Wild and Scenic Rivers Act of 1968 (U.S. Congress, 1968). As these national systems encompassed land from many federal agencies, coordination with other federal and in some cases state agencies was a new component of the management of lands within the NFs. By 2006, 23 percent of the National Forest System's lands were statutorily set aside in congressional designations—the National Wilderness, National Monuments, National Recreation Areas, National Game Refuges and Wildlife Preserve, Wild and Scenic Rivers, Scenic Areas, and Primitive Areas.

Environmental legislation of the 1970s established oversight by agencies other than the Forest Service for the environmental effect of land management within NFs. The Clean Air Act of 1970 and the Clean Water Act of 1972 gave the Environmental Protection Agency responsibility for setting air and water quality standards, and the states responsibility for enforcing these standards. Similarly, the U.S. Fish and Wildlife Service and the National Marine Fisheries Service were given a new responsibility through the required consultation process in the Endangered Species Act of 1973 to concur with proposed management on federal lands that could modify the habitat of listed species.

Additional legislation established greater public involvement in evaluating management impacts and in the forest planning process. The National Environmental Policy Act (NEPA) of 1970 required all federal agencies proposing actions that could have a significant environmental effect to evaluate the proposed action as well as a range of alternatives, and provide an opportunity for public comment (MacCleery, 2006). Increased public participation in the national forest planning process was provided for within the National Forest Management Act of 1976. Land management activities within the NFs were now, more than ever, in the local, regional, and national public limelight.

These laws and their associated regulations led to many changes within the organizational structure of the Forest Service, the composition of the skills within the local, regional, and national staffs, and the management philosophies used to guide natural resource management. Additionally, the public, environmental groups, internal agency sources, and the Forest Service's own research community were reporting that substantial changes were needed in natural resource management (MacCleery, 2006). In 1992, Forest Service Chief Dale Robertson announced that 'an ecological approach' would now govern the agency's management philosophy. In 1994, Chief Jack Ward Thomas issued the publication *Forest Service Ethics and Course to the Future*, which described the four components of ecosystem management: protecting ecosystems, restoring deteriorated ecosystems, providing multiple-use benefits for people within the capabilities of ecosystems, and ensuring organizational effectiveness. MacCleery (2006) notes that this shift to ecosystem management occurred without explicit statutory authority, and as an administrative response to many factors such as public involvement in the planning processes, increased technical diversity within the Forest Service staffs, increased demand for recreational opportunities, and increased understanding in the natural resource sciences.

After the active wildfire season in 2000, federal agencies drafted the National Fire Plan to reduce the risk of wildfire to communities and natural resources. The Plan has focused prevention on the reduction of woody biomass (mechanical thinning, prescribed fire) and the restoration of ecosystems where past land use had altered fire regimes. The Healthy Forest Restoration Act of 2003 included provisions to expedite NEPA and other processes to increase the rate at which fuel treatments were implemented in the wildland-urban interfaces of at-risk communities, at-risk municipal watersheds, areas where fuel treatments could reduce the risk of fire in habitat of threatened and endangered species, and where wind-throw or insect epidemics threaten ecosystem components or resource values (U.S. Congress, 2003a).

The 2004–2008 USDA Forest Service Strategic Plan describes the mission of the Forest Service, an agency with three branches: National Forest Systems, Research, and State and Private, as: “To sustain the health, diversity and productivity of the Nation’s forest and grasslands to meet the needs of present and future generations” (USDA Forest Service, 2004c). The mission reflects public and private interests in the protection and preservation of natural resources, a century of laws passed to inform the management of national forest lands, partnerships with states for stewardship of non-federal lands, and a century of research findings.

3.1.3 Interpretation of Goals

At the national level, the USDA Forest Service Strategic Plan identifies a set of national goals for all three branches of the Forest Service (Box 3.1). Within National Forest Systems, these goals are interpreted in each level of the organization: national, regional, and individual administrative unit (forest, grassland, prairie) (Fig. 3.2).

Figure 3.2. Jurisdiction and organizational levels within the National Forest System.

The forest level coordinates and conducts the forest planning process. The planning process identifies management goals specific to the ecosystem services and natural resources of each national forest that will reflect the national goals, the public interests. Individual forests have worked together to develop documents that guide management of a group of forests. For example, the Pacific Northwest Forest Plan was initiated in 1993 to end an impasse over the management of federal lands within the range of the northern spotted owl. The area encompassed 24.5 million acres; 17 NFs in Washington, Oregon, and California; and the Bureau of Land Management managed public lands in Oregon and Washington. Project planning within the administrative unit (forest, grassland, prairie) addresses specific on-the-ground management such as recreation projects, fisheries projects, restoration projects, vegetation management projects, and fuel treatments.

3.2 Current Status of Management Systems

3.2.1 Key Ecosystem Characteristics on Which Goals Depend

The National Forests System (NFS) (Fig. 3.3) comprises a large variety of ecosystems with diverse characteristics. The U.S. Forest Service (2000b)[1] describes 27 major forest types ranging

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[1] Map available online at: http://fia.fs.fed.us/library/maps/docs/forestcover.pdf

from tropical forests in Hawaii and Puerto Rico to boreal forests in Alaska to mixed hardwood forests in the Northeast and coniferous forests in the West. The NFS also includes aquatic systems (lakes, ponds, wetlands, and waterways) as well as areas dominated by meadows, grasslands, and rocky terrain. Considering its extent and diversity, the NFS is an important cultural and natural heritage and, as such, is valued by a wide variety of stakeholders.

Figure 3.3. One hundred fifty-five National Forests and 20 National Grasslands across the United States provide a multitude of goods and ecosystems services, including biodiversity (USDA Forest Service Geodata Clearinghouse, 2007).

National forests harbor much of the nation's terrestrial biodiversity. Specifically, NFs comprise three major attributes of biodiversity from the genetic to the landscape scale (see Noss, 1990): structural diversity (*e.g.*, genetic, population, and ecosystem structure), compositional diversity (*e.g.*, genes, species, communities, ecosystems, and landscape types), and functional diversity (*e.g.*, genetic, demographic, and ecosystem processes, life histories, and landscape-scale processes and disturbances). Biodiversity conservation has become an important goal of the USFS and is a consideration in planning (for example see USDA Forest Service, 2007c). National forests provide important habitat for many rare, threatened, and endangered plants and animals, ranging from charismatic species such as the grey wolf (*Canis lupus*) to the lesser known species such as Ute ladies' tresses (*Spiranthes diluvialis*). Climate change will amplify the current biodiversity conservation challenge because it is already affecting and will continue to affect the relationships between climate and the various attributes and components (*i.e.*, genes, species, ecosystems, and landscapes) of biodiversity (Hansen *et al.*, 2001; Root *et al.*, 2003; Malcolm *et al.*, 2006; Parmesan, 2006; see Section 3.2.4).

National forests also provide myriad goods and services—collectively called ecosystem services (Millennium Ecosystem Assessment, 2005; see next paragraph). Historically, timber, grazing, and fresh water have been the most important goods and services NFs provide. Although timber harvest (Fig. 3.4) and domestic livestock grazing now occur at lower than historical levels (see also Mitchell, 2000; Haynes *et al.*, 2007), NFs harvested over 2.2 million board feet in 2006 (USDA Forest Service, 2006a) and over 7000 ranchers relied on NFs and national grasslands for grazing their livestock (USDA Forest Service, 2007a). About 60 million Americans (1/5 of the nation's population in 3,400 towns and cities depend on water that originates in national forest watershed (USDA Forest Service, 2004c). In addition, NFs contain about 3,000 public water supplies for visitors and employees (*e.g.*, campgrounds, visitor centers, and administrative facilities; USDA Forest Service, 2004c), Thus, the condition of the watershed affects the quality, quantity, and timing of water flowing through them (Brown and Froemke, 2006), which is of critical importance for these people as well as for the functioning of the ecosystems themselves. Climate change will almost certainly affect all three of these historical ecosystems services of NFs (see Section 3.4.2) and likely complicate the USFS's already formidable task of restoring, sustaining, and enhancing forests and grasslands while providing and sustaining benefits to the American people.

Figure 3.4. Historical harvest levels and grazing across the National Forests (USDA FS Forest Management; Mitchell, 2000).

Over the past few decades, the USFS and the public have come to appreciate the full range of ecosystem services that NFs provide (see Box 3.2). The Millennium Ecosystem Assessment (2005) defines ecosystem services as the benefits people derive from ecosystems, and classifies these benefits into four general categories (Box 3.2): provisioning (*i.e.*, products from ecosystems), regulating (*i.e.*, regulation of ecosystem processes), cultural (*i.e.*, nonmaterial benefits), and supporting services (*i.e.*, services required for production of all other ecosystems services). The growing importance of regulating services such as water regulation (see Goal 5, Box 3.1) and cultural services such as aesthetics and especially recreation is reflected in the USFS national goals (see Goal 3, Box 3.1).

The achievement of strategic and tactical goals set forth by the USFS depends on conservation and enhancement of ecosystems services at various scales. It also depend on the conservation of biodiversity because biodiversity and ecosystem services are inextricably linked (Díaz *et al.*, 2006), and because biodiversity conservation generally has a positive effect on ecosystem services (Balvanera *et al.*, 2006). Maintenance of biodiversity and enhancement of ecosystems services on NFs is considered within the context of all potential uses and values of individual NFs. Unlike other federal lands afforded strict protection, NFs contain multiple resources to be managed for the benefit of current and future generations (see Multiple-Use Sustained-Yield Act of 1960). The USFS, as the steward of NFs and its resources, actively manages NFs to achieve the national goals outlined in Box 3.1 and the individual goals identified for each national forest and grassland.

The distinctive structure and composition of individual NFs are key characteristics that most national forest managers seek to sustain. Efforts to achieve a particular desired forest structure, composition, and function have often been based on historical references or baselines (*i.e.*, observed range of variation), and on the now outdated notion that communities and ecosystems are at equilibrium with their environment (Millar and Woolfenden, 1999). Under climate change, such an approach may no longer be sensible. Climate projections suggest a changing climate (increased temperatures, increased rainfall intensity, and greater occurrence of extreme events, such as drought, flooding, etc.). Ecosystem composition, structure, and function will change as species respond to these changes in climate. Thus, as climate change interacts with other stressors to alter national forest ecosystems, it will be important to focus as much on maintaining and enhancing ecosystem processes as on achieving a particular composition. For these reasons, which are further discussed in sections 3.3-3.7, it will be increasingly important for the USFS to consider managing for change. In this context, a re-evaluation of current management actions related to forests and grasslands may be needed as well as the development of new management approaches to deal with the interactions of climate change with the current suite of stressors that affect national forests.

3.2.2 Stressors of Concern on National Forests

3.2.2.1 Current Major Stressors

National forests are currently subject to many stressors and in this section we focus on the major stressors that affect the ability of the USFS to achieve its goals (Table 3.1). Disturbances, both human-induced and natural, shape ecosystems by influencing their composition, structure, and function (Dale *et al.*, 2001). Over long timeframes, ecosystems adapt and can come to depend on natural disturbances such as fire, hurricanes, windstorms, insects, and disease. For example, sites where fire is frequent have plant species with seed cones that open only in response to heat from wildfire. Turnover in northeastern forests depends on creation of gaps from individual trees falling down or being blown down by wind (Seymour, White, and deMaynadier, 2002). When disturbances become functions of both natural and human conditions (*e.g.*, forest fire ignition and spread), the nature (*i.e.*, temporal and spatial characteristics) of the disturbance may change such as when wildfire occurs outside of the recorded fire season. For this report, we use the term stressor (any physical, chemical, or biological entity that can induce an adverse response (U.S. Environmental Protection Agency, 2000) to define these threats (Table 3.1).

Land Use and Land Cover Change Surrounding National Forests

Changes in the land use and land cover surrounding NFs have been and continue to be associated with the loss of open space (subdivision of ranches or large timber holdings) (Birch, 1996; Sampson and DeCoster, 2000; Hawbaker *et al.*, 2006), the conversion of forestland to urban and built-up uses in the wildland-urban interface (WUI), and habitat fragmentation (related to increases in road densities and impervious surfaces). The amount of U.S. land in urban and built-up uses increased 34% between 1982 and 1997, the result primarily of the conversion of croplands and forestland (Alig, Kline, and Lichtenstein, 2004). Subdivision of large timber holdings also results in a change in management as private forest landowners no longer practice forest management (Sampson and DeCoster, 2000). The Wildland-Urban Interface (WUI) is defined as “the area where structures and other human developments meet or intermingle with undeveloped wildland” (Stewart, Radeloff, and Hammer, 2006). Between 1990 and 2000, 60% of all new housing units built in the United States were located in the WUI (Fig. 3.5) and currently 39% of all housing units are located in the WUI (Radeloff *et al.*, 2005) Over 80 percent of the total land area in the United States is within about 1 km of a road (Riitters and Wickham, 2003). “Perforated” (*i.e.*, fragmented) forests with anthropogenic edges affect about 20% of the eastern U.S. (Riitters and Coulston, 2005). These changes surrounding NFs can change the effective size of wildlife habitat, change the ecological flows (*e.g.*, fire, water) into and out of the NFs, increase opportunities for invasive species, increase human impact at the boundaries within the borders of NFs (Hansen and DeFries, 2007), and constrain management options (*e.g.* fire use). In addition to these land use and land cover changes surrounding the large contiguous NFs, some NFs contain large areas of checkerboard ownership where sections of Forest Service lands and private ownership intermingle.

Figure 3.5. Wildland Urban Interface across the United States (Radeloff et al., 2005).

Non-Native Invasive Species

Non-native invasive species have markedly altered the structure and composition of forest, woodland and grassland ecosystems (Table 3.1). Non-native insects expanding their ranges nationally in 2004 include Asian longhorned beetle, hemlock woolly adelgid, the common European pine shoot beetle, and the emerald ash borer (USDA Forest Service Health Protection, 2005). Non-native diseases continuing to spread include beech bark disease, white pine blister rust, and sudden oak death. Within the Northeast, 350,000 acres of NFs are annually infested and affected by non-native species, including 165 non-native plant species of concern (USDA Forest Service, 2003). Those plant species of greatest concern are purple loosestrife, garlic mustard, Japanese barberry, kudzu, knapweed, buckthorns, olives, leafy spurge, and reed and stilt grass (USDA Forest Service, 2003). Non-native earthworms have invaded and altered soils in previously earthworm-free forests throughout the northeastern United States (Fig. 3.6) (Hendrix and Bohlen, 2002; Hale *et al.*, 2005; Frelich *et al.*, 2006).

Figure 3.6. Influence of non-native earthworms on eastern forest floor dynamics (Frelich *et al.*, 2006). Forest floor and plant community at base of trees before (a, left-hand photo) and after (b) European earthworm invasion in a sugar maple-dominated forest on the Chippewa National Forest, Minnesota, USA. Photo credit: Dave Hansen, University of Minnesota Agricultural Experimental Station.

Non-native invasive plant species have altered fire regimes in the western United States, including Hawaii (Westbrooks, 1998; Mitchell, 2000), and consequently other important ecosystem processes (D'Antonio and Vitousek, 1992; Brooks *et al.*, 2004). Cheat grass (*Bromus tectorum*), now a common understory species in millions of hectares of sagebrush-dominated vegetation assemblages in the Intermountain West (Mack, 1981), alters the fuel complex, increases fire frequency, and reduces habitat provided by older stands of sagebrush (Tausch, 1999; Williams and Baruch, 2000; Smith *et al.*, 2000; Ziska, Faulkner, and Lydon, 2004; Ziska, Reeves, and Blank, 2005). Similarly, buffelgrass (*Pennisetum ciliare*) and other African grasses are now common in much of the Sonoran Desert, providing elevated fuel levels that could threaten cactus species with increased fire frequency and severity (Williams and Baruch, 2000). Fountain grass *Pennisetum setaceum*), introduced to the island of Hawaii, greatly increases fire susceptibility in the dry forest ecosystems where fire was not historically frequent (D'Antonio, Tunison, and Loh, 2000). Cogongrass invasions have similarly altered fire regimes in pine savannas in the southeastern United States (Lippincott, 2000).

Air Pollution

Ozone, sulfur dioxide, nitrogen oxides (NO_x), and mercury transported into NFs from urban and industrial areas across the United States affect resources such as vegetation, lakes, and wildlife (Table 3.1). A combination of hot, stagnant summer air masses, expansive forest area, and high rates of NO_x emissions in the Northeast combine to produce some of the highest levels of ozone in the United States (Fiore *et al.*, 2002), a phenomenon also experienced in the western and southern parts of the country. Current levels of ozone exposure are estimated to reduce eastern and southern forest productivity by 5–10% (Joyce *et al.*, 2001; Felzer *et al.*, 2004). Elevated nitrogen deposition downwind of large, expanding metropolitan centers or large agricultural operations has been shown to impact forests when nitrogen deposited is in excess of biological demand (nitrogen saturation). Across the southern United States it is largely confined to high elevations of the Appalachian Mountains (Johnson and Lindberg, 1992), although recent increases in both hog and chicken production operations have caused localized nitrogen saturation in the Piedmont and Coastal Plain (McNulty *et al.*, In Press). In the western United States, increased nitrogen deposition has altered plant communities (particularly, alpine in the Rocky Mountains) and reduced lichen and soil mychorriza (particularly, in the Sierra Nevada mountains of Southern California);(Baron *et al.*, 2000; Fenn *et al.*, 2003). In Southern California, the interaction of ozone and nitrogen deposition has been shown to cause major physiological disruption in ponderosa pine trees (Fenn *et al.*, 2003). Mercury deposition negatively affects aquatic food webs as well as terrestrial wildlife as a result of bioaccumulation throughout the US (Chen *et al.*, 2005; Driscoll *et al.*, 2007; Peterson *et al.*, 2007). In the Ottawa National Forest (Michigan), for example, 16 lakes and four streams have been contaminated by mercury that was deposited from pollution originating outside of national forest borders (Ottawa National Forest, 2006a).

Altered Fire Regimes

Fire is a major driver of forest dynamics in the West, South and the Great Lakes region (Agee, 1998; Frelich, 2002), and the fire regimes (fire frequency, size, interval, season, intensity, and severity) vary widely across the United States (Noss *et al.*, 2006). Fire and insect disturbance clearly interact, often synergistically, compounding rates of change in forest ecosystems (Veblen *et al.*, 1994). Increased wildfire activity and altered fire regimes in some forests have been associated with historical fire suppression, resulting in increased density of trees and increased build-up of fuels (Sampson *et al.*, 2000; Minnich, 2001; Moritz, 2003; Brown, Hall, and Westerling, 2004). Lack of fire or altered fire frequency and intensity are considered sources of stress in those ecosystems dependent upon fire, such as forests dominated by ponderosa pine and lodgepole pine in the West and longleaf pine in the South.

In the western U.S., the frequency of large wildfires (> 400 ha) has increased, length of fire season (time between first reported wildfire and last wildfire control date) has increased by 78 days and average burn duration (time between discovery and control) has increased from 7.5 days over the last 34 years (Westerling *et al.*, 2006). In the Southwest, stand-replacing fires are becoming common in what were historically low-severity fire regimes (Allen *et al.*, 2002). Fire suppression has allowed these ecosystems to reach their water-limited carrying capacity and increased their susceptibility to drought, insect outbreaks, and more severe fires (Covington *et al.*, 1994; Sampson *et al.*, 2000; Lenihan *et al.*, In Press).

Unmanaged Recreation

National forests are increasingly being used by a variety of outdoor enthusiasts. Between 1964 and 1996 (*i.e.*, since passage of the Wilderness Act) recreational use of wilderness areas increased by a factor of six (Cole, 1996). Unmanaged recreation by millions of visitors cause a variety of ecosystem impacts (reviewed in Leung and Marion, 2000). Activities damaging the ecosystem that are associated with recreation include cutting trees for fire, starting fires in inappropriate places, damaging soil and vegetation from road and trail creation, target practice and lead contamination, and polluting waterways (National Forest Foundation, 2006). Impacts of these activities include vegetation and habitat loss from trampling, soil and surface litter erosion, soil compaction, air and water pollution, decreased water quality, introduction of non-native invasive species, and wildfires. The creation of unauthorized roads and trails by off-highway vehicle (OHVs) causes erosion, degrades water quality, and destroys habitat (Foltz, 2006). OHV conflicts and threats are highlighted in the South and West (Stokowski and LaPointe, 2000), but remain a concern in the Northeast as well.

Extreme Weather Events: Wind, Ice, Freeze-thaw events, Floods, and Drought

Severe wind is the principal cause of natural disturbance (Papaik and Canham, 2006) and is one of the three principal drivers (along with fire and herbivory) of forest dynamics in temperate forests of northeastern and north-central North America (for an example of a wind event, see Box 3.3) (Frelich, 2002). Winds from severe storms (*e.g.*, from tornadoes, hurricanes, derechos, and nor'easters) occurring at very infrequent intervals also replace stands at various spatial scales (0.2-3,785 ha; Seymour, White, and deMaynadier, 2002). Worrall, Lee, and Harrington (2005) found that windthrow, windsnap, and chronic wind stress expand gaps initiated by insects, parasites, and disease in New Hampshire sub-alpine spruce-fir forests. Thus, wind, insects, and disease interact to cause chronic stress to forests in this region, whereas extreme storms typically are stand-replacing events.

Ice storms are another important part of the natural disturbance regime (Irland, 2000; Lafon, 2006) that stress individual trees (Bruederle and Stearns, 1985), influence forest structure and composition (Rhoads *et al.*, 2002) and, when severe, can affect important ecosystem processes such as nitrogen cycling (Houlton *et al.*, 2003). The extent to which trees suffer from the stress and damage caused by ice appears to vary with species, slope, aspect, and whether severe winds accompany or follow the ice storm (Bruederle and Stearns, 1985; De Steven, Kline, and Matthiae, 1991; Rhoads *et al.*, 2002; Yorks and Adams, 2005). Growth form, canopy position, mechanical properties of the wood, and tree age and health influence the susceptibility of different species to ice damage (Bruederle and Stearns, 1985). Severe ice storms, such as the 1999 storm in New England, can shift the successional trajectory of the forest due to the interactions between the storm itself and effects of more chronic stressors such as beech bark disease (Rhoads *et al.*, 2002).

Climate variability has been demonstrated to affect ecosystem response and these extreme events may be associated with future climate change. Auclair, Lill, and Revenga, (1996) identified the relationships between thaw-freeze and root-freeze events in winter and early spring and severe episodes of dieback in northeastern and Canadian forests. These extreme events were key factors in triggering (and synchronizing) severe episodes of dieback in that once injured by freezing, heat and drought stress resulted in forest dieback. In northern hardwoods, freezing, as opposed to drought, was significantly correlated with increasing global mean annual temperatures and low values of the Pacific tropical Southern Oscillation Index (Auclair, Lill, and Revenga, 1996). Auclair, Eglinton, and Minnemeyer (1997) identified large areas in the Northeast and Canada where this climatic phenomenon affected several hardwood species.

Droughts (and even less-severe water stress) weaken otherwise healthy and resistant trees and leave them more susceptible to both native and non-native insect and disease outbreaks (for example, see Box 3.4). Protracted droughts have already contributed to large-scale dieback of species such as ponderosa pine that are adapted to low-severity fires (Allen and Breshears, 1998).

Extreme precipitation events that cause floods are another important stressor in NFs. Flooding facilitates biotic invasions both by creating sites for invasive species to become established and by dispersing these species to the sites.

3.2.2.2 Stress Complexes in Western Ecosystems

A warmer climate is expected to affect ecosystems in the western United States by alterin*g stress complexes* (Manion, 1991)—combinations of biotic and abiotic stresses that compromise the vigor and sustainability of ecosystems—leading to increased extent and severity of disturbances (McKenzie, Peterson, and Littell, In Press). Increased water deficit will accelerate the stress complexes experienced in forests, which typically involve some combination of multi-year drought, insects, and fire. Increases in fire disturbance superimposed on ecosystems with increased stress from drought and insects may have significant effects on growth, regeneration, long-term distribution and abundance of forest species, and carbon sequestration (Fig. 3.7).

Figure 3.7. Conceptual model of the relative time scales for disturbance vs. climatic change alone to alter ecosystems. Times are approximate. From McKenzie *et al.* (2004).

Forests of western North America can be partitioned into energy-limited vs. water-limited domains (Milne, Gupta, and Restrepo, 2002; Littell and Peterson, 2005). Energy-related limiting factors are chiefly light (*e.g.*, productive forests where competition reduces light to most individuals) and temperature (*e.g.*, high-latitude or high-elevation forests). Energy-limited ecosystems in general appear to be responding positively to warming temperatures over the past 100 years (McKenzie, Hessl, and Peterson, 2001). In contrast, productivity in water-limited systems may decrease with warming temperatures, as negative water balances constrain photosynthesis (Hicke *et al.*, 2002), although this may be partially offset if CO_2 fertilization significantly increases water-use efficiency in plants (Neilson *et al.*, 2005b). Littell (2006) found that most montane Douglas fir (*Pseudotsuga menziesii*) forests across the northwestern United States appear to be water limited; under current climate projections these limits would increase in both area affected and magnitude.

Temperature increases are a predisposing factor causing often lethal stresses on forest ecosystems of western North America, acting both directly through increasingly negative water balances (Stephenson, 1998; Milne, Gupta, and Restrepo, 2002; Littell, 2006) and indirectly through increased frequency, severity, and extent of disturbances—chiefly fire and insect outbreaks (Logan and Powell, 2001; McKenzie *et al.*, 2004; Logan and Powell, 2005; Skinner, Shabbar, and Flanningan, 2006). Four examples of forest ecosystems whose species composition and stability are currently compromised by stress complexes precipitated by a warming climate are described below. Two cases involve the loss of a single dominant species, and the other two involve two or more dominant species.

Pinyon-Juniper Woodlands of the American Southwest

Pinyon pine (*Pinus edulis*) and various juniper species (*Juniperus* spp.) are among the most drought-tolerant trees in western North America, and pinyon-juniper ecosystems characterize lower treelines across much of the West. Pinyon-juniper woodlands are clearly water-limited systems, and pinyon-juniper ecotones are sensitive to feedbacks from environmental fluctuations and existing canopy structure that may buffer trees against drought (Milne *et al.*, 1996) (Box 3.4). However, severe multi-year droughts periodically cause dieback of pinyon pines, overwhelming any local buffering. Interdecadal climate variability strongly affects interior dry ecosystems, causing considerable growth during wet periods. This growth increases the evaporative demand, setting the ecosystem up for dieback during the ensuing dry period (Swetnam and Betancourt, 1998). The current dieback is historically unprecedented in its combination of low precipitation and high temperatures (Breshears *et al.*, 2005). Fig. 3.8 shows the stress complex associated with pinyon-juniper ecosystems. Increased drought stress via warmer climate is the predisposing factor, and pinyon pine mortality and fuel accumulations are inciting factors. Ecosystem change, possibly irreversible, comes from large-scale severe fires that lead to colonization of invasive species (D'Antonio, 2000) that further compromises the ability of pinyon pines to re-establish.

Figure 3.8. Stress complex in pinyon-juniper woodlands of the American Southwest. Adapted from McKenzie *et al.* (2004).

Mixed Conifer Forest of the Sierra Nevada and Southern California

These forests experience a Mediterranean climate with long, dry summers. Fire frequency and extent have not increased concomitantly with warmer temperatures, but instead have decreased to their lowest levels in the last 2,000 years. Stine (1996) attributed this decline to decreased fuel loads from sheep grazing, decreased ignition from the demise of Native American cultures, and fire exclusion. Continued fire exclusion has led to increased fuel loadings, and competitive stresses on individual trees as stand densities have increased (Van Mantgem *et al.*, 2004). Elevated levels of ambient ozone from combustion of fossil fuels affect plant vigor in the Sierra Nevada and the mountains of southern California (Peterson, Arbaugh, and Robinson, 1991; Miller, 1992). Sierra Nevada forests support endemic levels of a diverse group of insect defoliators and bark beetles, but bark beetles in particular have reached outbreak levels in recent years facilitated by protracted droughts and biotic complexes that include bark beetles interacting with root diseases and mistletoes (Box 3.5) (Ferrell, 1996). Dense stands, fire suppression, and exotic pathogens such as white pine blister rust (*Cronartium ribicola*) can exacerbate biotic interactions (Van Mantgem *et al.*, 2004) and drought stress. Fig. 3.9 shows the stress complex associated with Sierra Nevada forest ecosystems, and is likely applicable to the mountain ranges east and north of the Los Angeles basin.

Figure 3.9. Stress complex in Sierra Nevada and southern Californian mixed-conifer forests. From McKenzie, Peterson, and Littell (In Press).

Interior Lodgepole Pine Forests

Lodgepole pine (*Pinus contorta* var. *latifolia*) is widely distributed across western North America, often forming nearly monospecific stands in some locations. It is the principal host of the mountain pine beetle (*Dendroctonus ponderosae*), and monospecific stands are particularly vulnerable to high mortality during beetle outbreaks. Recent beetle outbreaks have caused extensive mortality across millions of hectares (Logan and Powell, 2001; Logan and Powell, 2005), with large areas of mature cohorts of trees (age 70–80 yr) contributing to widespread vulnerability (Carroll, 2006). Warmer temperatures facilitate bark beetle outbreaks in two ways: 1) drought stress makes trees more vulnerable to attack, and 2) insect populations respond to increased temperatures by speeding up their reproductive cycles (*e.g.*, to one-year life cycles). Warming temperatures would be expected to exacerbate these outbreaks and facilitate their spread northward and eastward across the continental divide (Logan and Powell, 2005; but see Moore *et al.*, 2006). Fig. 3.10 shows the stress complex for interior lodgepole pine forests. Warmer temperatures, in combination with the greater flammability of dead biomass associated with beetle mortality, set up some ecosystems for increasing dominance by lower elevation fire-tolerant species such as ponderosa pine and Douglas-fir and higher elevation forests for increasing dominance of lodgepole pine following stand-replacing fires.

Figure 3.10. Stress complex in interior (BC and USA) lodgepole pine forests. From McKenzie, Peterson, and Littell (In Press).

Alaskan Spruce Forests

The state of Alaska has experienced historically unprecedented fires in the last decade, including the five largest fires in the United States. More than 2.5 million hectares burned in the interior in 2004. During the 1990s, massive outbreaks of the spruce bark beetle (*Dendroctonus rufipennis*) occurred on and near the Kenai Peninsula in southern Alaska (Berg *et al.*, 2006). Although periodic outbreaks have occurred throughout the historical record, these most recent ones may be unprecedented in extent and percentage mortality (over 90% in many places; Ross *et al.*, 2001; Berg *et al.*, 2006). Both these phenomena are associated with warmer temperatures in recent decades (Duffy *et al.*, 2005; Berg *et al.*, 2006; Werner *et al.*, 2006). Although fire-season length in interior Alaska is associated with the timing of onset of the late-summer monsoon, the principal driver of annual area burned is early summer temperature (Duffy *et al.*, 2005). In the interior of Alaska, white spruce (*Picea glauca*) and black spruce (*P. mariana*) are more flammable than their sympatric deciduous species (chiefly paper birch, *Betula papyrifera*). Similarly, conifers are the target of bark beetles, so in southern Alaska they will be disadvantaged compared with deciduous species. Fig. 3.11 shows the stress complex for Alaska forest ecosystems, suggesting a significant transition to deciduous life forms via more frequent and extensive disturbance associated with climate variability and change. This transition would be unlikely without changes in disturbance regimes even under climate change, because both empirical and modeling studies suggest that warmer temperatures alone will not favor a life-form transition (Johnstone *et al.*, 2004; Bachelet *et al.*, 2005; Boucher and Mead, 2006).

Figure 3.11. Stress complex in the interior and coastal forests of Alaska. From McKenzie, Peterson, and Littell (McKenzie, Peterson, and Littell, In Press).

3.2.3 Management Approaches and Methods Currently in Use to Manage Stressors

3.2.3.1 Management Approaches

Laws, regulations, and policies direct Forest Service management. Policies are the Forest Services rules defining management, and are documented in agency manuals and handbooks. Focus here is on the National Forest System (NFS), which has several levels of organization (Fig. 3.2). While timber harvest, permitted domestic livestock grazing and mining remain uses on NFs, changing demographics and resources values of new residents moving into the WUI have resulted in a re-evaluation of management goals in NFs. For many NFs, recreation is now the primary use. Management practices have also been reconsidered. Clearcuts have declined in size and as a percentage of the total area harvested on NFs, with natural regeneration techniques increasingly being favored.

Management approaches across the NFS are influenced by the local climate, physical environment (soils), plant species, ecosystem dynamics, and the landscape context (*e.g.*, WUI, proximity to large metropolitan areas for recreational use). Climate change would facilitate the movement of some native species into the habitats of others, which would create novel species assemblages, potentially affecting current goods and services. Some of the dispersing native species will likely become problematic invaders that place many threatened and endangered species at greater risk of local extinction due to enhanced competition, herbivory, predation, and parasitism (Neilson *et al.*, 2005a; 2005b). For example, in the Pacific Northwest, barred owls, which are rapidly migrating generalists from eastern forests of the United States, have invaded the spotted owl's range in the Pacific Northwest and are now competing with spotted owls for nest sites (Kelly, Forsman, and Anthony, 2003; Noon and Blakesley, 2006; Gutierrez *et al.*, 2007). An increase of 3°C in minimum temperature could extend the southern pine beetle's northern distribution limit by 170 km, with insect outbreaks spreading into the mid-Atlantic states (Williams and Liebhold, 2002). Novel species assemblages may require a re-examination of what constitutes an invasive species, appropriate management approaches for threatened, endangered and rare species, and where NFs can manage for what services, goods, and ecosystem services.

Lessening the damages caused by native insects and pathogens is the goal of the Forest Service Forest Health Protection (FHP) Program. This program includes efforts to control the native species of southern pine beetle, and western bark beetles. FHP funds southern pine beetle suppression, prevention, and restoration projects on state and private lands and NFs in the South. FHP's forest health monitoring program determines the status, changes, and trends in indicators of forest condition on an annual basis. The program uses data from ground plots and surveys, aerial surveys, and other biotic and abiotic data sources, and develops analytical approaches to address forest health issues that affect the sustainability of forest ecosystems.

Of the estimated 99.2 million acres of oil and gas resources on federal lands (USDA, USDI, and DOE, 2006), 24 million are under Forest Service management. The Bureau of Land Management has the major role in issuing oil and gas leases and permits in NFs; however, the Forest Service determines the availability of land and the conditions of use, and regulates all surface-disturbing activities conducted under the lease (GAO, 2004). Principal causes of stress are transportation systems to access oil and gas wells, the oil and gas platforms themselves, pipelines, contamination resulting from spills or the extraction of oil and gas, and flue gas combustion and other activities in gas well and oil well productions. The extent to which these stressors impact forests depends on the history of land use and ownership rights to subsurface materials in the particular national forest. For example, oil and gas development is an important concern in the Allegheny National Forest because 93% of the subsurface mineral rights are privately held and because exploration and extraction have increased recently due to renewed interest in domestic oil supplies and higher crude oil prices (Allegheny National Forest, 2006).

When extreme climate- or weather-related events occur, such as large wind blowdown events, management plans to address the stressor are developed in response to the situation (such as after the blowdown event on the Superior National Forest, USDA Forest Service, 2006b).

3.2.3.2 Invasive Species

A species is considered invasive if 1) it is non-native to the ecosystem under consideration, and 2) its introduction causes or is likely to cause economic or environmental harm, or harm to human health (Clinton, 1999). The goal of the Forest Service National Strategy and Implementation Plan for Invasive Species Management (USDA Forest Service, 2004a) is to reduce, minimize, or eliminate the potential for introduction, establishment, spread, and impact of invasive species across all landscapes and ownerships. The Plan encompasses four program elements: 1) prevention, 2) early detection and rapid response (EDRR), 3) control and management, and 4) rehabilitation and restoration. Activities in the EDRR program include the annual cooperative survey of federal, tribal, and private forestland for damage caused by forest insects and pathogens and the establishment of the EDRR system for invasive insects in 10 ports and surrounding urban forests. Control and Management activities include treating invasive plants each year on federal, state and private forested lands and collaborating with biological control specialists to produce a guide to biological control of invasive plants in the eastern United States. Rehabilitation and Restoration activities highlight the importance of partnerships in such work as developing resistant planting stock for five-needle pines restoration efforts following white pine blister rust mortality, and coordinating at the national and regional levels to address the need for and supply of native plant materials (for example, seed and seedlings) for restoration.

3.2.3.3 Altered Fire Regimes

The federal National Fire Plan has four goals: 1) improve fire prevention and suppression, 2) reduce hazardous fuels, 3) restoration and post-fire recovery of fire-adapted ecosystems, and 4) promote community assistance. The updated implementation plan (2006) emphasizes a landscape-level vision for restoration of fire adapted ecosystems, the importance of fire as a management tool, and the need to continue to improve collaboration among governments and stakeholders at the local, state, regional, and national levels.

Land managers reduce hazardous fuels through the use of prescribed fire, mechanical thinning, herbicides, grazing, or combinations of these and other methods. Treatments are increasingly being focused on the expanding wildland/urban interface areas. The Forest Service Woody Biomass Strategy is being developed to guide the appropriate removal and use of woody biomass. This strategy has the potential to contribute to a number of the Forest Service's strategic goals, including the restoration and maintenance of ecosystem health, while providing a market-based means to reduce costs.

3.2.3.4 Unmanaged Recreation

The phenomenal increase in the use of the NFs for all recreational activities raises the need to manage most forms of recreation, including the use of off-highway vehicles. The Forest Service's new travel management rule provides the framework for each national forest and grassland to designate a sustainable system of roads, trails and areas open to motor vehicle use (36 CFR Parts 212, 251, 261, and 295 Travel Management; Designated Routes and Areas for Motor Vehicle Use; Final Rule, November 9, 2005). The rule aims to secure a wide range of recreational opportunities while ensuring the best possible care of the land. Designation includes class of vehicle and, if appropriate, time of year for motor vehicle use. Designation decisions are made locally, with public input and in coordination with state, local, and tribal governments.

3.2.3.5 Air Pollution

The Federal Land Manager (broadly, the federal agency charged with protecting wilderness air quality; *e.g.*, the Forest Service or the National Park Service) has a responsibility to protect the Air Quality Related Values (AQRV) of Class I wilderness areas identified in and mandated by the Clean Air Act. Air resources managers develop monitoring plans for AQRV, such as pH and acid neutralizing capacity in high-elevation lakes. The Federal Land Manager must advise the air quality permitting agency if a new source of pollution, such as from an energy or industrial development, will cause an adverse impact to any AQRV.

3.2.4 Sensitivity of management goals to climate change

All Forest Service national goals (Box 3.1) and one additional goal related to conservation of biodiversity are sensitive to climate change. In general, the direction and magnitude of the effect of climate change on each management goal depends on the temporal and spatial nature of the climate change features, their impact on the ecosystem, and the current status and degree of human alteration of the ecosystem (*i.e.*, whether the ecosystem has lost key components such as late-seral forests; free-flowing streams; or keystone species such as beaver, large predators, and native pollinators). The sensitivity of the management goals to climate change also will depend on how climate change interacts with the major stressors in each eco-region and national forest. And finally, the sensitivity of the management goals to climate change will depend on the assumptions about climate that the management activities currently make. These assumptions range from the relationship between natural regeneration and climate to seasonal distributions of rainfall and stream flow and management tied to these distributions. The case studies in sections 3.4, 3.5, and 3.6 provide detailed descriptions of the implications of climate change to individual national forests.

3.2.4.1 Goal 1: Reduce the Risk from Catastrophic Wildland Fire

Fire regimes are tightly linked to key climate variables (*i.e.*, temperature, precipitation, and wind) (Agee, 1996; Pyne, Andrews, and Laven, 1996; McKenzie *et al.*, 2004). As a result, changes in weather and climate are quickly reflected in altered fire frequency and severity (Flannigan, Stocks, and Wotton, 2000; Dale *et al.*, 2001). The goal of reducing wildland fire risk to communities and natural resources may become more challenging in the future because future climate scenarios suggest a continued increase in fire danger across the United States (Flannigan, Stocks, and Wotton, 2000; Bachelet *et al.*, 2001; Brown, Hall, and Westerling, 2004).

Climate change and wildfire management

Changes in climate over the past 30–40 years and interdecadal climate variability have contributed to increased wildfire activity in the western U.S. (Westerling *et al.*, 2006; Running, 2006). Climate change is likely to increasingly affect future wildfire risk and activity across the United States (McKenzie *et al.*, 2004; Running, 2006) by increasing fire season length, the potential size of fires, and the areas vulnerable to fire, as well as by altering vegetation, which, in turn, will influence fuel loadings and consequently fire behavior. Future climate change may offer opportunities to conduct prescribed fire outside of traditional burn seasons with increased accessibility in some areas in the winter (see Tahoe case study). A continual reassessment of climate and land management assumptions may be necessary for effective wildfire management under future climate change.

Over the last 34 years, the greatest absolute increase in wildfires occurred in the Northern Rockies (Westerling *et al.*, 2006), forests where land use influences do not appear to have altered fire regimes (Schoennagel, Veblen, and Romme, 2004; Keeley, Pfaff, and Safford, 2005). Future climate projections for western North America project June to August temperature increases of 2–5°C by 2040 to 2069, and precipitation decreases of up to 15% (Running, 2006). The potential for increased fire activity in these high-elevation forests could be exacerbated by the increased fuel loads expected to result from enhanced winter survival of mountain pine beetles and similar pest species (Guarin and Taylor, 2005; Millar, Westfall, and Delany, In Press).

Increases in the area burned or biomass burned under future climate scenarios are seen in a number of studies across the United States. Using historical data, warmer summer temperatures were shown to be significant in western state-level statistical models of area burned (McKenzie *et al.*, 2004). Using the IPCC B2 climate scenario and the Parallel Climate Model, wildfire activity was projected to increase from 1.5 to 4 times historical for all western states (except California and Nevada) by the 2070-2100 period. The highest increases were for Utah and New Mexico. The analysis of 19 climate models and their scenarios used in the Fourth IPCC Assessment Report (Seager *et al.*, 2007) show a consistency in the projections for increased drought in the Southwest, unlike any seen in the instrumental record.

In Alaska, warmer and longer growing seasons and associated vegetation shifts under two future climate scenarios indicated an increase in the area of forests burned by a factor of two or three (Bachelet *et al.*, 2005). Increased wildfire activity influences vegetation shifts also. The consumption of formerly frozen peatland by fire, where removal of trees results in drying, and large fires may shift dominant trees from spruce to hardwoods, can only be inferred to increase at this time, given the state of model development (Bachelet *et al.*, 2005).

The combination of extended dry periods resulting from fewer, stronger rainfall events with warmer temperatures could render northeastern forests more susceptible to fire than they have been for the past 100 years of fire suppression (Scholze *et al.*, 2006). Similarly, drought may become an increasingly important stressor in eastern forests, which in turn may increase the risk of fire in areas that have experienced low frequency fire regimes during the past century or more (Lafon, Hoss, and Grissino-Mayer, 2005). Because climate gradients and terrain are quite shallow in northeastern forests, droughts and fire are expected to affect very large geographic areas, and possibly convert extant forests to savannas, woodlands, or grasslands with high fire return intervals (Lenihan *et al.*, In Press).

Some climate scenarios project less and others more precipitation for the southern U.S (Bachelet *et al.*, 2001). Even under the wetter scenarios, however, the South is projected to experience an increase in temperature-induced drought and an increase in fires (Lenihan *et al.*, In Press). On average, biomass consumed by fire is expected to increase by a factor of two or three (Bachelet *et al.*, 2001; Bachelet *et al.*, In Press).

Interactions of Climate Change with Other Stressors

Both the direct impacts of climate change on ecosystems and the effects of interactions of climate change with other major stressors may render NFs increasingly prone to more frequent, extensive, and severe disturbances, especially drought (Breshears *et al.*, 2005; Seager *et al.*, 2007) and wildfire (Logan and Powell, 2001; Brown, Hall, and Westerling, 2004; McKenzie *et al.*, 2004; Logan and Powell, 2005; Skinner, Shabbar, and Flanningan, 2006) (see also section 3.2.2). The elevated water stress resulting from warmer temperatures in combination with greater variability in precipitation patterns and altered hydrology (*e.g.*, from less snowpack and earlier snowmelt, Mote *et al.*, 2005) would increase the frequency and severity of both droughts and floods (IPCC, 2001a). Vegetation in NFs with sandy or shallow soils is more susceptible to drought stress than vegetation growing in deeper or heavier soils (Hanson and Weltzin, 2000), hence achieving this management goal may become particularly challenging where soil type and drought interact to substantially increase catastrophic fire risk.

Insect and disease outbreaks also may become more frequent because warmer temperatures may accelerate their life cycles (*e.g.*, Logan and Powell, 2001). As hardiness zones shift north (National Arbor Day Foundation, 2006) and frost-free days and other climatic extremes increase (Tebaldi et al., 2006), the hard freezes that in the past slowed the spread of insect and disease outbreaks may become less effective especially if the natural enemies (*e.g.*, parasitoids) of insects are less tolerant of the climate changes than their hosts or prey (Hance et al., 2007). In addition, previously confined southern insects and pathogens may move northward as temperatures warm (see Box 3.5) (Ungerer, Ayres, and Lombardero, 1999; Volney and Fleming, 2000; Logan, Regniere, and Powell, 2003; Parmesan, 2006) especially in the absence of predatory controls. While the expectation is for increased wildfire activity associated with increased fuel loads (*e.g.*, Fleming, Candau, and McAlpine, 2002), in some ecosystems (*e.g.*, subalpine forests in Colorado), insect outbreaks may decrease susceptibility to severe fires (*e.g.*, Kulakowski, Veblen, and Bebi, 2003).

Invasive plants can alter fire regimes, increasing both the frequency and severity of fires (Tausch, 1999; Williams and Baruch, 2000; Lippincott, 2000; Pimentel *et al.*, 2000; Ziska, Reeves, and Blank, 2005). Positive responses to elevated carbon dioxide have been reported for several invasive plants (Ziska, 2003), including red brome, a introduced non-native annual grass in the Southwest (Smith *et al.*, 2000). Red brome, like cheatgrass, produces lots of fine fuel. Increasing presence of this exotic grass and the potential for increased wildfire would result in vegetation shifts within Southwest ecosystems and increased fire frequency (Smith et al., 2000) where the vegetation has not evolved under frequent fire.

3.2.4.2 Goal 2: Reduce Impacts from Invasive Species

Invasive species are currently contributing to a homogenization of the earth's biota (McKinney and Lockwood, 1999; Mooney and Hobbs, 2000; Rahel, 2000; Olden, 2006), increasing extinction risks for native species (Wilcove and Chen, 1998; Mooney and Cleland, 2001; Novacek and Cleland, 2001; Sax and Gaines, 2003), and harming the economy and human health (Pimentel et al., 2000). Species that can shift ranges quickly and tolerate a wide range of environments, traits common to many invasive species, will benefit under a rapidly changing climate (Dukes and Mooney, 1999). Thus, this strategic goal is sensitive to climate change.

Climate Change and Invasive Species Management

Prevention, early detection and rapid response, control and management, and rehabilitation and restoration are the program elements of the Forest Service invasive species strategy. Climate change is expected to compound the invasive species problem because of its direct influence on native species distributions and because of the effects of its interactions with other stressors (Chornesky *et al.*, 2005). A reassessment of current management practices may be necessary as these rapidly adapting species expand across the landscape under a changing climate.

In general, the impacts of invasive species with an expanded range are difficult to predict in part because the interactions among changing climate, elevated CO_2 concentrations, and altered nutrient dynamics are themselves still being elucidated (Simberloff, 2000), but in some cases the likely impacts are better understood. For example, future warming may accelerate the northern expansion of European earthworms, which have already substantially altered the structure, composition, and competitive relationships in North American temperate and boreal forests (Frelich *et al.*, 2006). In arid and semi-arid regions of the United States, increases in annual precipitation are expected to favor non-native invasive species at the expense of native vegetation on California serpentine soils (Hobbs and Mooney, 1991) and in Colorado steppe communities (Milchunas and Lauenroth, 1995). Understanding the potential to prevent and control invasives will require research on invasive species' population and community dynamics interacting with a changing ecosystem dynamic.

Increasing concentrations of carbon dioxide (CO_2) in the atmosphere may also be a competitive advantage to some invasive species (Dukes, 2000; Smith *et al.*, 2000; Ziska, 2003; Weltzin, Belote, and Sanders, 2003) and these positive responses may require a re-evaluation of current management practices. The positive response to current (from pre-industrial) levels of atmospheric CO_2 by six invasive weeds—Canada thistle (*Cirsium arvense* (L.) Scop.), field bindweed (*Convolvulus arvensis* L.), leafy spurge (*Euphorbia esula* L.), perennial sowthistle (*Sonchus* L.), spotted knapweed (*Centaurea stoebe* L.), and yellow star-thistle (*Centaurea solstitialis* L.)—suggests that 20th century increases in atmospheric CO_2 may have been a factor in the expansion of these invasives (Ziska, 2003). Because increasing CO_2 concentrations allow invasive species to allocate additional carbon to root biomass, efforts to control invasive species with some currently used herbicides may be less effective under climate change (Ziska, Faulkner, and Lydon, 2004).

In the northern and eastern regions of the U.S., invasive species are already a problem (Stein *et al.*, 1996; Pimentel *et al.*, 2000; Rahel, 2000; Von Holle and Simberloff, 2005), and the combination of elevated CO_2 concentrations and warmer temperatures is expected to exacerbate the problem (Sasek and Strain, 1990; Simberloff, 2000; Weltzin, Belote, and Sanders, 2003). The northward expansion of the range of invasive species currently restricted by minimum temperatures (*e.g.*, kudzu and Japanese honeysuckle) is a particular concern (Sasek and Strain, 1990; Simberloff, 2000; Weltzin, Belote, and Sanders, 2003). Invasive species with a C4 photosynthetic pathway (*e.g.*, itchgrass, *Rottboellia cochinchinensis*) are particularly likely to invade more northerly regions as frost hardiness zones shift northward (Dukes and Mooney, 1999). Although C3 species (*e.g.*, lamb's quarters, *Chenopodium album*) are likely to grow faster under elevated CO_2 concentrations (Bazzaz, 1990; Drake, Gonzalez-Meler, and Long, 1997; Nowak, Ellsworth, and Smith, 2004; Ainsworth and Long, 2005; Erickson *et al.*, 2007), C4 species seem to respond better to warmer temperatures (Alberto *et al.*, 1996; Weltzin, Belote, and Sanders, 2003), probably because the optimum temperature for photosynthesis is higher in C4 species (Dukes and Mooney, 1999).

Species, whether or not they are indigenous to the United States, may act invasively and increase the stress on ecosystems and on other native species. The rapid advance of the mountain pine beetle beyond its historic range (Logan and Powell, 2005) is a case in which a native species, indigenous to the American West, has begun to spread across large areas like an invasive species (as reflected by faster dispersal rates and greater range extension) because longer and warmer growing seasons allow it to more rapidly complete its lifecycle and because warmer winters allow winter survival (Logan and Powell, 2001; Carroll et al., 2003; Millar, Westfall, and Delany, In Press) Examples such as this one suggest that the Forest Service's invasive species strategy, which principally focuses on introduced species, may need to be broadened to include examining the potential effects of expanding native species as a result of climate change.

Interactions of Climate Change with Other Stressors

As noted above, climate change may increase the severity, extent, and frequency of disturbances, all of which create opportunities for invasive species to become established. Disturbances that cause severe ecological damage across large areas (from multiple stands to landscapes), such as fires, hurricanes, tornadoes, ice storms, and floods, open large areas to invasive species, many of which thrive under such conditions. Some disturbances, like flooding, may facilitate biotic invasions both by creating sites for invasive species to become established and by dispersing these species to the sites. Increases in flooding may occur as a result of the increased storm intensity projected by future climate models (IPCC, 2007). Similarly, fragmentation and urbanization facilitate the spread of invasive species and are key drivers contributing to biotic homogenization in the United States in general (Olden, 2006).

3.2.4.3 Goal 3: Provide Outdoor Recreational Opportunities

National forests across the United States are managed for a variety of outdoor recreational opportunities, capitalizing on the natural resources and ecosystem services available within each national forest (Cordell *et al.*, 1999). Because individual recreational opportunities are often a function of climate (cold water fisheries or winter snow), climate change may affect both the opportunity to recreate and the quality of recreation (Irland *et al.*, 2001), curtailing some recreational opportunities and expanding others.

Climate Change and Recreation Management

The demands on NFs for recreation have increased as population growth (local, regional, and national), preferences for different types of recreation, and technological influences on recreation (off-road motorized vehicles, mountain biking, snowboarding) have increased. To the historical activities of camping, hunting and fishing, recreational activities now include skiing (downhill, cross-country), snowboarding, mountain biking, hiking, kayaking, rafting, and birdwatching. Access to more remote areas of the forest has been increased with motorized off-road vehicles.

Climate change may diminish recreational opportunities and the feasibility of sustaining these opportunities may be challenging. Winter outdoor recreation—such as alpine and Nordic skiing, snowmobiling, skating, ice fishing, and other opportunities—may decrease and/or shift in location due to fewer cold days and reduced snowpack (National Assessment Synthesis Team, US Global Change Research Program, 2001). The costs of providing these opportunities (*e.g.*, increased snowmaking) are likely to rise (Irland *et al.*, 2001) or may result in potential conflicts with other uses (*e.g.*, water) (Aspen Global Change Institute, 2006). Other winter recreational activities (*e.g.*, ice skating, ice fishing, and ice climbing) may also become more restricted (both geographically and seasonally) as winter temperatures warm (National Assessment Synthesis Team, US Global Change Research Program, 2001), with limited opportunities for management to sustain these opportunities.

Altered streamflow patterns and warmer stream temperatures, observed trends that are projected to continue with future climate change (Regier and Meisner, 1990; Eaton and Scheller, 1996; Rahel, Keleher, and Anderson, 1996; Stewart, Cayan, and Dettinger, 2004; Barnett, Adam, and Lettenmaier, 2005; Milly, Dunne, and Vecchia, 2005), may change fishing opportunities from salmonids and other cold-water species to species that are less sensitive to warm temperatures (Keleher and Rahel, 1996; Melack *et al.*, 1997; Ebersole, Liss, and Frissell, 2001; O'Neal, 2002; Mohseni, Stefan, and Eaton, 2003) and altered streamflow (Marchetti and Moyle, 2001). One estimate indicates that cold water fish habitat may decrease by 30% nationally and by 50% in the Rocky Mountains by 2100 (Preston, 2006). More precise estimates of the climate change impacts on fish populations will depend on the ability of modelers to consider other factors (*e.g.*, land use change, fire, invasive species, and disease) in addition to temperature and streamflow regimes (Clark *et al.*, 2001). The projected reductions in volume of free-flowing streams during summer months due to advances in the timing of flow in these streams (Stewart, Cayan, and Dettinger, 2004; Barnett, Adam, and Lettenmaier, 2005; Milly, Dunne, and Vecchia, 2005) may also restrict canoeing, rafting, and kayaking opportunities (Irland *et al.*, 2001).

Climate change may also increase recreational opportunities depending on the preferences of users, the specific climatic changes that occur, and the differential responses of individual species to those changes. Fewer cold days, for example, may encourage more hiking, biking, off-road vehicle use, photography, swimming, and other warm-weather activities. The different growth responses of closely related fish species to increases in temperature and streamflow (Guyette and Rabeni, 1995) may enhance opportunities for species favored by some anglers.

Interactions of Climate Change with Other Stressors

An increase in the frequency, extent, and severity of disturbances such as fire and severe storms also may affect the quality of recreation experienced by visitors to NFs during the disturbance and after the disturbance. Recreational opportunities may be curtailed if forest managers decide (for public safety or resource conservation reasons) to reduce access during and in the wake of major disturbances such as fire, droughts, insect outbreaks, blowdowns, and floods, all of which are projected to increase in frequency and severity during the coming decades (IPCC, 2007). Unlike smoke from prescribed fires, which is subject to NAAQS (national ambient air quality standards) (Story *et al.*, 2005), wildfire smoke is considered a temporary "natural" source by EPA and the departments of environmental quality (DEQs) in Montana, Idaho, and Wyoming, and is therefore not directly regulated. Within the Greater Yellowstone Ecosystem, prescribed fire smoke is managed to minimize smoke encroachment on sensitive areas (communities, Class 1 areas, high use recreation areas, scenic vistas) during sensitive periods (Story *et al.*, 2005). After wildfire, the quality of the recreational experience has been shown to be affected by the need to travel through a historical fire area (Englin *et al.*, 1996) and by the past severity of fire (Vaux, Gardner, and Thomas, 1984). Groups experiencing different types of recreation (hiking versus mountain biking) react differently to wildfire, and reactions vary across geographic areas (Hesseln *et al.*, 2003). Changes in vegetation and other ecosystem components (*e.g.*, freshwater availability and quality) caused by droughts, insect and disease outbreaks (Rouault *et al.*, 2006), fires, and storms may alter the aesthetics, sense of place, and other cultural services that the public values.

The projected increases of pests and vector-borne diseases may also affect the quality of recreational experiences in NFs. Hard freezes in winter have been shown to kill more than 99% of pathogen populations annually (Burdon and Elmqvist, 1996; as cited in Harvell *et al.*, 2002). The hard freezes necessary to slow the spread of insect and disease outbreaks may become less effective (Gutierrez *et al.*, 2007). In particular, warmer temperatures are expected to increase the development, survival, rates of disease transmission, and susceptibility of both human and non-human hosts (Harvell *et al.*, 2002; Stenseth *et al.*, 2006). Land-use change leading to conversion of forests adjacent to NFs may compound the effect of climate change on disease, because increases in disease vectors have been associated with loss of forests (Sutherst, 2004). Conversely, where climate change contributes to a decline in the impacts of pathogens—or in cases where species have demonstrated an ability to adapt to changes in disease prevalence (*e.g.*, Woodworth *et al.*, 2005)—the goal may become easier to achieve because visitors may have a positive experience.

3.2.4.4 Goal 4: Help Meet Energy Resource Needs

To accomplish the goal of helping to meet the energy resource needs (USDA Forest Service, 2004c), the Forest Service planned to: 1) Improve energy conservation. 2) Develop the potential of short-rotation woody crops as a renewable source of biomass energy; stimulate the local industrial infrastructure development required for harvesting, processing, and marketing biomass for energy; and develop marketing options to improve domestic wood use, especially the use of small-diameter, low value trees and residues. 3) Eliminate unnecessary, redundant, or conflicting requirements for processing energy and energy-related proposals. 4) Provide technical and financial assistance to rural communities, tribes, organizations, and enterprises to increase their use of biomass for energy and other products and markets to improve forest and grassland health. We focus here on objectives that will be met from National Forest lands. The potential impact of climate change on oil/gas and mining activities were discussed above (Section 3.2.3.1). At this time, the challenges associated with the harvest of small-diameter low value trees and residues are related to transportation costs and distance to markets (Rummer *et al.*, 2003). Climate change may alter the probability of such harvest through increased wildfire activity. Recent discussion has also focused on mitigation activities (*e.g.*, carbon sequestration) that may possibly occur on National Forest lands. Climate change is expected to alter forest productivity (Joyce and Nungesser, 2000; Aber *et al.*, 2001; Hanson *et al.*, 2005; Norby, Joyce, and Wullschleger, 2005; Scholze *et al.*, 2006), which in turn will influence biomass available for wood products or for energy (Richards, Sampson, and Brown, 2006), whether as a direct energy source or for conversion to a biofuel. The interactions of climate change (*e.g.*, warming temperatures, droughts) and other stressors—including altered fire regimes, insects, invasive species, and severe storms—may affect the productivity of forests, which in turn would affect volume of material that could be harvested for wood products or for energy or the rate at which a forest would sequester carbon on site.

Climate Change and Energy Resource Needs

Co-benefits of joint carbon sequestration and biofuel production, along with other potential synergies, are certainly possible via forest management, and would enable contribution to both the country's energy needs and its carbon sequestration and greenhouse gas mitigation goals. Forest management practices designed to achieve goals of removing and storing CO_2 are diverse, and the forestry sector has the potential for large contributions on the global to regional scales (Malhi, Meir, and Brown, 2002; Krankina and Harmon, 2006). Key activities include avoiding deforestation, afforestation, reforestation, forest management, and post-harvest wood-product development (Harmon and Marks, 2002; Von Hagen and Burnett, 2006). Reducing deforestation (Walker and Kasting, 1992) and afforestation provide important terrestrial sequestration opportunities (Nilsson and Schopfhauser, 1995; Kadyszewski *et al.*, 2005), as do many forest plantation and forest ecosystem management practices (*e.g.*, Briceno-Elizondo *et al.*, 2006). Many suggested approaches duplicate long-recognized best forest management practices, where goals are to maintain healthy, vigorous growing stock, keep sites fully occupied with minimal spatial or temporal gaps in non-forest conditions, and minimize disturbance by fire, insects, and disease (Gottschalk, 1995). Projects planned to delay return of CO_2 to the atmosphere (*e.g.*, by lengthening rotations; Richards, Sampson, and Brown, 2006), both *in situ* (in the forest or plantation) and post-harvest are most successful.

Interactions of Climate Change with Other Stressors

Although forests are projected to be more productive under elevated CO_2 (Joyce and Birdsey, 2000; Hanson *et al.*, 2005; Norby, Joyce, and Wullschleger, 2005), productivity increases are expected to peak by 2030 and then start declining thereafter due to temperature increases, changes in precipitation, ozone effects, and other climate change stressors (Scholze *et al.*, 2006). Productivity increases may be offset especially where water and/or nutrients are limiting and increases in summer temperature further increase water stress (Angert *et al.*, 2005; Boisvenue and Running, 2006), and where ozone exposure reduces the capacity of forests to increase their productivity in response to elevated CO_2 (Karnosky, Zak, and Pregitzer, 2003; Hanson *et al.*, 2005; Karnosky *et al.*, 2005; King *et al.*, 2005). In cooler regions where water will not be a limiting resource, and where other stressors do not offset potential productivity increases, the opportunities may increase for the production of biofuels and biomass energy. The feasibility of taking advantage of these opportunities may hinge on whether economic, political, and logistical barriers can be overcome (Richards, Sampson, and Brown, 2006), and fires can be prevented (Scholze *et al.*, 2006). If, as projected, climate change enhances woody expansion and productivity for the near term in the intermountain West (Bachelet *et al.*, 2003), then forests and woodlands in that region could provide a source of fuel while mitigating the use of fossil fuels (Bachelet *et al.*, 2001).

3.2.4.5 Goal 5: Improve Watershed Condition. Increase the Number of Forest and Grassland Watersheds that are in Fully Functional Hydrologic Condition

The hydrological regimes of NFs are closely linked to climate, as well as to the many other variables that climate change may affect. Changes in precipitation patterns, including declining snowpack, earlier snowmelt, more precipitation falling as rain vs. snow (Mote *et al.*, 2005), advances in streamflow timing (Stewart, Cayan, and Dettinger, 2004; Barnett, Adam, and Lettenmaier, 2005; Milly, Dunne, and Vecchia, 2005), and the increasing frequency and intensity of extreme precipitation events (Karl and Knight, 1998; Nearing, 2001; Groisman *et al.*, 2005) have affected the hydrology, and hence condition of watersheds and ecosystems throughout the United States (Dettinger *et al.*, 2004; Hayhoe *et al.*, 2004). Changes in the distribution, form, and intensity of precipitation will make it more challenging to achieve the goal of improving watershed conditions.

Climate Change and Watershed Management

Water shortages in some areas are projected, due to increasing temperatures and changing precipitation patterns as well as to shifting demography and increased water demand (Arnell, 1999; Whiles and Garvey, 2004). National forest ecosystems in more arid parts of the country are expected to be particularly affected by projected climatic changes (Hayhoe *et al.*, 2004; Seager *et al.*, 2007). However, even in wetter regions (*e.g.*, the southeastern United States), hot temperatures and high evapotranspiration rates cause only 50% of annual precipitation to be available for streamflow (Sun *et al.*, 2005b). Thus, future scenarios of climate and land-use change indicate that the water yield for this region will become increasingly variable (Sun *et al.*, 2005a). In the Northeast, a temperature increase of 3^{o}C was projected to decrease runoff by 11–13% annually, and to a greater extent during the summer months when flow is typically lowest (Huntington, 2003). The vegetation in NFs could experience increased water stress, because gains in water use efficiency from elevated CO_2 may be negated or overwhelmed by changes in the hydrological variables described above (Baron *et al.*, 2000; but see Huntington, 2003).

Interactions of Climate Change with Other Stressors

The projected increase in frequency, severity, and extent of fire also would affect hydrological condition in NFs. By burning surface litter and altering the soil surface, wildfires reduce infiltration rates, in turn increasing overland flow and erosion rates (Hubbert *et al.*, 2006). Thus, severe rainstorms following large scale fire events could lead to substantial soil erosion and sedimentation, which would not only deleteriously affect the ecosystem itself but also decrease water quantity and quality for municipalities dependent on NFs for their fresh water supply. Fires also alter nutrient cycling and availability (Wagle and Kitchen, Jr., 1972; Certini, 2005; Neff, Harden, and Gleixner, 2005; Murphy *et al.*, 2006; Deluca and Sala, 2006), and thus affect watershed condition (Neary *et al.*, 1999; Spencer, Gabel, and Hauer, 2003; Hauer, Stanford, and Lorang, 2007).

The increasing frequency and severity of droughts projected in future climate scenarios would also negatively affect watershed condition. The extent and severity of fire impacts is closely associated with droughts; the most widespread and severe fires occur in the driest years (Taylor and Beaty, 2005; Westerling *et al.*, 2006). The temporal and spatial distribution of droughts also affects watershed condition by affecting surface water chemistry (Inamdar *et al.*, 2006).

Exposure to ozone is expected to further exacerbate the effects of drought on both forest growth and stream health (McLaughlin *et al.*, 2007a; McLaughlin *et al.*, 2007b). McLaughlin et al. (2007a) found that ozone exposure increased canopy conductance, depleted soil moisture in the rooting zones of trees, and reduced late-season streamflow in the southern Appalachians. Ozone exposure is expected to amplify the deleterious hydrological impacts resulting from warmer temperatures. Nitrogen fluxes are generally positively correlated with discharge; as precipitation and discharge rates increase, the proportion of anthropogenic nitrogen exported from forested watersheds is also expected to increase (Howarth *et al.*, 2006). The combined effects of fire suppression and increasing drought, insect outbreaks, and fire are expected to cause widespread changes in vegetation, which in turn would influence watershed condition (Guarin and Taylor, 2005).

Invasive species can alter hydrological patterns (Pimentel *et al.*, 2000) and in some cases increase runoff, erosion, and sediment loads (*e.g.*, Lacey, Marlow, and Lane, 1989), altering and influencing watershed condition.

3.2.4.6 Goal 6: Promote Biodiversity, Managing for Wildlife Habitat and Threatened and Endangered Species

Changes in climatic variables as well as the effects of interactions of climate change with other stressors (Noss, 2001; Thomas *et al.*, 2004; Millennium Ecosystem Assessment, 2005; Malcolm *et al.*, 2006) may affect all attributes and components of biodiversity (sensu Noss, 1990). Numerous effects of climate change on biodiversity components (*e.g.*, ecosystems, populations, and genes) and attributes (*i.e.*, structure, composition, and function of these components) have already been documented (reviewed in Parmesan, 2006).

Climate Change and Biodiversity Management

Climate change directly affects biodiversity by altering the physical conditions to which many species are adapted. Although species with large geographic ranges have a wide range of physiological tolerance, species that are rare, threatened, endangered, narrowly distributed, and endemic, as well as those with limited dispersal ability, will be particularly at risk under climate change (Pounds *et al.*, 2006) because they may not be able to adapt *in situ* or migrate rapidly enough to keep pace with changes in temperature (Hansen *et al.*, 2001; Wilmking *et al.*, 2004; Neilson *et al.*, 2005b). Changes in precipitation patterns may disrupt animal movements and influence recruitment and mortality rates (Inouye *et al.*, 2000). The projected changes in fish habitat associated with increases in temperature and changes in hydrology (Preston, 2006) would cause shifts in the distributions of fish and other aquatic species (Kling *et al.*, 2003). Projected declines in suitable bird habitat of 62–89% would increase the extinction risk for Hawaiian honeycreepers (Benning *et al.*, 2002). Similar projected losses of suitable habitat in U.S. forests would decrease Neotropical migratory bird species richness by 30–57% (Price and Root, 2005).

Tree species richness is projected to increase in the eastern United States as temperatures warm, but with dramatic changes in forest composition (Iverson and Prasad, 2001). Projections indicate that spruce-fir forests in New England could be extirpated and maple-beech-birch forests greatly reduced in area, whereas oak-hickory and oak-pine forest types would increase in area (Bachelet *et al.*, 2001; Iverson and Prasad, 2001). Projected changes in temperature and precipitation suggest that southern ecosystems may shift dramatically. Depiction of the northern shift of the jet stream and the consequent drying of the Southeast (Fu *et al.*, 2006) varies among future climate scenarios, with some showing significant drying while others show increased precipitation (Bachelet *et al.*, 2001). However, even under many of the somewhat wetter future scenarios, the Southeast is at risk of converting from a closed-forest region to a savanna, woodland, or grassland under temperature-induced drought stress and a significant increase in fire disturbance (Bachelet *et al.*, 2001; Scholze *et al.*, 2006). The less favorable moisture status and higher temperatures also produce simulations of reduced tree species diversity and reductions in bird and mammal richness (Currie, 2001).

Landscape fragmentation may exacerbate or cause other unexpected changes (Iverson and Prasad, 2001; Price and Root, 2005). Interactions among species may also amplify or reverse the direct impacts of climate change on biodiversity (Suttle, Thompsen, and Power, 2007).

Ecosystems at high latitudes and elevations (including many coniferous forests), as well as savannas, ecosystems with Mediterranean (*e.g.*, California) climates, and other water-limited ecosystems, are expected to be particularly vulnerable to climate change (Thomas *et al.*, 2004; Millennium Ecosystem Assessment, 2005; Malcolm *et al.*, 2006). These ecosystems may be especially vulnerable because temperature-induced droughts are expected to contribute to forest diebacks (Bugmann, Zierl, and Schumacher, 2005; Millar, Westfall, and Delany, In Press). Alpine ecosystems are also projected to decrease in area as temperatures increase (Bachelet *et al.*, 2001). Specifically, as treelines move upward in elevation, many species could be locally extirpated as they get "pushed" off the top of the mountains (Bachelet *et al.*, 2001). Also, given the strong species-area relationship that has been shown for the "island" habitats on the tops of western mountains, species diversity could be significantly reduced as these habitats become smaller or even disappear (McDonald and Brown, 1992).

Interactions of Climate Change with Other Stressors

The interactions of climate change with other stressors such as insects (Volney and Fleming, 2000; Logan, Regniere, and Powell, 2003), disease (Pounds *et al.*, 2006), and fire (Flannigan, Stocks, and Wotton, 2000; Whitlock, Shafer, and Marlon, 2003) will challenge biodiversity conservation in NF ecosystems. Indeed, Flannigan, Stocks, and Wotton (2000) noted that "the change in fire regime has the potential to overshadow the direct effects of climate change on species distribution and migration." The projected increases in the frequency and severity of wildfire (Whitlock, Shafer, and Marlon, 2003) and insect and disease outbreaks (Carroll *et al.*, 2003) would affect recruitment and migration of extant species in NFs. Interactions between fire and climate change may cause forested ecosystems in the southern United States to be replaced by savannas by 2100 (Bachelet *et al.*, 2001), especially under the warmest scenarios (Scholze *et al.*, 2006).

Similar shifts in the dominance of life forms have already been observed in the Southwest, where stand-replacing fires are becoming common in what were historically low-severity fire regimes (Allen *et al.*, 2002), and protracted drought is killing species (ponderosa pine) adapted to low-severity fire (Allen and Breshears, 1998). If these trends continue, ponderosa pine may be lost from some of its current range in the Southwest. In contrast, if warming temperatures permit doubling of mountain pine beetle reproductive cycles (Logan and Powell, 2001) such that outbreaks are more frequent and more prolonged, lodgepole pine might be replaced by Douglas-fir, at least on more mesic sites where conditions for establishment are favorable. Simulations of future vegetation distribution in the Interior West show a significant increase in woody vegetation as a result of enhanced water-use-efficiency from elevated CO_2, moderate increases in precipitation, and a strengthening of the Arizona Monsoon (Neilson *et al.*, 2005a) with the greatest expansion of woody vegetation in the northern parts of the interior West (Lenihan *et al.*, In Press). The drier interior vegetation shows a large increase in savanna/woodland types, suggesting possibly juniper and yellow pine species range expansions. However, this region is also projected to be very susceptible to fire and drought-induced dieback, mediated by insect outbreaks (Neilson *et al.*, 2005a). Such outbreaks have already altered the species composition of much of this region (Breshears *et al.*, 2005).

Land-use change and invasive species are expected to exacerbate the effects of these interactions, and hence make this goal more challenging to achieve. Fragmentation (including the loss of open space) is of particular concern because it may impede species' migration and exacerbate edge effects (*e.g.*, windthrow, drought, and non-native invasive species) during extreme climatic events, and possibly result in increased population extirpation (Ewers and Didham, 2006).

A key predicted effect of climate change is the expansion of native species' ranges into biogeographic areas in which they previously could not survive (Simberloff, 2000; Dale *et al.*, 2001). The observed northward shift in the ranges of several species, both native and introduced, due to the reduction of cold temperature restrictions supports this prediction (Parmesan, 2006). In general, climate change would facilitate the movement of some species into the habitats of others, which would create novel species assemblages, especially during post-disturbance succession. An entire flora of forest-sensitive species from the Southwest may invade ecosystems from which they have been hitherto restricted, and in the process displace many extant native species over the course of decades to centuries (Neilson *et al.*, 2005b) as winter temperatures warm (Kim *et al.*, 2002; Coquard *et al.*, 2004) and hard frosts occur less frequently in the interior West (Meehl, Tebaldi, and Nychka, 2004; Tebaldi *et al.*, 2006). Similar migrations of frost-sensitive flora and fauna occurred during the middle-Holocene thermal maximum, which was comparable to the minimum projected temperature increases for the 21st century (Neilson and Wullstein, 1983). A well-documented example of this biogeographic shift during the middle Holocene warm period is the 400 km (~250 mile) northern migration of *Quercus turbinella nutt* into the Great Basin (Neilson and Wullstein, 1983). The movement of southwestern species may also be enhanced by a northward shift and intensification of the Arizona Monsoon (Lenihan *et al.*, In Press). If the Arizona Monsoon shifts north, as it did during the middle Holocene warm period and as future climate scenarios project, then lower elevation ecotones would likely shift down in elevation (Bachelet *et al.*, 2001). Projected changes in the Arizona Monsoon would also facilitate the overall expansion of savannas and woodlands into the Great Basin at the expense of the sagebrush ecosystem (Bachelet *et al.*, 2001; Lenihan *et al.*, In Press).

Similarly increases in warm temperate/subtropical mixed forest are projected in the coastal mountains of both Oregon and Washington, with an increase in broadleaved species such as various oak species, tanoak and madrone under many scenarios (Bachelet *et al.*, 2001; Lenihan *et al.*, In Press). However, slow migratory rates of southerly (California) species would likely limit their presence in Oregon through the 21st century (Neilson *et al.*, 2005b).

These potential shifts in species may or may not enhance the biodiversity of the areas into which they migrate. This shift will potentially confound management goals based on the uniqueness of species for which there are no longer habitats. The challenge will be to define invasive in a climate changing world.

3.3 Adapting to Climate Change

3.3.1 The Need for Anticipatory Adaptation

Climate is constantly changing at a variety of time scales, thus prompting natural and managed ecosystems to adjust to these changes. As a natural process, without human intervention, adaptation typically refers to the autonomous and reactive changes that species and ecosystems make in response to environmental change such as a climate forcing (Kareiva, Kingsolver, and Huey, 1993; Smit *et al.*, 2000; Davis and Shaw, 2001; Schneider and Root, 2002). Organisms respond to environmental change (including climate change) in one of three ways: adaptation, migration, or extinction. Adaptation typically refers to *in situ* phenological (*e.g.*, breeding, flowering, migration), behavioral or genetic changes, but also includes *in situ* acclimation (adaptation to the changing environment while remaining in place). This natural adaptation in the ecosystem is important to understand, as it constitutes one important influence on the on-the-ground management of ecosystems as climate change accelerates.

We focus on adaptation as interventions and adjustments made by humans in ecological, social, or economic systems in response to climate stimuli and their effects, such as fire, wind damage, and so on. More specifically, in the social-science literature, the term adaptation refers to “a process, action, or outcome in a system (household, community, [organization], sector, region, country) in order for the system to better cope with, manage or adjust to some changing condition, stress, hazard, risk or opportunity” (Smit and Wandel, 2006).

Human adaptation to climate change impacts is increasingly viewed as a necessary complementary strategy to mitigation—reducing greenhouse gas emissions from energy use and land use changes in order to minimize the pace and extent of climate change. Because adaptive strategies undertaken will have associated carbon effects, it is important to consider carbon impacts of any proposed adaptive strategy. Forest management practices designed to achieve mitigation goals of reducing greenhouse gases (CO_2 in particular) are diverse and have large potential mitigation contributions on the global to regional scales (Malhi, Meir, and Brown, 2002; Krankina and Harmon, 2006). Options for minimizing return of carbon to the atmosphere include storing carbon in wood products (Wilson, 2006), or using biomass as bioenergy, both electrical and alcohol-based. While many positive opportunities for carbon sequestration using forests appear to exist, evaluating specific choices is hampered by considerable difficulty in accounting the net carbon balance (Cathcart and Delaney, 2006), in particular from unintentional sources such as wildfire and extensive forest mortality from insects and disease. (Westerling *et al.*, 2003; Westerling and Bryant, 2005; Lenihan *et al.*, 2005; Westerling *et al.*, 2006). Management practices that lower forest vulnerabilities to wildfire and non-fire mortality would meet multiple goals. Both strategies—adaptation and mitigation—are needed to minimize the potential negative impacts and to take advantage of any possible positive impacts from climate variability and change (Burton, 1996; Smit *et al.*, 2001; Moser *et al.*, In Press).

Several concepts related to adaptation are important to fully appreciate the need for successful anticipatory adaptation to climate-related stresses, as well as the opportunities and barriers to adaptation. The first of these is *vulnerability*. Vulnerability is typically viewed as the propensity of a system or community to experience harm from some stressor as a result of (a) being *exposed* to the stress, (b) its *sensitivity* to it, and (c) its potential or *ability to cope* with and/or *recover* from the impact (see review of the literature by Adger, 2006). Of particular importance here is a system's *adaptive capacity*: the ability of a system or region to adapt to the effects of climate variability and change. How feasible and/or effective this adaptation will be depends on a range of characteristics of the ecological system, such as biological diversity; physical characteristics of the ecosystem; pre-existing stresses, such as the presence of invasive species or loss of foundation species; and on characteristics of the social system interacting with, or dependent on, the ecosystem (Blaikie *et al.*, 1994; Wilbanks and Kates, 1999; Kasperson and Kasperson, 2001; Walker *et al.*, 2002; Adger, 2003).

As Smit and Wandel (2006) state in their recent review, "Local adaptive capacity is reflective of broader conditions (Yohe and Tol, 2002; Smit and Pilifosova, 2003). At the local level, the ability to undertake adaptations can be influenced by such factors as managerial ability; access to financial, technological, and information resources; infrastructure; the institutional environment within which adaptations occur; political influence, etc. (Blaikie, Brookfield, and Allen, 1987; Watts and Bohle, 1993; Adger, 1999; Handmer, Dovers, and Downing, 1999; Toth, 1999; Adger and Kelly, 2001; Smit *et al.*, 2001; Wisner *et al.*, 2004)." Adaptive capacity is determined mainly by local factors (*e.g.*, local forest managers' training in ecological processes, available staffing with appropriate skills, available financial resources, local stakeholder support) while other factors reflect more general socioeconomic and political systems (*e.g.*, federal laws, federal forest policies and regulations, state air quality standards, development pressures along the forest/urban interface, timber market conditions, stakeholder support).

While the literature varies in the use of these and related concepts such as *resilience* and *sustainability*, adaptation in the context of national forest management would be viewed as successful if stated management goals (see Section 3.2 above) were continued to be achieved under a changing climate regime while maintaining the ecological integrity of the nation's forests at various scales. For example, Section 3.2 identified the close relationship between ecosystem services and management goals. While these stated management goals are periodically updated or modified, and this re-examination entails a risk of setting goals lower (*e.g.*, lower quality, quantity, or production) as environmental and climatic conditions deteriorate, for the purposes of this report it is assumed that the larger tenets of the cumulative laws directing national forest management remain intact: "the greatest good of the greatest number in the long run…without impairment of the productivity of the land…[and] secure for the American people of present and future generations."

Below, we distinguish different adjustments of forest management approaches by reference to timing and intention. By "timing" we mean *when* the managing agency thinks about a management intervention: after a climate-driven, management-relevant event, or in advance of such an event. By "intention" we mean whether the managing agency acknowledges that a change is likely, anticipates possible impacts, and begins planning for a response prior to it occurring—for example, developing a monitoring or early warning system to detect changes as they occur (see Fig. 3.12). We distinguish three different adaptation scenarios: no active adaptation; planned management responses to changing climate regimes; management responses in anticipation of future climate change and in preparation for climate change now.

Figure 3.12. Anticipatory and reactive adaptation for natural and human systems (IPCC, 2001b).

3.3.1.1 No Active Adaptation

An approach of "no active adaptation" could be described as event- or crisis-driven, where the reaction to a climate or related environmental stimulus is without foresight and planning or where consideration of the potential effects of climate change and management investment resulted in a conscious decision not to manage for climate change. These reactions could be at any level of policy or decision-making—national, regional, forest planning level, or project level (for example, see Section 3.4.5.1).

The extent and severity of an extreme weather event or climate event vis-à-vis the ecosystem's ability to naturally adjust to recover from it, as well as the management agency's ability to quickly marshal the necessary response resources (money, staff, equipment, etc.) when the event occurs, will determine the ultimate impacts on the ecosystem and the cost to the managing agency. Depending on the extent of the impacts on the ecosystem and on the managing agency, future attainment of management goals may also be affected. While unforeseen opportunities may emerge, the cost of such unplanned reactive management is typically larger than if management tools can be put in place in a timely and efficient manner (a common experience with reactive vs. proactive resource or hazard management, *e.g.,* Tol, 2002; Multihazard Mitigation Council, 2006). The development of the National Fire Plan is an example of an attempt to plan for increasingly challenging wildfires in a cost-efficient manner.

This reactive approach, which does not take into account changing climate conditions, is sometimes used when scientific uncertainty is considered too great to plan well for the future. There is a strong temptation to not plan ahead because it avoids the costs and staff time needed for preparation for an event that is uncertain to occur. It also avoids dealing objectively and proactively with uncertain but probable futures. The risk to the agency of initiating expensive and politically challenging management strategies is large in the absence of a strong scientific consensus on climate change effects. However, not planning ahead also can mean incurring greater cost and may bring with it great risk later on—risk that results from inefficiencies in the response when it is needed, wasted investments made in ignorance of future conditions, or potentially even greater damages because precautionary actions were not taken.

The reactive approach would also reflect the continuation of resource management without including the potential for gradual climate-driven changes. Most past forest planning documents typically described a multi-decadal future without climate variability or change. Most management strategies or practices (*e.g.*, natural regeneration or cold-water fisheries restoration) assume a relatively constant climate or weather pattern. A careful study of the historical range of natural variability provides a wealth of information on ecological process—how diverse and variable past plant community dynamics have been. However, pre-settlement patterns of vegetation dynamics (*e.g.,* a point in time such as mid 1800s, the end of the so-called Little Ice Age) are associated with a climate that was much cooler, and may not adequately reflect the current climate or an increasingly warmer future climate and the associated vegetation dynamics. Many quantitative tools currently used do not have climate or weather included in the dynamics. Growth and yield models, unmodified by growth and density control functions (Dixon, 2003), project forest growth without climate information. The past climate may not be an adequate guide to future climate.

An approach of no proactive adaptation could also result from consideration of the potential for climate change and a conscious decision to not prepare for or adapt to climate change. Examples could include low sensitivity ecosystems, short-term projects, or a decision to triage. For low sensitivity ecosystems, the likely impacts of climate change are very low or the effects of climate change are not undesired. Short-term projects, such as high-value short-rotation timber that is about to be harvested, could be considered not critical to prepare for climate change, assuming that the harvest will occur before any major threat of climate change or indirect effects of climate change emerge. The risk is deemed low enough to continue with current management. And finally, the decision to not manage for a particular species would reflect a strategy of no active adaptation. Proper and systematic triage planning is so different from most prioritizing methods precisely because it includes the necessary option of *not* treating something that could/should be treated if more resources (time, money, staff, technology) were available. Issues needing treatment are relegated untreatable in triage prioritizing by virtue of assessing that greater gain will ensue by allocating scarce resources elsewhere; *i.e.*, in emergency situations where resources for treatment are limited, one can’t treat everything. Thus, conscious decisions are made for no action or no management.

Major institutional obstacles or alternative policy priorities can also lead to inattention to changing climatic and environmental conditions that affect forest management. Moreover, sometimes this approach is chosen unintentionally or inadvertently when climatic conditions change in ways that no one could have anticipated.

3.3.1.2 Planned Management Responses to Changing Climate Regimes, Including Disturbances and Extreme Events

This approach to adaptation assumes that adjustments to historical management approaches are needed eventually, but are best made during or after a major climatic event. In this case, the managing agency would identify climate-change-cognizant management approaches that are to be implemented at the time of a disturbance, as it occurs, such as a historically unprecedented fire, insect infestation, or extreme windfall event, hurricanes, droughts and other extreme climatic events. A choice is made to not act now to prepare for climate change, but rather to react once the problem is evident. The rationale, again, could be that the climate change impacts are too uncertain to enact or even identify appropriate anticipatory management activities, or even that the best time for action from a scientific as well as organizational efficiency standpoint may be post-disturbance (*e.g.,* from the standpoint of managing successional processes within ecosystems and across the landscape)

For example, forest managers may see large disturbances as opportunities to react to climate change. Ecological disturbances such as fire are projected to increase in frequency and size as a result of climate change (Westerling *et al.*, 2003; Westerling *et al.*, 2006; Lenihan *et al.*, In Press). Those disturbances could also be windows of opportunity for implementing adaptive practices, such as reforesting with species tolerant to low soil moisture and high temperature, using a variety of genotypes in the nursery stock, and moving plant genotypes and species into the disturbed area from other seed zones. For example, where ecosystems move toward being more water-limited under climate change, populations from drier and warmer locations will be more resistant to such changing conditions. In practice, this typically means using trees from provenances that are farther south or at lower elevation than what is currently indicated for a particular geographic location. This assisted migration is already occurring on a limited basis on forested lands managed by Weyerhaeuser in British Columbia. Because local climate trends and variability will always be uncertain, managers can hedge their bets by planting a variety of species and genotypes with a range of tolerances to low soil moisture and higher temperatures. In general, genetic diversity provides resilience to a variety of environmental stressors (Moritz, 2002; Reed and Frankham, 2003; Thorsten *et al.*, 2005). Furthermore, disturbed landscapes can be used as templates for “management experiments” that provide data for improving adaptive management of natural resources in a warmer climate. An example may be to reforest an area after a fire or windfall event with a type of tree species that is better adjusted to the new or unfolding regional climate. This may be difficult to achieve, as the climate that exists during the early years of tree growth will be different from those that will persist during the later stages of tree growth.

Significant cost efficiencies, relative to the unplanned approach, may be achieved in this approach as management responses are anticipated—at least generically—well in advance of an event, yet are implemented only when “windows of opportunity” open. Constraints to implementing such changes may need to be removed in advance for timely adaptation to be able to occur when the opportunity arises. For example, managers could ensure that the genetic nursery stock is available for wider areas, or they could re-examine regulations restricting practices so that, immediately after a disturbance, management can act rapidly to revegetate and manage the site. Such an approach may be difficult to implement, however, as crises often engender political and social conditions that favor “returning to the status quo” that existed prior to the crisis rather than doing something new (*e.g.*, Moser, 2005).

3.3.1.3 Management Responses in Anticipation of Future Climate Change and in Preparation for Climate Change Now

The management approach that is most forward-looking is one that uses the best currently available information about future climate, future environmental conditions, and the future societal context of forest management, to begin making changes to policy and on-the-ground management now and when future windows of opportunity open. Opportunities for such policy and management changes would include the forest planning process, or a project analysis in which a description of the changing ecosystem/disturbance regime as climate changes would be used to identify a proactive management strategy.

Relevant information for forest managers may include projections of regional or even local climates, including changes in average temperature, precipitation, changes in patterns of climatic extremes and disturbance patterns (*e.g.*, fire, drought, flooding), shifts in seasonally important dates (*e.g.*,growing degree-days, length of fire season), and changes in hydrological patterns. Climate science's ability to provide such information at higher spatial and temporal resolution has been improving steadily over recent years and is likely to improve further in coming years (IPCC, 2007). Current model predictions have large uncertainties, which must be considered in making management adaptation decisions (see Section 3.3.2.1, and Section 3.3.3.1 for other treatments of uncertainty). Other relevant information may be species-specific, such as the climatic conditions favored by certain forest ecosystem species over others, or the ways in which changed climatic conditions and the resultant habitats may become more or less favorable to particular species (*e.g.*, for threatened or endangered species). The overall goals of planned anticipatory management would be to facilitate adaptation and continued resilience in the face of the changing climate.

For example, based on the available information, large-scale thinnings might be implemented to reduce stand densities in order to minimize drought effects, avoid large wildfire events, and insect and disease outbreaks under a changing climate. Widely spaced stands in dry forests are generally less stressed by low soil moisture during summer months (*e.g.*, Oliver and Larson, 1996). Disease and insect concerns are at least partially mitigated by widely spaced trees because trees have less competition and higher vigor. Low canopy bulk densities in thinned stands, with concurrent treatments to abate surface fuels, can substantially mitigate wildfire risk (Peterson *et al.*, 2005). However, not all forest landscapes and stands are amenable to thinning. In these situations, shelterwood cutting that mitigates extreme temperatures at the soil surface can facilitate continued cover by forest tree species while mitigating risks of fire, insects, and disease (Graham *et al.*, 1999). This approach is economically feasible in locations where wood removed through thinnings and shelterwood cuttings can be marketed as small-dimensional wood products or biomass (Kelkar *et al.*, 2006). To provide the most relevant information to forest managers in support of such an anticipatory approach to adaptation, it is critical that scientists and managers form a growing mutual understanding of information needs and research capabilities in the context of ongoing, trusted relationships (Slovic, 1993; Earle and Cvetkovich, 1995; Cash, 2001; Cash *et al.*, 2003; Cash and Borck, 2006; Tribbia and Moser, In Press; Vogel *et al.*, In Press). Further examples of such information needs are described in the next section and in the case studies (Box 3.6).

Again, significant cost efficiencies and maybe even financial gains may be achieved in this approach, as management responses are anticipated well in advance and implemented at the appropriate time. If climatic changes unfold largely consistent with the scientific projections, this approach to adaptation may turn out to be the most cost-effective and ecologically effective (referred to as the "perfect foresight" situation by economists; see *e.g.*, Sohngen and Mendelsohn, 1998; Mastrandrea and Schneider, 2001; Yohe, Andronova, and Schlesinger, 2004). For example, Sohngen and Mendelsohn (1998) use models that assume “perfect foresight” and explore the forest sector response when a diverse set of management options to extensive mortality events from climate change are available. Similar to other studies, their results indicate that the forest sector can adapt when managers are proactive in their responses to extensive mortality events (Joyce, In Press).

This approach may not be able to maintain the ecosystems that currently exist (as those are better adapted to current climate regimes), but this approach may be best suited to support natural adaptive processes—such as species migration to more appropriate climates, or protection of viable habitats for threatened and endangered species (see Section 3.3.4.2). Under such a management approach, the management goals may themselves be adjusted over time, and thus may have a greater chance of being met. Importantly, such an approach would need to involve managers at various levels to: monitor changes in the ecosystem they manage (*i.e.*, observed on the ground); coordinate and make appropriate changes in policies, laws and regulations, plans, and programs at all relevant scales; and modify the on-the-ground practices needed to implement these higher-level policies. This degree of cross-scale integration is not typically achieved at present, and would need greater support in the future to effectively support such an approach to adaptation. For example, in the post-fire analysis of the Hayman fire (Graham, 2003), the importance of establishing relationships with existing community assets and organizations early on in a wildfire incident was identified in order to help incorporate local knowledge into firefighting and rehabilitation efforts and to establish a recovery base that continues once the emergency personnel and resources have left the community. It was also noted that partnerships should be developed as early as possible during the fire by the incident command, and perhaps these partnerships might best be developed before any fire in order to systematize actions, increase efficiency, and decrease potential contentions between locals and federal agencies by building trust (Graham, 2003).

3.3.2 Approaches for Planning in the Context of Climate Change

3.3.2.1 Use of Models and Forecasting Information

Many forest managers are awaiting information from quantitative models about future climates and environments to guide climate-related planning. Increasingly sophisticated models are being developed at regional scales. Useful as these model outputs will be, an important caveat is to evaluate the level of uncertainty inherent in any model, and the management risks associated with that model error. At the global scale, this uncertainty is dealt with through simultaneous analysis of multiple scenarios (IPCC, 2007), which yields a wide range of potential future climate conditions.

While science is progressing, uncertainty about climate projections may be much greater at the local and regional scales important to land managers, because uncertainties generally amplify as models are downscaled. Some climate parameters, such as changes in average annual temperature, may be more robust than others, such as changes in annual precipitation, which have higher uncertainties associated with them. The kinds of actions a land manager might take in anticipation of a wetter future, however, would differ markedly from those for a drier future. Rather than viewing models as forecasts or predictions of the future, they are better used for attaining insight into the nature of potential processes and about generalized trends. Focusing on results that are similar across diverse models may indicate results of greater likelihood.

Augmenting this uncertainty in physical conditions is the difficulty of modeling biological responses. Ecological response to climate-related changes is highly likely to be more difficult than climate to model accurately at local scales because threshold and non-linear responses, lags and reversals, individualistic behaviors, and stochastic (involving probability) and catastrophic events are common (Webb, III, 1986; Davis, 1989). Models typically rely on directional shifts following equilibrium dynamics of entire plant communities, whereas especially in heterogeneous and mountainous regions, patchy environments increase the likelihood of complex, individualistic responses.

Understanding the levels of uncertainty in a model is often difficult within the management context, but should be investigated and evaluated before management plans are built that depend on model results. In general, while model information will be important for planning, the best use of this information at local and regional scales is to help organize thinking and understand qualitatively the range of magnitudes and likely direction and trends of possible future changes.

Models can also be used for scenario analysis (alternative future climate scenarios can be used to drive ecosystem and other natural resource models), thus examining the possible range of future conditions. Uncertainty does not imply a complete lack of understanding of the future. Scenario analysis can help to identify potential management options that could be useful to minimize negative impacts and enhance the likelihood of positive impacts, within the range of uncertainty.

A contrasting problem to over-reliance on model results is a decision to take no action in the face of uncertainty, with the defense that without adequate information an informed decision cannot be made. As described in section 3.3.1.1, there are substantial risks associated with no action or taking an “anything goes” approach, even without precise information. Managing in the face of uncertainty will best involve a suite of approaches, including planning analyses that incorporate modeling with uncertainty, and short-term and long-term strategies that focus on enhancing ecosystem resistance and resilience, as well as action taken that assist ecosystems and resources to move in synchrony with the ongoing changes that result as climates and environments vary.

3.3.2.2 Planning Analyses for Climate Change

RPA Assessment

The only legislatively required analysis with respect to climate change and Forest Service planning was identified in the 1990 Food Protection Act, which amended the 1974 Resources Planning Act (RPA). The 1990 Act required the Forest Service to assess the impact of climate change on renewable resources in forests and rangelands, and to identify the rural and urban forestry opportunities to mitigate the buildup of atmospheric carbon dioxide. Since 1990, the RPA Assessments (*e.g.*, USDA Forest Service, 1993; USDA Forest Service, 2000a; USDA Forest Service, In Press) have included an analysis of the vulnerability of U.S. forests to climate change, and the impact of climate change on ecosystem productivity, timber supply and demand and carbon storage (Joyce, Comandor, and Fosberg, 1990; Joyce, 1995; Joyce and Birdsey, 2000; Haynes *et al.*, 2007). The analyses have identified the importance of the temporal dynamics of the climate change effect on ecosystems and consequently the timber supply and demand dynamics in the forest sector, the influence of the forest sector trade at the global scale, and the importance of identifying the regional response where management decisions will be made (Joyce, In Press). Most critically, all of these analyses have stressed the importance of evaluating the ecological and the economic response in an integrated fashion. Taken in isolation, the ecological results overstate the impact of climate change on the forest sector.

Forest Planning

In a survey of the forest plans available online in December 2006, only 15 plans from a total of 121 individual forests had included the terms "climate change," "climate variability," or "global warming." These references were found in the sections of the plan describing trends affecting management or performance risks, or, in earlier plans, as a concern in the environmental impact statement.

Given the challenges of the uncertainty in climate scenarios at fine spatial scale (Section 3.3.3.1), a set of assumptions to be considered in planning has been proposed (West, 2005). Specifically, the recommendations make use of an adaptive management approach to make adjustments in the use of historical conditions as a reference point. Flexibility to address the inherent uncertainty about local effects of climate change could be achieved through enhancing the resiliency of forests and specific aspects of forest structure and function are mentioned (Box 3.7). These assumptions would allow the plan components to be designed in a way that allows for adaptability to climate change even though the magnitude and direction of that change is uncertain. The list of assumptions to be examined (Box 3.7) explore underlying assumptions about climate and climate change in the management processes.

3.3.3 Approaches for Management in the Context of Climate Change

3.3.3.1 The Tool Box of Management Approaches

A primary premise for adaptive approaches is that change, novelty, uncertainty, and uniqueness of individual situations are expected to define the planning backdrop of the future. Rapid changes that are expected in physical conditions and ecological responses suggest that management goals and approaches will be most successful when they emphasize ecological processes rather than primary focus on structure and composition. Information needs (*e.g.*, projections of future climates, anticipated ecological responses) will vary in availability and accuracy at local spatial and temporal scales. Thus, strategic flexibility and willingness to work in a context of varying uncertainty will improve success at every level (Anderson *et al.*, 2003). Learning from experience and iteratively incorporating lessons into future plans—adaptive management in its broadest sense—is an appropriate lens through which natural-resource management is conducted (Holling, 2001; Noss, 2001; Spittlehouse and Stewart, 2003). Dynamism in natural conditions is appropriately matched by dynamic approaches to management and adaptive mindsets.

Given the nature of climate and environmental variability, the inevitability of novelty and surprise, and the range of management objectives and situations, a central dictum is that *no single approach will fit all situations* (Spittlehouse and Stewart, 2003; Hobbs *et al.*, 2006). From a toolbox of options such as those proposed below, appropriate elements (and modifications) should be selected and combined to fit the situation. Some applications will involve existing management approaches used in new locations, seasons, or contexts. Other options may involve experimenting with new practices.

A toolbox approach recognizes that strategies may vary based on the spatial and temporal scales of decision-making. Planning at regional scales may involve acceptance of different levels of uncertainty and risk than appropriate at local (*e.g.*, national forest or watershed) scales. When beginning any project, the following planning steps have been suggested as appropriate in a climate-change context (Spittlehouse and Stewart, 2003; see examples therein):

1. Define the issue (management situation, goals, and environmental and institutional contexts)
2. Evaluate vulnerabilities under changing conditions.
3. Identify suitable adaptive actions that can be taken at present or in the short term.
4. Develop suitable adaptive actions that could be taken in the longer term.

The options summarized below fall under adaptation, mitigation, and conservation practices (Dale *et al.*, 2001; IPCC, 2001a). Based on the toolbox approach, an overall adaptive strategy will usually involve integrating practices having different individual goals. An important consideration in building an integrative strategy is to first evaluate the various types of uncertainty: for example, uncertainty in present environmental and ecological conditions, including the sensitivity of resources; uncertainty in models and information sources about the future; uncertainty in support resources (staff, time, funds available); uncertainty in planning horizon (short- vs. long-term); and uncertainty in public and societal support. This evaluation would lead to a decision on whether it is best to develop reactive responses to changing disturbances and extreme events, or proactive responses anticipating climate change (see Section 3.3.1). If the latter, a further decision involves whether to develop deterministic or indeterministic approaches. The former approach bases planning on a specific projected future climate and ecological scenario, assuming that quantitative models, forecasting tools, and available information have high enough certainty or low enough risk for a given management situation. In contrast, indeterministic approaches base planning on an assumption that the future is not adequately knowable, and plan instead directly for uncertainty. Deterministic approaches "put all the eggs in one basket" and risk potential failures if an assumed future does not unfold, while indeterministic approaches employ "bet hedging" strategies that attempt to minimize risks by taking multiple courses of action. The following options provide a framework for building management strategies in the face of climate change and provide examples of both approaches (Millar *et al.*, 2006). Some examples of specific adaptation options are presented in Box 3.8 and are elaborated upon further in the sections that follow.

3.3.3.2 Adaptation (Preparation) Options

Forestalling Ecosystem Change

Create Resistance to Change

Notwithstanding the importance of dynamic approaches to change and uncertainty, one set of adaptive options is to manage forest ecosystems and resources so that they are better able to resist the influence of climate change (Parker *et al.*, 2000; Suffling and Scott, 2002). From high-value forest plantation investments near rotation to rare species with limited available habitat, maintaining the status quo for a limited period of time may be the only or best option in some cases. Creating resistance includes improving forest defenses against climate effects *per se*, but also creating resistance against climate-exacerbated disturbance impacts. In the arid West, this will almost always involve protecting resources from risks of climate-exacerbated drought, insect outbreak, and forest fire. Resistance practices include thinning and fuels abatement treatments at the landscape scale to reduce crown fire potential and risk of insect epidemic, maintaining existing fuelbreaks, strategically placed area treatments that will reduce fuel continuity and drought susceptibility of forests, creating defensible fuel profile zones around high value areas (such as WUI, critical habitat, or municipal watersheds), and similar treatments. Intensive and aggressive fuelbreaks may be necessary around highest-risk or highest-value areas, such as wildland-urban interfaces, valuable plantations, or at-risk species, while mixed approaches may best protect habitat for biodiversity and general forest zones (Wheaton, 2001).

In addition to fire, aggressive prophylactic actions may be taken to increase resistance of forest ecosystems to climate-related insect and disease outbreaks. Traditional silvicultural methods may be applied creatively. These may involve intensive treatments such as those used in high-value agricultural situations: resistance breeding, novel pheromone applications (such as sprayable micro-encapsulated methods), complex pesticide treatments, and aggressive fuelbreaks. Abrupt invasions, changes in behavior and population dynamics, and long-distance movements of native and non-native species may occur in response to changing climates. Climate changes may also catalyze conversion of already problematic native insects or disease species into invasive species in new environments, such as mountain pine beetle and pine species (Carroll, 2006). Monitoring non-native species and taking aggressive early and proactive actions at key migration points to remove and block invasions are important steps to increase resistance.

Efforts to increase resistance may be called for in other high-value situations. Building resistance to exacerbated effects of air pollution from climate change may require that aggressive thinning and age-control silvicultural methods are applied at broad landscape scales, that mixed species plantations be developed, or that plantations are switched to resistant species entirely (Papadopol, 2000). Fragmentation and land-use changes that are already problematic may be worsened under climate change due to shifts in species behaviors and changed habitat requirements. Anticipating these impacts for high-value, high-risk, and sensitive resources may require adopting landscape management practices that enable species movements. Creating larger management unit sizes, broad habitat corridors, and continuity of habitat would increase resistance of forest species to climate by improving their ability to migrate.

Resisting climate change influences on natural forests and vegetation will almost always require aggressive treatments, accelerating efforts and investments over time, and a recognition that eventually these efforts may fail as conditions cumulatively change. Creating resistance in most forest situations to directional change is akin to "paddling upstream," and eventually conditions may change so much that resistance is no longer possible. For instance, climate change in some places will drive environments to change so much that site capacities shift from favoring one species to another, and a type conversion occurs.

Maintaining prior species may require significant extra and repeated efforts to supply needed nutrients and water, remove competing understory, fertilize young plantations, develop a cover species, thin, and prune. More seriously, forest conditions that have been treated to resist climate-related changes may cross thresholds and convert (*i.e.*, be lost) catastrophically through extreme events such as wildfire, ice storm, tornado, insect epidemic, or drought, resulting in significant resource damage and loss. For this reason, in some situations, resistance options may best be applied in the short term and for projects with short planning horizons and high value, such as short-rotation biomass or biofuels plantings. Conditions with low sensitivity to climate will be those most likely to accommodate resistance treatments, and high-sensitivity conditions will require the most intensive efforts to maintain. Alternative approaches that work with processes of change rather than against the direction of climate-related change may enable inevitable changes to happen more gradually over time, and with less likelihood of cumulative, rapid, and catastrophic impact. For example, widely spaced thinning or shelterwood cuttings that create many niches for planted or naturally established seedlings may facilitate adaptation to change on some sites. In selection of these alternative approaches, a holistic analysis may be required to identify the break point beyond which intervention to natural selection and adaptation to climate changes may not be possible or managed at reasonable cost.

Promote Resilience to Climate Change

Resilient forest plantations and ecosystems are those that not only accommodate gradual changes related to climate but resile (return to a prior condition) after disturbance. Promoting resilience is the most commonly suggested adaptive option discussed in a climate-change context (*e.g.*, Dale *et al.*, 2001; Spittlehouse and Stewart, 2003; Price and Neville, 2003), but has its drawbacks. Resilience in forest ecosystems can be increased through management practices similar to those described for resisting change, but applied more broadly, and specifically aimed at coping with disturbance (Dale *et al.*, 2001; Wheaton, 2001).

An example of promoting resilience in forest ecosystems is a strategy that combines practices to reduce fire or insect and disease outbreaks (resistance) in concert with deliberate and immediate plans to encourage return of the site to desired species post-disturbance (resilience). Given that the plant establishment phases tend to be most sensitive to climate-induced changes in site potential, intensive management dedicated to the revegetation period through the early years of establishment may enable retention of the site by a desired species, even if the site is no longer optimal for it (Spittlehouse and Stewart, 2003). Practices could include widely spaced thinnings or shelterwood cuttings to promote resilience with living stands, and rapid treatment of forests killed by fire or insects. Thinnings that favor early seral species would increase drought tolerance and resistance to both insect and disease stressors. Concurrently they would preserve forested microenvironments needed for many shrubs and forbs. Where disease is extensive or there are many trees that have succumbed to insects or disease, shelterwood harvests would facilitate continuation of the more drought-tolerant elements of the current forest. In forests killed by fire or other disturbance, resilience could be promoted by maintaining some degree of shade as appropriate for the forest type; intensive site preparation to remove competing vegetation; replanting with high-quality, genetically appropriate and diverse stock; diligent stand-improvement practices; and minimizing invasion of non-native species (Dale *et al.*, 2001; Spittlehouse and Stewart, 2003). Many of these intensive forestry practices may have undesired effects on other elements of ecosystem health, and, thus, have often come under dispute. However, if the intent is to return a forest stand to its prior condition after disturbance under changing climate (*i.e.*, to promote resilience), then deliberate, aggressive, intensive, and immediate actions may be necessary. Many examples are accumulating in which resilience is declining in natural forests due to an inability to practice these silvicultural methods safely or with public acceptance (see Case Studies Sections 3.5, 3.6).

Similar to the situation with regard to resistance options, the capacity to maintain and improve resiliency will, for many contexts, become more difficult as changes in climate accumulate and accelerate over time. These options may best be exercised in projects that are short-term, have high value such as commercial plantations, or under ecosystem conditions that are relatively insensitive to the potential climate change effects (*e.g.*, warming temperatures).

Managing for Ecosystem Change

Enable Forests to Respond to Change

This suite of adaptation options intentionally plans for change rather than resisting it, with a goal of enabling forest ecosystems to naturally adapt as environmental changes accrue. Given that many ecological conditions will be moving naturally toward significant change in an attempt to adapt (*e.g.*, species migration, stand mortality and colonization events, changes in community composition, insect and disease outbreaks, and fire events), these options seek to work with the natural adaptive processes. In so doing, options encourage gradual adaptation over time, thus hoping to avoid sudden thresholds, extreme loss, or conversion that may occur if natural change is cumulatively resisted.

Depending on the environmental context, management goals, and availability and adequacy of modeling information (climate and otherwise), different approaches may be taken. In this context change is assumed to happen—either in known directions (deterministic), and goals are planned for a specific future, or in unknown directions (indeterministic), and goals are planned directly for uncertainty. Examples of potential practices include the following:

1. Assist transitions, population adjustments, range shifts, and other natural adaptations. Use coupled and downscaled climate and vegetation models to anticipate future regional conditions and project future forest stands and plantations into new habitat and climate space. With such information, managers might plan for transitions to new conditions and habitats, and assist the transition—*e.g.*, as appropriate, move species uphill, plan for higher-elevation insect and disease outbreaks, reduce existing anthropogenic stresses such as air quality or land cover changes, anticipate forest mortality events and altered fire regimes, or consider loss of species' populations on warm range margins and do not attempt restoration there (Ledig and Kitzmiller, 1992; Parker *et al.*, 2000; Spittlehouse and Stewart, 2003). Further examples might be to modify rotation lengths and harvest schedules, alter thinning prescriptions and other silvicultural treatments, consider replanting with different species, shift desired species to new plantation or forest locations, or take precautions to mitigate likely increases in stress on plantation and forest trees.

A nascent literature is developing on the advantages and disadvantages of "assisted migration," that is, intentional movement of propagules or juvenile and adult individuals into areas assumed to become their future habitats (Halpin, 1997; Collingham and Huntley, 2000).

While it has become a common assumption based on modeling, for instance, that species and communities will shift uphill to find favorable sites as climates warm, and similarly that moving managed plantations uphill is the appropriate response, it is important to not generalize assumptions about habitat and climate in specific areas. Local climate trajectories may be far different than state or regional trends, and local topography and microclimatology interact in ways that may yield very different climate conditions than those given by broad-scale models. In mountainous terrain especially, the climate landscape is patchy and highly variable, with local inversions, wind patterns, aspect differences, soil relations, storm tracks, and hydrology influencing the weather that a site experiences. Sometimes lower elevations may be refugial during warming conditions, as in inversion-prone basins, deep and narrow canyons, riparian zones, and north slopes. Such patterns, and occupation of them by plants during transitional climate periods, are corroborated in the paleoecological record (Millar and Woolfenden, 1999; Millar *et al.*, 2006). Additionally, land use and agricultural practices can insert feedbacks to precipitation and climate patterns (Foley *et al.*, 2005; Pielke, Sr. *et al.*, 2006).

Despite the challenges in mountainous terrain, anticipating where climate and local species habitats will move will become increasingly important. On-the-ground monitoring of native species gives insight into what plants themselves are experiencing, and can suggest the directions of change and appropriate natural response at local scales. This can allow management strategies that mimic emerging natural adaptive responses. For instance, new species mixes (mimicking what is regenerating naturally or outperforming plantation species), altered genotype selections, modified age structures, and novel silvicultural contexts (*e.g.*, selection harvest versus clearcut) may be considered.

2. Increase Redundancy and Buffers. This set of practices intentionally manages for an uncertain but changing future rather than a specific climate future. Practices that involve spreading risks in diverse opportunities rather than concentrating in a few are favored; using redundancy and creating diversity are key. These can be achieved, for instance, by spreading plantations over a range of environments rather than within the historic distribution or within a modeled future location. Options that include using diverse environments and even species margins will provide additional flexibility. A benefit of redundant plantings across a range of environments is that they can provide monitoring information if survival and performance are measured and analyzed. Further, plantations originating as genetic provenance tests and established over the past several decades could be re-examined for current adaptations. In addition to plantations, a range of sites representing the diversity of conditions on a national forest could be set aside after disturbance events to allow natural regeneration and successional processes identify the most resistant species and populations. Other examples include planting with mixed species and age classes as in agroforestry (Lindner, Lasch, and Erhard, 2000); increasing locations, sizes and range of habitats for landscape scale vegetation treatments; assuring that fuels are appropriately abated where vegetation is treated; and increasing the number of rare plant populations targeted for restoration and targeting higher population levels within them (Millar and Woolfenden, 1999). In the same way, opportunistic monitoring, such as horticultural plantings of native species in landscaping, gardens, or parks, may provide insight into how species respond in different sites as climate changes.

3. Expand Genetic Diversity Guidelines. Existing guidelines for genetic management of forest plantations and restoration projects dictate maintenance of and planting with local germplasm. In the past, small seed zones, used for collecting seed for reforestation or restoration, have been delineated to ensure that local gene pools are used and to avoid contamination of populations with genotypes not adapted to the local site. These guidelines were developed assuming that neither environments nor climate were changing—*i.e.*, a static background. Relaxing these guidelines may be appropriate under assumptions of changing climate (Ledig and Kitzmiller, 1992; Spittlehouse and Stewart, 2003; Millar and Brubaker, 2006). In this case, either deterministic or indeterministic options could be chosen. In the former, germplasm would be moved in the anticipated adaptive direction; for instance, rather than using local seed for a plantation or restoration site, seed from a warmer (often, downhill) current population would be used. Transfer rules could be developed for standard application along modeled future climate gradients. By contrast, if an uncertain future is accepted, expanding seed zone sizes in all directions and requiring that seed collections be well distributed within these zones would be appropriate, as would relaxing seed transfer guidelines to accommodate multiple habitat moves, or introducing long-distance germplasm into seed mixes. Adaptive management of this nature is experimental by design and will require careful documentation of treatments, seed sources, and outplanting locations in a corporate data structure to learn from both failures and successes of such mixes.

Traditional best genetic management practices will become even more important to implement under changing climates. Paying attention not only to the source but the balance of genetic diversity within seedlots and outplanting collections (*i.e.*, maintaining high effective population sizes) is prudent: approaches include maximizing the number of parents, optimizing equal representation by parents (*e.g.*, striving for equal numbers of seeds/seedlings per family), and thinning plantations such that existing genetic diversity is not greatly reduced. Genotypes known or selected for broad adaptations could also be favored. By contrast, although economic incentives may override, using a single or few genotypes (*e.g.*, a select clone or small clonal mix) is a riskier choice in a climate change context.

4. Manage for Asynchrony and Use Establishment Phase to Reset Succession to Current Conditions. Changing climates over paleoecologic timescales have repeatedly reset ecological community structure (species diversity) and composition (relative abundances) as plants and animals have adapted to natural changes in their environments. To the extent that climate acts as a region- and hemispheric-wide driver of change, the resulting shifts in biota often occur as synchronous changes across the landscape (Swetnam and Betancourt, 1998). At decadal and century scales, for instance, recurring droughts in the West and windstorms in the East have synchronized forest species, age composition, and stand structure across broad landscape. These then become further vulnerable to rapid shifts in climate, such as is occurring at present, which appear to be synchronizing forests through massive drought-insect related diebacks. An opportunity exists to proactively manage these early successional stages that follow widespread mortality by deliberately reducing synchrony (Mulholland, Betancourt, and Breshears, 2004). Asynchrony can be achieved through a mix of activities that promotes diverse age classes, species mixes, stand diversities, genetic diversity, etc., at landscape scales. Early successional stages are likely the most successful (and practical) opportunities for resetting ecological trajectories that are adaptive to present rather than past climates, because this is the best chance for widespread replacement of plants. Such ecological resetting is evidenced in patterns of natural adaptation to historic climate shifts (Davis and Shaw, 2001).

5. Establish "Neo-Native" Plantations and Restoration Sites. Information from historic species ranges and responses to climate change can provide unique insight about species behaviors, ecological tolerances, and potential new habitats. For instance, areas that supported species in the past under similar conditions to those projected for the future might be considered sites for new plantations or "neo-native" stands of the species. These may be well outside the current species range, in locations where the species would otherwise be considered exotic. For instance, Monterey pine (*Pinus radiata*), endangered throughout its small native range, has naturalized along the north coast of California far disjunct from its present native distribution. Much of this area was paleohistoric range for the pine, extant during climate conditions that have been interpreted to be similar to expected futures in California (Millar, 1999). Using these locations specifically for "neo-native" conservation stands rather than planning for the elimination of the trees as undesired exotics, which is the current management goal, is an example of how management thinking could accommodate a climate-change context (Millar, 1998). This option is relevant to both forest plantation and ecological restoration contexts.

6. Promote Connected Landscapes. Capacity to move (migrate) in response to changing climates is key to adaptation and long-term survival of plants and animals in natural ecosystems (Gates, 1993). Plants migrate, or "shift ranges" by dying in unfavorable sites and colonizing favorable edges, including internal species' margins. Capacity to do this is aided by managing for porous landscapes; that is, landscapes that contain continuous habitat with few physical or biotic restrictions, and through which species can move readily (recruit, establish, forage) (Halpin, 1997; Noss, 2001). Promoting large forested landscape units with flexible management goals that can be modified as conditions change will encourage species to respond naturally to changing climates (Holling, 2001). This enables managers to work with rather than against the flow of change. Evaluating and reducing fragmentation, and planning cumulative landscape treatments to encourage defined corridors as well as widespread habitat availability is a proactive approach.

7. Realign Significantly Disrupted Conditions. For forest species or ecosystems that have been significantly or cumulatively disturbed and are far outside natural ranges of current variation, restoration treatments are often prescribed. Because historical targets, traditionally used as references for restoration, are often inappropriate in the face of changing climates, re-alignment with current process rather than restoration to historic pre-disturbance condition may be a preferred choice (Harris *et al.*, 2006; Millar and Brubaker, 2006; Willis and Birks, 2006). In this case, management goals seek to bring processes of the disturbed landscape into the range of current or anticipated future environments (Halpin, 1997). An example comes from the Mono Lake ecosystem in the western Great Basin of California (National Research Council, 1987; Millar and Woolfenden, 1999). A basin lake with no outlet, Mono Lake is highly saline, thus is naturally fishless but rich in invertebrate endemism and productivity, provides critical habitat for migratory waterfowl, and supports rich communities of dependent aquatic and adjacent terrestrial species. In 1941, the Los Angeles Department of Water and Power diverted freshwater from Mono Lake's tributaries; the streams rapidly dried and Mono Lake's level declined precipitously. Salinity increased, groundwater springs disappeared, and ecological thresholds were crossed as a series of unexpected consequences unfolded, threatening Mono Lake's aquatic and terrestrial ecosystems. An innovative solution involved a 1990 court-mediated re-alignment process. Rather than setting pre-1941 lake levels as a restoration goal, a water-balance model approach, considering current climates as well as future climatic uncertainties, was used to determine the most appropriate lake level for present and anticipated future conditions (State of California, 1994).

Options Applicable to Both Forestalling Change and Managing for Change

Anticipate and Plan for Surprise and Threshold Effects

Evaluate potential for indirect and surprise effects that may result from cumulative climate changes or changes in extreme weather events. This may involve thinking outside the range of events that have occurred in recent history. For example, reductions in mountain snowpacks lead to more bare ground in spring, so that “average” rain events run off immediately rather than being buffered by snowpacks and produce extreme unseasonal floods (*e.g.*, Yosemite Valley, May 2005; Dettinger *et al.*, 2006). Similarly, without decreases in annual precipitation, and even with increasing precipitation, warming minimum temperatures are projected to translate to longer dry growing-season durations. In many parts of the West, especially Mediterranean climate regions, additional stresses of longer summers and extended evapo-transpiration are highly likely to push plant populations over thresholds of mortality, as occurred in the recent multi-year droughts throughout much of the West (Breshears *et al.*, 2005). Evidence is accumulating to indicate that species interactions and competitive responses under changing climates are complex and unexpected (Suttle, Thompsen, and Power, 2007). Much has been learned about likely surprises and rapid events as a result of climate change from paleo-historic studies. Anticipating these events in the future means planning for more extreme ranges than in recent decades, and arming management systems accordingly (Millar and Woolfenden, 1999; Harris *et al.*, 2006; Willis and Birks, 2006).

Experiment with Refugia

Plant ecologists and paleoecologists recognize that some environments appear more buffered against climate and short-term disturbances, while others are sensitive. If such “buffered” environments can be identified locally, they could be considered sites for long-term retention of plants, or for new plantations (commercial or conservation). For instance, mountainous regions are highly heterogeneous environmentally; this patchiness comprises a wide range of micro-climates within the sites. Further, unusual and nutritionally extreme soil types (*e.g.*, acid podsols, limestones etc.) have been noted for their long persistence of species and genetic diversity, resistance to invasive species, and long-lasting community physiognomy compared with adjacent fertile soils (Millar, 1989). During historic periods of rapid climate change and widespread population extirpation, refugial populations persisted on sites that avoided the regional climate impacts and the effects of large disturbance. For example, Camp (1995) reported that topographic and site characteristics of old-growth refugia in the Swauk Pass area of the Wenatchee National Forest were uniquely identifiable. These populations provided both adapted germplasm and local seed sources for advance colonization as climates naturally changed toward favoring the species. In similar fashion, a management goal might focus specific attention to protect populations that currently exist in environmentally and climatically buffered, cooler, or unusually mesic environments.

3.3.4 Prioritizing Management Responses in Situations of Resource Scarcity

Species, plant communities, regional vegetation, and forest plantations will respond to changing climates individualistically. Some species and situations will be sensitive and vulnerable, while others will be naturally buffered and resilient to climate-influenced disturbances (Holling, 2001; Noss, 2001). Management goals for species and ecosystems across the spectrum of NFs also vary for many reasons. As a result, proactive climate planning will reflect a range of management intensities. Some species and ecosystems may require aggressive treatment to maintain viability or resilience, others may require reduction of current stressors, and others less intensive management, at least in the near future.

While evaluating priorities has always been important in resource management, the magnitude and scope of anticipated needs, combined with diminishing availability of human resources, dictate that priorities be evaluated swiftly, strictly, and definitively. A useful set of guidelines for certain high-demand situations comes from the medical practice of triage (Cameron *et al.*, 2000). Coming from the French *triare*, to sort, triage approaches were developed from the need to prioritize the care of injured soldiers in battlefield settings where time is short, needs are great, and capacity to respond is limited. Well-established emergency and disaster triage steps can be modified to fit resource needs when conditions cannot be handled with traditional planning or institutional capacity. Triage in a natural-resource context sorts management situations (“patients”) into categories according to urgency, sensitivity, and capacity of available resources to achieve desired goals (“survival”). Cases are rapidly assessed and sorted into three to five major categories (“color tags”) that determine further action:

1. *Red*: Significant ongoing emergency; immediate attention required. Cases in this category are extremely urgent, but may be successfully treated with immediate attention given available resources. Without attention, they will rapidly fail; in the medical sense, the patient will die soon if untreated. These cases receive the highest priority for treatment and use of available resources. Depending on available resources, some of these cases may be assigned black rather than red.

2. *Yellow*: Strong to medium potential for emergency. Cases in this category are sensitive to disruption, vulnerable due to history or disturbance (degree and extent of trauma), have the capacity with small additional disturbance to become rapidly worse, but are marginally stable at the time of assessment. These cases have medium priority.

3. *Green*: Low likelihood for emergency conditions. Cases in this category may have some problems but overall are relatively resistant to disturbance, have low stress or high capacity to deal with stress, a history of low vulnerability, and show signs of retaining stability at least in the short term with little need for intervention. These cases receive low priority, but conditions are monitored regularly for change.

4. *Black*: Conditions altered beyond hope of treatment. Cases in this category are so disrupted, altered, and weakened that chances of successfully treating them with available resources are nil. In medical context, patients are either dead or unable to be kept alive with existing capacity. These cases have the lowest priority in the short term, and alternative resolutions have to be developed.

While triage is valuable to practice under conditions of scarce resources or apparently overwhelming choice, it is not viable as a long-term or sole-use approach to priority-setting. Other approaches may be used for quick prioritizing of traditional management plans and practices. An example would be rapid assessments of current national forest land management plans, performed by teams of climate experts that visit NFs. Teams would rapidly review planning documents, interview staff, and visit representative field sites; they would conclude their visits with a set of recommendations on what aspects of the overall local forest management practices and plans are in 1) immediate need of significant revision, 2) need of revision in a longer timeframe, and 3) no need of revision; already climate-savvy. Similar integrated threat assessment tools are being developed that assist managers and decision-makers to grasp categories of urgency. At present, use of such rapid assessment and implementation processes is hampered by the demands for long public scoping and review often necessitated by environmental laws, such as NEPA.

In situations where available resources can be augmented, where time is not a critical factor, and where more information can be obtained, traditional evaluations and priority-setting will be most appropriate. Triage may be used, however, at any time and at any scale where urgency arises, and when demands become greater than normally managed. The common alternative under these conditions, reacting to crises chaotically and without rules of assessment, will achieve far less success in the long run than triage-based approaches.

3.4 Case study: Tahoe National Forest

3.4.1 Setting and Context of Tahoe National Forest

Tahoe National Forest (TNF) is located in eastern California, where it straddles the northern Sierra Nevada (Fig. 3.13). The administrative boundary encompasses 475,722 ha (1,175,535 ac), of which one-third are privately owned forest industry lands arranged in alternate sections (“checkerboard”) with TNF land. Elevations range from 365 m (1,200 ft) at the edge on the western slope to 2,788 m (9,148 ft) at the crest of the Sierra. The eastern slopes of TNF abut high-elevation (~1,525 m; 5,000 ft) arid steppes of the Great Basin. TNF experiences a Mediterranean-type climate with warm, dry summers alternating with cool, wet winters. The orientation of the Sierra Nevada paralleling the Pacific coast creates a steep west-east climatic gradient that contributes to strong orographic effects in temperature and a precipitation rainshadow. Near TNF’s western boundary, average precipitation is low (125 cm; 50 in), highest at west-side mid-elevations (200 cm; 80 in), and lowest near the eastern boundary (50 cm; 20 in). Snow dominates winter precipitation in the upper elevations, providing critical water reserves for the long annual summer drought.

Figure 3.13. Map and location of the Tahoe National Forest, within California (a) and the Forest boundaries (b) (USDA Forest Service, 2007b; USDA Forest Service, 2007d).

Floral and faunal diversity of TNF parallels the topographic and climatic gradients of the Sierra Nevada, with strong zonation along elevational bands. The long Mediterranean drought is a primary influence on the species that can grow and the natural disturbance regimes. Pine forests occupy low elevations on the western side. These grade upslope to a broad zone of economically and ecologically important mixed-conifer forests. Higher, at the elevation of the rain-snow zone, true-fir forests dominate; diverse subalpine forests are the highest-elevation tree communities.

East of the crest, sparse eastside pine communities grade downslope to woodlands and shrublands of the Great Basin. Terrestrial and aquatic environments of TNF support critical habitat for a large number of plant and animal species, many of which have long been subjects of intense conservation concern. The TNF environments are used by 387 vertebrate species and more than 400 plant species (Tahoe National Forest, 1990; Shevock, 1996). Several keystone species at the Sierra rangewide scale depend on now-limited old-growth forest conditions or other rare habitats.

Cultural legacies have played significant roles in shaping present forest conditions and vulnerabilities in TNF. Timber, water, mining, and grazing, which started in the mid-1800s, remained intensive uses until the late 20th century. Low- to mid-elevation forests were denuded in the mid-1800s through early 1900s to provide wood for settlement (Beesley, 1996). Subsequently the forests regrew, but although they continued to be extensively harvested until recently, decades of fire suppression contributed to extremely dense stands, even-age classes, and low structural diversity. These conditions led to extreme fire susceptibilities; large fire events have occurred in recent years, and fire vulnerability is the highest concern for management. Modern human use of TNF and adjacent lands has changed the way in which natural resources are managed. Population and development in the communities adjacent to the low elevations have exploded in the past decades, creating extensive wildland-urban interface issues (Duane, 1996). Changing demographies and consequent resource values of new residents have forced re-evaluation of TNF goals and practices, many of which limit the capacity of TNF to implement adaptive but manipulative practices in the face of changing climates. Recreation is now a primary use of TNF lands; timber management is minor. Fuels reduction is a key issue both for protection of TNF resources and of adjacent rural communities.

3.4.2 Recent and Anticipated Regional Climate Changes and Impacts

The trend of temperature increase over the 20th century for California has paralleled the global pattern (IPCC, 2007) although at greater magnitude (1.5-2°C; Millar *et al.*, 2004; Western Regional Climate Center, 2005). Precipitation has not shown strong directional changes, but has been variable at annual and interannual scales (Cayan *et al.*, 1998). Whereas multi-year droughts have been common in recent as in past centuries (National Oceanic and Atmospheric Administration, 2007), interaction of drought with increased temperature has resulted in higher stress to vegetation than under cooler climates of prior centuries. Forest insect and disease, mortality, and fire events have become more severe in TNF, as throughout the West (Logan and Powell, 2001; Westerling *et al.*, 2006). Decreases in average snowpack up to 80% are documented throughout much of the West; snowpacks peak as much as 45 days earlier (Hamlet *et al.*, 2005; Mote *et al.*, 2005) and peak streamflow peaks up to three weeks earlier in spring (Stewart, Cayan, and Dettinger, 2005) than the 1950s based on an analysis of the last 50 years.

Many of the climate and ecological trends documented for the 20th century are projected to continue and exacerbate in the 21st century. Future climate scenarios and effects on water, forests, fires, insects, and disease for California are summarized in Hayhoe et al. (2004) and the California Climate Action Team reports (California Climate Action Team, 2005). All models project increased annual temperatures over California ranging from 2.3–5.8°C (range of models to show model uncertainties). Model projections also indicate slight drying, especially in winter; interannual and interdecadal variability is projected to remain high in the next century.

Snowpacks, however, are consistently projected to decline by as much as 97% at 1,000 m elevation and 89% for all elevations. The combined effects of continued warming, declining snowpacks, and earlier stream runoff portend longer summer droughts for TNF, and increasing soil moisture deficits during the growing season. This would increase stress that an already long, dry Mediterranean summer imposes on vegetation and wildlife.

Coupling climate models with vegetation models yields major contractions and expansions in cover of dominant montane vegetation types by the late 21st century (Hayhoe *et al.*, 2004; Lenihan *et al.*, 2005). By 2070–2099, alpine and subalpine forest types are modeled to decline by up to 90%, shrublands by 75%, and mixed evergreen woodland by 50%. In contrast, mixed evergreen forest and grasslands are each projected to expand by 100%. The following conditions are expected to be exacerbated in TNF as a result of anticipated changes (Dettinger *et al.*, 2004; Hayhoe *et al.*, 2004; Cayan *et al.*, 2005):

- Increased fuel build-up and risk of uncharacteristically severe and widespread forest fire.
- Longer fire seasons; year-round fires in some areas (winter fires have already occurred).
- Higher-elevation insect and disease and wildfire events (large fires already moving into true fir and subalpine forests, which is unprecedented).
- Increased interannual variability in precipitation, leading to fuels build up and causing additional forest stress. This situation promotes fire vulnerabilities and sensitivities.
- Increased water temperatures in rivers and lakes and lower water levels in late summer.
- Increased stress to forests during periodic multi-year droughts; heightened forest mortality.
- Decreased water quality as a result of increased watershed erosion and sediment flow.
- Increased severe flood-event likelihoods.
- Loss of seed and other germplasm sources as a result of population extirpation events.

3.4.3 Current TNF Natural-Resource Policy and Planning Context

In addition to national laws and regional management directives, management goals and direction for the lands and resources of TNF are specified by several overarching planning documents (Box 3.6). These relate to different landscape scales and locations. The 1990 Tahoe National Forest Land and Resource Management Plan (LMP) (Tahoe National Forest, 1990) remains the comprehensive document for all resource management in TNF. The primary mission of TNF is to “serve as the public’s steward of the land, and to manage the forest’s resources for the benefit of all American people…[and]…to provide for the needs of both current and future generations” (Tahoe National Forest, 1990). Within this broad mission, specific goals, objectives, desired future conditions, and standards and guidelines are detailed for the following resource areas: recreation; interpretive services; visual management; cultural resources; wilderness; wildlife and fish; forage and wood resources; soil, water, and riparian areas; air quality; lands; minerals management; facilities; economic and environmental efficiency; security; human and community resources; and research.

Specific direction in the LMP has been amended by the Sierra Nevada Forest Plan Amendment (FPA; USDA Forest Service, 2004b) and the Herger-Feinstein Quincy Library Group Forest Recovery Act (U.S. Congress, 1998). The FPA is a multi-forest plan that specifies goals and direction for protecting old forests, wildlife habitats, watersheds, and communities on the 11 NFs of the Sierra Nevada and Modoc Plateau. Goals for old-growth forests focus on protection, enhancement, and maintenance of old forest ecosystems and their associated species through increasing density of large trees, increasing structural diversity of vegetation, and improving continuity of old forests at the landscape scale. A 2003 decision by the U.S. Fish and Wildlife Service to not list the California Spotted Owl as endangered was conditioned on the assumption that NFs (including TNF) would implement the direction of the FPA.

In regard to aquatic, riparian, and meadow habitat, the FPA goals and management direction are intended to improve the quantity, quality, and extent of highly degraded wetlands throughout the Sierra Nevada, and to improve habitat for aquatic and wetland-dependent wildlife species such as the willow flycatcher and the Yosemite toad.

Fire and fuels goals are among the most important in the FPA. In general, direction is given to provide a coordinated strategy for addressing the risk of catastrophic wildfire by reducing hazardous fuels while maintaining ecosystem functions and providing local economic benefits. The specific approaches to these goals are conditioned by the National Fire Plan of 2000 (USDA Forest Service, 2000c) and the Healthy Forests Restoration Act of 2003 (U.S. Congress, 2003b), which emphasize strategic placement of fuel treatments across the landscape, removing only enough fuels to cause fires to burn at lower intensities and slower rates than in untreated areas, and are cost-efficient fuel treatments.

The FPA contained a Sierra-wide adaptive management and monitoring strategy. This strategy is being implemented as a pilot project on two NFs in the Sierra Nevada, one of which includes TNF. This seven-year pilot project, undertaken via a Memorandum of Understanding between the U.S. Forest Service, the U.S. Fish and Wildlife Service, and the University of California, applies scientifically rigorous design, treatment, and analysis approaches to fire and forest health, watershed health, and wildlife. Several watersheds of TNF are involved in each of the three issue areas of the FPA adaptive management project.

The Herger-Feinstein Quincy Library Group Forest Recovery Act of 1998 provides specific management goals and direction for a portion of TNF (the Sierraville Ranger District, 164,049 ac) and adjacent NFs. The Act derived from an agreement by a coalition of representatives of fisheries, timber, environmental, county government, citizen groups, and local communities that formed to develop a resource management program to promote ecologic and economic health for certain federal lands and communities in the northern Sierra Nevada. The Act launched a pilot project to test alternative strategies for managing sensitive species, a new fire and fuels strategy, and a new adaptive management strategy. The Herger-Feinstein Quincy Library Group Pilot is the resulting project with goals to test, assess, and demonstrate the effectiveness of fuelbreaks, group selection, individual tree selection, avoidance or protection of specified areas; and to implement a program for riparian restoration.

3.4.4 TNF management and planning approaches to climate change

Management practices identified by TNF staff as being relevant to climate issues are listed below, relative to the three categories of responses described in previous sections of this report: unplanned, reactive adaptation, or no adaptation measures planned or taken; management responses reacting to crisis conditions or targeting disturbance, extreme events; and proactive management anticipating climate changes.

3.4.4.1 No Active Adaptation

Few if any of TNF's management policies or plans specifically mention or address climate or climate adaptation. Thus, while it would appear that "no adaptation" is the dominant paradigm at TNF, many practices are de-facto "climate-smart," where climatic trends or potential changes in climate are qualitatively or quantitatively incorporated into management consideration, as indicated in following sections.

3.4.4.2 Management Responses Reacting to Changing Disturbance and Extreme Events

Most post-disturbance treatments planned by TNF were developed to meet goals of maintaining ecosystem health (*e.g.*, watershed protection, succession to forest after wildfire, fuel reduction after insect mortality) rather than catalyzing climate-adaptive conditions. Nonetheless, many of these best-forest-management practices are consistent with adaptive conditioning for climate contexts as well, as the example here suggests:

Salvage and Planting Post-Fire

While in most cases the capacity cannot meet the need, TNF is able to respond adaptively on a small number of acres post-disturbance if the effort to develop NEPA documentation is adequate to defend against appeal and litigation (Levings, 2003). In these circumstances, watershed protection measures are implemented and species-site needs are considered in decisions about what and where to plant, or what seed to use.

3.4.4.3 Management Anticipating Climate Change

While TNF has not addressed climate directly through intentional proactive management, staff have been discussing climate change and climate implications for many years. This proactive thinking in itself has pre-conditioned TNF to taking climate into account in early management actions, and has started the discussion among staff regarding potential changes in strategic planning areas. Further, advances have been made in integrated planning processes that may be useful vehicles for incorporating climate-related treatments, thus pre-adapting TNF institutionally to move forward with proactive climate management. The following examples of actions and opportunities demonstrate how the TNF is moving forward with dynamic management.

Staff Support by Line Officers

The leadership team at TNF promotes broad science-based thinking and rewards adaptive and proactive behaviors. This practice clearly sets a stage where management responses to climate can be undertaken where possible, providing an incentive and the intellectual environment to do so.

Fireshed Assessment

The new Fireshed Assessment process is a major step toward integrated management of TNF lands. Effective implementation of this process already provides a vehicle for other dynamic and whole-landscape planning processes such as are needed for climate adaptation.

Fuel Reduction Projects

Strategies implemented by TNF as a result of FPA and Herger-Feinstein Quincy Library Group Pilot directions to reduce fuels and minimize chances of catastrophic fires are increasing the adaptability and resilience of TNF forests (Fig. 3.14). Strategically placed area treatments, a form of adaptive and dynamic approach to fuel management, are being tested on the adaptive management pilot of TNF.

Figure 3.14. Thinned stands for fuel reduction and resilience management, part of the Herger-Feinstein Quincy Library Pilot Project. Photo courtesy of Tahoe National Forest.

Riparian Management Policies

New policies in the FPA for riparian and watershed management restrict road construction for timber management (*e.g.*, near or across perennial streams). Helicopters are used for logging in all situations where roads cannot be built. This allows more flexibility, adaptability, and reduces fragmentation and watershed erosion.

Post-Event Recovery

While certain kinds of standardized post-fire restoration practices (*e.g.*, Burned Area Emergency Rehabilitation procedures) are not climate-proactive, a post-event recovery team at the Pacific Southwest regional level is investigating dynamic approaches to recovery post-major disturbance. These approaches might include planning for long-term changes on disturbed sites and taking advantage of new planting mixes, broadening gene pool mixes, planting in new spacing and designs, etc.

Revegetation and Silvicultural Choices

In stand improvement projects and revegetation efforts, choices are being considered to favor and/or plant different species and species mixes. For instance, where appropriate based on anticipated changes, white fir could be favored over red fir, pines would be preferentially harvested at high elevations over fir, and species would be shifted upslope within seed transfer guides.

Forest Plan Revision

The TNF LMP is due for revision. Climate considerations are being evaluated as the plan revision unfolds, including such options as flexible spotted owl (*Strix occidentalis occidentalis*) "Protected Activity Center" boundaries, species shifts in planting and thinning, and priority-setting for sensitive-species management.

Resisting Planned Projects That May Not Succeed Under Future Climate Conditions

Restoring salmon to TNF rivers is a goal in the current LMP (Fig. 3.15). With waters warming, however, future conditions of TNF rivers are not likely to provide suitable habitat for salmon. Thus, TNF is considering the option to not restore salmon. Meadow restoration is another example: Rather than proceeding with plans for extensive and intensive meadow restoration, some areas are being considered for non-treatment due to possible succession of non-meadow conditions in these locations.

Figure 3.15. Former salmon habitat (rivers marked in bold black) of the Sierra Nevada. Tahoe National Forest (TNF) rivers are scheduled to have salmon restored to them in current national forest planning. Adaptive approaches suggest that future waters may be too warm on the TNF for salmon to survive, and thus, restoration may be inappropriate to begin. Map adapted from (Sierra Nevada Ecosystem Project Science Team, 1996).

Resilience Management

All forms of proactive management that improve the resilience of natural resources are improving the adaptiveness of TNF by decreasing the number of situations where TNF must take crisis-reaction responses.

Dynamic Management

TNF staff is using opportunities available at present (*i.e.*, under current policy) to manage dynamically and experimentally. An example is cases in which plans treat critical species' range margins differently, favoring active management at advancing edges or optimal habitat rather than static or stressed margins.

Managing for Process

TNF staff is also using opportunities available at present to manage for process rather than structure or composition in proposed projects; for example, those involving succession after fires, where novel mixes of species and spacing may reflect likely natural dynamic processes of adaptation.

3.4.5 Proactive Management Actions Anticipating Climate Change

3.4.5.1 Examples of Potential Future Proactive Management Actions

The ideas listed below were identified by TNF staff as being examples of how management actions could be leveraged in the future to increase the TNF adaptive responses to climate change.

- Rapid assessments of current planning and policy. A science-based (*e.g.*, U.S. Forest Service research team) rapid assessment or "audit" of existing TNF planning documents (*e.g.*, the LMP and project plans) could focus on the level of climate adaptedness, pitfalls, and areas for improvement in current TNF plans and operations. Such an audit could focus on current management direction (written policy); current management practices (implementation); and priorities of species (*e.g.*, specific targeted species) and processes (fire, insects/disease). The audit would highlight concrete areas of the plans and projects that are ill-adapted as well as those that are proactive and already climate-proactive, and would recommend a set of specific areas where changes are needed and improvements could be made.

- Assessment/audit of the Sierra Nevada FPA. This would be a similar assessment to that above, but would be undertaken at the FPA scale. The FPA did not originally include climate, and the science consistency review highlighted this problem. A more comprehensive assessment of the FPA's strengths and weaknesses is needed, with a call for revision as appropriate.

- TNF as a pilot for the U.S. Forest Service Ecosystem Services program. Tapping into the ecosystems services market opportunities and acting as a pilot national forest within the ecosystems services goals and objectives may provide management flexibility needed for climate adaptation.

- Management unit size. Increase sizes of management units on the forest, so whole landscapes (watersheds, forest types) could be managed in a single resource plan; decrease administrative fragmentation. Whole ecosystem management, rather than piecemeal by small management unit or by single species or single issue, would favor adaptability to climate-related challenges.

- Watershed management; water storage. To increase groundwater storage capacities, treatments to improve infiltration could be implemented. For instance, in TNF, consider decreasing road densities and other activities (evaluate grazing) in order to change surfaces from impervious to permeable.

- Watershed management; salvage harvest. To decrease erosion and sediment loss following disturbance, there is widespread need in TNF to salvage-harvest affected trees and reforest soon after disturbance. This is the plan at present, but mostly cannot be implemented in adequate time due to time required for NEPA processing and general public opposition.

- Event recovery. Post-disturbance mortality and shrub invasion must be dealt with swiftly to keep options open for forest regeneration on the site. The means are known; the capacity (money, legal defense) is needed.

3.4.6 Barriers and Opportunities to Proactive Management for Climate Change at TNF

3.4.6.1 Barriers

The situations listed below were identified by TNF staff as barriers that limit TNF's capacity to respond adaptively to climate change.

- Public opposition. Appeals and litigation of proposed active management projects directly restrict ability of TNF to implement adaptive practices (Levings, 2003). There is a large public constituency that opposes active management of any kind. Thus, no matter the purpose, if adaptive management proposals involve on-the-ground disturbance, these publics attempt to prohibit their implementation. The likelihood of appeals and litigation means that a large proportion of staff time must necessarily be used to develop "appeal-proof" NEPA documents, rather than undertaking active management projects on the ground. This often results in a situation in which no-management action can be taken, regardless of the knowledge and intent to implement active and adaptive practices.

- Funding. Overall lack of funds means that adaptive projects, while identified and prioritized, cannot be implemented. General funding limitations are barriers throughout TNF operations. The annual federal budget process limits capacity to plan or implement long-term projects.

- Staff capacity. Loss of key staff areas (*e.g.*, silviculture) and general decline in resource staff and planning capacity translate to lower capacity to respond adaptively to needed changes.

- Scope of on-the-ground needs. As a result of legacy issues (fire-suppression, land-use history, etc.), as well as responses to changing climates (increasing densification of forests, increasing forest mortality), the area of land needing active management is rapidly escalating, and far exceeds staff capacity or available funds to treat it.

- Crisis reaction as routine planning approach. Inadequate TNF funding and staff capacity, combined with persistent legal opposition by external publics, force a continuous reactive approach to priority-setting. This results in crisis-management being the only approach to decision-making that is possible, as opposed to conducting or implementing long-term, skillful, or phased management plans.

- Checkerboard ownership pattern. The alternating sections of TNF and private land create barriers to planning or implementing landscape-scale management, which is needed for adaptive responses to climate challenges. Achieving mutually agreeable management goals regarding prescribed fire, road building, fire suppression, post-fire recovery, and many other landscape treatments is extremely difficult; thus, often no management can be done. This is especially challenging in the central part of TNF, where important corridors, riparian forests, and continuous wildlife habitat would be actively enhanced by management, but cannot be due to mixed ownership barriers.

- Existing environmental laws. Many current important environmental laws that regulate national forest actions such as the Endangered Species Act, the National Forest Management Act, and the National Environmental Policy Act are highly static, inhibit dynamic planning, and impede adaptive responses (Levings, 2003). Further, these laws do not allow the option of not managing any specific situation—such choices may be necessary as triage-based adaptation in the future. Finally, while coarse-filter approaches are more adaptive, many existing laws force a fine-filter approach to management.

- Current agency management concepts and policies. Current agency-wide management paradigms limit capacity to plan in a proactive, forward-looking manner. For instance, the policies requiring use of historic-range-of-variability or other historic-reference approaches for goal-setting restrict dynamic, adaptive approaches to management. This problem was identified in vegetation management, dam construction (“100-year” flood references), and sensitive-species management (owls, salmon). Certain current regional policies and procedures limit adaptive responses. An example is the Burned Area Emergency Rehabilitation approach to post-fire rehabilitation. Burned Area Emergency Rehabilitation is a static and short-term set of practices that does not incorporate the capacity to respond flexibly and adaptively post-fire, such as taking actions to actively move the site in new ecological trajectories with different germplasm sources and different species mixes.

- Static management. Other current management paradigms that limit dynamic planning and managing include the focus on "maintaining," "retaining," and "restoring" conditions. The consequence of these imperatives in planning documents is to enforce static rather than dynamic management.

- Air quality standards. Regional regulatory standards for smoke and particulates are set low in order to optimize air quality. These levels, however, limit the capacity of TNF to conduct prescribed fires for adaptive fuel reduction or silvicultural stand treatment purposes.

- Community demographics and air quality/urban fuels. Changing demographics of foothill Sierran communities adjacent to TNF are moving toward less acceptance of smoke. Older and urban residents moving into the area in the past few years have little experience with fire and its effects, and have little understanding of or tolerance for smoke from prescribed fire treatments. Similarly, these residents are not apt to subscribe to Fire-Safe Council home ownership/maintenance recommendations, thus putting their homes and landscaping at high risk from wildfire.

- Agency target and reward system. The current system at the national agency level for successful accomplishments (*i.e.*, the reward system) focuses on achieving narrowly prescribed targets ("building widgets"). Funds are allocated to achieving targets; thus simplistic, in-the-box thinking, and routine, easily accomplished activities are encouraged. There are few incentives for creative project development or implementation.

- Small landscape management units. Fragmentation and inflexibility result from partitioning TNF into small management units; small unit sizes also restrict the capacity for full understanding of ongoing dynamics and process. For instance, even the adaptive management pilot projects under the FPA are too small to be meaningful under the conditions anticipated in the future—at least 20,000 acres are needed.

3.4.6.2 Opportunities

The activities listed below were identified by TNF staff as current or potential future opportunities to enhance managers' ability to proactively manage for climate change, some of which are currently employed at TNF.

- Year-round management opportunities. TNF is experiencing later winters (snow arriving later in the year), lower snowpacks, and earlier runoff. The TNF staff has taken advantage of these changes by continuing fuel treatments far beyond the season where historically these treatments could be done. At present, winter-prescribed fires are being undertaken, and conditions are ideal to do so. This enables treating more acres in adaptive practices than could be done if only summer were available for these management activities.

- Responses to public concerns through active dialog. TNF has effectively maintained a capacity to implement adaptive projects when in-depth, comprehensive analysis has been done on NEPA process. In addition, intensive education of the interested publics through workshops, scoping meetings, face-to-face dialog, and informal disposition processes have helped to develop support for plans (avoiding appeal), and thus these activities are enabling TNF's adaptive projects to be conducted.

- Responses to public concerns by demonstration. Specifically, TNF was able to gain public approval to cut larger-diameter classes (needed for active management to achieve dynamic goals) than had been previously acceptable, through the use of 3-D computer simulations (visualizations), on-the-ground demonstration projects, "show-me" field trips, and other field-based educational efforts.

- Emerging carbon markets are likely to promote the (re-)development of regional biomass and biofuels industries. These industries will provide economic incentives for active adaptive management, in particular funds to support thinning and fuel-reduction projects.

- Planning flexibility in policy. The existence of the Herger-Feinstein Quincy Library Group Pilot and the FPA Adaptive Management project on TNF mean that there is more opportunity than in most other Sierra Nevada NFs to implement active management, especially at broader landscape scales.

- New staff areas defined. When capacity to add staff arises, new positions (climate-smart) may be added. Through incremental changes in staff, TNF may "reinvent and redefine" its institutional ability to better respond adaptively to novel challenges.

- Public education. There is an opportunity to further educate the local public about the scientific bases for climate change, the implications for the northern Sierra Nevada and TNF, and the need for active resource management.

3.4.7 Increasing Adaptive Capacity to Respond to Climate Change

The ideas listed below were identified by TNF staff as being scientific, administrative, legal, or societal needs that would improve the capacity to respond adaptively to climate change challenges.

- New management strategies. Operationally appropriate and practical management strategies to address the many challenges and contexts implied by changing climates are needed.

- Scientifically supported practices for integrated management. Integration of resource management goals (*e.g.*, fuels, sensitive species, water, fire) rather than partitioning tasks into individual plans is already a barrier to effective ecosystem management. Changing climates are anticipated to increase the need for integration and integrated plans. Input from the science community on integrated knowledge, synthesis assessments, and toolboxes for integrated modeling, etc. will improve the capacity to respond adaptively.

- Projections and models. Modeled simulations of future climate, vegetation, species movements; rates of changes of all of these; and probabilities/uncertainties associated with the projections are needed.

- Case studies. Case studies of management planning and practices implemented as adaptive responses to climate are needed. Demonstration and template examples would allow ideas to disseminate quickly and be iteratively improved.

- Prioritization tools for managing a range of species and diverse ecosystems on TNF. Given the large number of species in the forest, it is impossible to manage all of them. Thus, new tools for adaptive decision-making are needed, as well as development of strategic processes to assist effective prioritizing of actions.

- Dynamic landscape and project planning. Scientific assistance is needed to help define targets and management goals that are appropriate in a changing climate context. Additional work on probabilistic management units, ranges of conditions likely, continuingly variable habitat probabilities, and habitat suitability contour mapping would be useful. Management planning guidelines that allow rules to change adaptively as conditions change need to be developed.

- Scientific clearinghouse on climate information. In high demand is a reference/resource center, such as a website, with current and practical climate-related material. To be useful at the scale of individual forests such as TNF, the information needs to be locally relevant, simply written, and presented in one clear, consistent voice.

- Scientific support and assistance to individual and specific TNF proposed actions. A consistent, clear voice from science is needed to help build the most appropriate and adaptive plans and actions. There is also a need for clear scientific evidence that demonstrates both the appropriateness of proposed TNF actions and the problems that would result from no action. A website could include such information as brief and extended fact sheets, regional assessments, archives of relevant long-term data or links to other websites with climate-relevant data, model output and primers (climate-relevant ecological, economic, and planning models), training packages on climate change that can be delivered through workshops and online tutorials, and access to climate-based decision-support tools.

- Seed banks. Seed banks need to be stocked to capacity as buffer for fire, insects and disease, and other population extirpation events.

3.5 Case study: Olympic National Forest

3.5.1 Setting and Context of the Olympic National Forest

3.5.1.1 Biogeographic Description

The Olympic Peninsula, in western Washington State (Fig. 3.16), consists of a mountain range and foothills surrounded by the Pacific Ocean (west); the Strait of Juan de Fuca (north); Puget Sound (east); and low elevation, forested land (south). Its elevation profile extends from sea level to nearly 2,500 m at Mount Olympus in the Olympic Mountains. The range creates a strong precipitation gradient, with historic precipitation averages of about 500 cm in the lowlands of the southwestern peninsula, 750 cm in the high mountains, and only 40 cm in the drier northeastern lowlands. The climate is mild temperate rainy, with a Mediterranean (dry) summer. Most of the precipitation falls in winter and at higher elevations; nearly all of it is snow that persists well into summer. The resulting biophysical landscape is a diverse array of seasonal climates and ecological conditions, including coastal estuaries and forests, mountain streams and lakes, temperate rainforests, alpine tundra, mixed conifer forests, and prairies.

Figure 3.16. Olympic Peninsula land ownership and Northwest Forest Plan allocation map. Olympic National Forest contains lands (dark boundary) with different land use mandates and regulations. These include adaptive management areas, late-successional reserves, and Wilderness areas. Map courtesy of Robert Norheim, Climate Impacts Group, University of Washington.

The ecosystems on the peninsula are contained within a mosaic of federal, state, tribal, and private ownership. Olympic National Forest (ONF), comprising ~257,000 ha (including five wilderness areas), surrounds Olympic National Park (ONP, ~364,000 ha), the core of the peninsula. ONP is both a World Heritage Site and an International Biosphere Reserve. There are 12 Native American tribes on the peninsula. Approximately 3.5 million people live within four hours' travel of the ONF, and the east side is considered an urban forest because of its proximity to the cities of the greater Seattle area. Ecosystem services from ONF are notably diverse and include water supply to several municipal watersheds, nearly pristine air quality, abundant fish and wildlife (including several unique/endemic species of plants and animals, such as the Olympic marmot and the Roosevelt elk, as well as critical habitat for four threatened species of birds and anadromous fish), recreation, and a substantially reduced timber economy following implementation of the Northwest Forest Plan amendment (NWFP) to the Olympic National Forest Plan. Hereafter, reference to the Olympic National Forest Plan (ONFP) refers to the 1990 Olympic National Forest Plan, as amended by the NWFP in 1994 (Box 3.1).

Managing ONF lands therefore requires consideration of complex geographical, climatological, ecological, and sociocultural issues. Climatic change is likely to influence the factors responsible for the Olympic Peninsula's diversity and biogeography, and numerous stakeholders and land management mandates will need to adapt to those changes to protect the natural and cultural resources on the Peninsula.

3.5.2 Recent and Anticipated Climate Change and Impacts

The Pacific Northwest has warmed approximately 1°C since 1920; most of this warming (0.9°C) has been since 1950, and winter has warmed faster than summer (Mote, 2003). The trend in annual precipitation is less clear, though most sites show an increase between 1920 and 2000; decadal variability, rather than trends, best characterizes the region's 20th century precipitation (Mote, 2003). However, the winter temperature increase has caused the form of winter precipitation to change at mid- and low- elevation sites, and 30–60% declines in April 1 snow water equivalent have been observed in the Olympics and Cascade Range (Mote *et al.*, 2005). The timing of spring runoff was 10–30 days earlier in 2000 compared with 1948 (Stewart, Cayan, and Dettinger, 2004).

Proxy records indicate that climatic variability has affected ecological processes on the Olympic Peninsula for millennia (Heusser, 1974; Gavin *et al.*, 2001). For example, pollen spectra from subalpine lakes in the Olympics indicate common responses after the retreat of Pleistocene glaciers, divergent vegetation in the early Holocene, and convergent responses in the late Holocene (McLachlan and Brubaker, 1995). More recently, tree growth for many lower elevation species increased with water supply and decreased with high summer temperatures (Ettl and Peterson, 1995; Nakawatase and Peterson, 2006). A common lesson from both paleo and modern studies is that, for a given regional shift in climate, the ecological and climatic context of a particular site determines the degree and nature of the response (Holman and Peterson, 2006)—so much so that high versus low elevations and the wet versus the dry side of the Olympics may have very different responses to a uniform climatic change.

Hydrological resources also respond to climate. The timing, duration, and magnitude of stream runoff depend on the abundance of winter snowpack and winter-to-spring temperatures. The Olympic Mountains mirror regional patterns of decadal climatic variability and trends in climatic change. During the 20th century, snowpacks were smaller (especially at low elevations), temperatures were warmer (especially minimum temperatures), and precipitation varied significantly with the fluctuations of the Pacific Decadal Oscillation. Regional anadromous fish populations (Mantua *et al.*, 1997), tree growth (Peterson and Peterson, 2001), glacier mass balance (Bitz and Battisti, 1999), and forest fire activity (Mote, Keeton, and Franklin, 1999); (Littell, 2006) have responded to these changes.

Predictions of future climate for the Pacific Northwest are uncertain because of uncertainty about future fossil fuel emissions, global population, efficacy of mitigation, and the response and sensitivity of the climatic system. However, by comparing a range of scenarios and models for future events, climate modelers can estimate future climatic conditions. Regional climate models suggest an increase in mean temperature of 1.2–5.5°C, with a mean of 3.2°C by 2090 (Salathé, Jr., 2005). Summer temperatures are projected to increase more than winter temperatures. Precipitation changes are less certain due to large natural variability, but slight increases in annual and winter precipitation are projected, while slight decreases in summer precipitation are possible (Salathé, Jr., 2005).

Projected changes in temperature and precipitation would lead to lower snowpacks at middle and lower elevations, shifts in timing of spring snowmelt and runoff, and increases in summer evapotranspiration (Mote *et al.*, 2005; Hamlet *et al.*, 2007). Runoff in winter (October to March) would increase, and summer runoff (April to September) would decrease (Hamlet *et al.*, 2007). For basins with vulnerable snowpack (*i.e.*, mid-elevations), streamflow would increase in winter and decrease in summer. Higher temperatures and lower summer flows would have serious consequences for anadromous and resident fish species (salmon, steelhead, bull trout). Floods may increase in frequency because the buffering effect of snowpacks would decrease and because the severity of storms is projected to increase (although less snow can decrease the maximum impacts of rain-on-snow events due to lower water storage in snow). Sea level rise would exacerbate flooding in coastal areas. Some effects, especially the timing of snowmelt and peak streamflow, are likely to vary substantially with topography.

Increased summer temperature may lead to non-linear increases in evapotranspiration from vegetation and land surfaces (McCabe and Wolock, 2002). This, in turn, would decrease the growth (Littell, 2006; Nakawatase and Peterson, 2006), vigor, and fuel moisture in lower elevation (*e.g.*, Douglas-fir and western hemlock) forests while increasing growth (Ettl and Peterson, 1995; Nakawatase and Peterson, 2006) and regeneration in high elevation (*e.g.*, subalpine fir and mountain hemlock) forests (Woodward, Schreiner, and Silsbee, 1995). Higher temperatures would also affect the range and decrease generation time of climatically limited forest insects such as the mountain pine beetle (Logan, Regniere, and Powell, 2003), as well as increase the area burned by fire in ecoprovinces of western Washington and Oregon ecoprovinces (Littell, 2006).

The distribution and abundance of plant and animal species would change over time (Zolbrod and Peterson, 1999), given that paleoecological data show this has always been a result of climatic variability in the range projected for future warming. This change may be difficult to observe at small scales, and would be facilitated in many cases by large-scale disturbances such as fire or windstorms that remove much of the overstory and “clear the slate” for a new cohort of vegetation. The regeneration phase will be the key stage at which species will compete and establish in a warmer climate, thus determining the composition of future vegetative assemblages and habitat for animals.

Thus, ecosystem services in ONF are likely to be affected by climatic change. Water quality for threatened fish species may decline as temperatures increase and, potentially, as increasing storm intensity causes road failures. Water quantity may decline in summer when it is most needed, as streamflow timing shifts with temperature changes. Air quality will decline if drought frequencies or durations increase and cause increased area burned by fire. The influence of climate change on habitat for threatened species is less certain, but high elevation and currently rare species would be more vulnerable (*e.g.*, Olympic Marmot, bull trout, whitebark pine).

3.5.3 Current ONF Policy Environment, Planning Context and Management Goals

Current natural resources management issues in ONF stem primarily from policy mandates, historical land use and forest fragmentation, and the multi-agency checkerboard of land ownership on the peninsula (Fig. 3.16). ONF is a “restoration forest” charged with managing large, contiguous areas of second-growth forest. Objectives include: (1) managing for native biodiversity and promoting the development of late-successional forests (*e.g.*, NWFP), (2) restoring and protecting aquatic ecosystems from the impacts of an aging road infrastructure, and, (3) managing for individual threatened and endangered species as defined by the Endangered Species Act (ESA) or other policies related to the protection of other rare species.

Most ONF natural resources management activities are focused on restoring important habitats (*e.g.*, native prairies, old-growth forests, pristine waterways), rehabilitation or restoration of impacts related to unmaintained logging roads, invasive species control, and monitoring. Collaboration with other agencies occurs, and is a cornerstone of the NWFP. Without clear consensus on climate change, cross-boundary difficulties in solving problems may arise due to differing mandates, requirements, and strategies, but there is no evidence that this is currently a problem.

Planning guidelines for ONF are structured by mandates from the National Forest Management Act (NFMA) and the NWFP. ONF planning is affected by NEPA because it is a time- and resource-intensive process. The ONF forest plan (to be revised in the future in coordination with other western Washington NFs) is influenced by the NWFP as well as regional Forest Service policy. Planning also is influenced by comments from the public served by ONF. NEPA planning is carried out at a site-specific level, so incorporating regional climatic change information into Environmental Assessment/Environmental Impact Statement documents can be difficult because assessment takes place at the site scale, while there is still substantial uncertainty surrounding climate change predictions—especially precipitation—at sub-regional scales.

Adaptation to climatic change is not yet addressed formally in the ONFP or included in most management activities. With respect to climate change, current management objectives are essentially to attempt to confer resilience by promoting landscape diversity and biodiversity. To this end, tools available to ONF managers include restoration of aquatic systems (especially the minimization of the impacts of roads, bridges, and culverts); active management of terrestrial systems (through thinning and planting); and, increasingly, treatment of invasive species. Prescribed fire and wildland use fire are unlikely tools because of the low historical area burned, limitations of the Clean Air Act, and low funding levels. The range of strategies and information in using these tools varies across ONF land use designations. Late-successional reserves and wilderness have less leeway than adaptive management areas, because there are more explicit restrictions on land use and silvicultural treatment. Second-growth forests are managed primarily with thinning, and silvicultural treatments have been used to create 0.5–2 ha “openings” for the benefit of elk. However, ONF has funding to treat only ~600 ha per yr, and the forest has initiated a strategic plan to maximize the efficacy of treatments that do occur.

3.5.4 Proactive Management Actions Anticipating Climate Change

ONF’s policy and regulatory environment encompasses a great deal of responsibility, but little scientific information or specific guidance is available to guide adaptation to climatic change. The scope of possible adaptation, clear strategies for successful outcomes, and the tools available to managers are all limited. Under current funding restrictions, most tools would need to be adapted from management responses to current stresses (Table 3.2). Future impacts on ecological and socioeconomic sensitivities can result in potential tradeoffs or conflicts. For example, currently threatened species may become even more rare in the future (*e.g.*, bull trout, spotted owl, marbled murrelet, Olympic marmot) due to stress complexes, undermining the likelihood of successful protection. Another example is when short-term impacts must be weighed against long-term gains. Fish species may be vulnerable to failures of unmaintained, closed roads caused by increased precipitation/storminess, but road rehabilitation may produce temporary sedimentation and may invite invasive weeds. Ideally, triage situations could be avoided, but in the face of climate change and limited resources it may be necessary to prioritize management actions with the highest likelihood of success, at the expense of actions that divert resources and have less-certain outcomes.

Generally, success of adaptation strategies should be defined by their ability to reduce the vulnerability of resources to a changing climate while attaining current management goals. Effective strategies include prioritizing treatments with the greatest likelihood of being effective (resources are too limited to do otherwise) and recognizing that some treatments may cause short-term detrimental effects but have long-term benefits. For structures, using designs and engineering standards that match future conditions (*e.g.*, culvert size) will help minimize future crises. Specific strategies likely to be used in ONF terrestrial ecosystems are to increase landscape diversity, maintain biological diversity, and employ early detection/rapid response for invasive species.

Landscape diversity can be achieved by: (1) targeted thinning (increases diversity, can decrease vulnerability by increasing tree vigor, and can reduce vulnerability to disturbance); (2) avoiding a "one size fits all" toolkit, and using a variety of treatments even if new prescriptions are required; (3) creating openings large enough for elk habitat, but small enough to minimize invasive exotics; (4) considering preserves at many elevations, not just high-elevation wilderness; and (5) considering "blocking" ownerships (land trades) to reduce edges, maintain corridors, and consolidate habitat.

Biological diversity may be maintained by: (1) planting species in anticipation of climate change—using different geographical locations and nursery stock from outside current seed zones; (2) maintaining within-species diversity; and (3) providing corridors for wildlife. However, there must be credible rationale for decisions to use seed and seedlings other than local native plant species.

Early detection/rapid response focuses on solving small problems before they become large, unsolvable problems, and recognizes that proactive management is more effective than long delays in implementation. For example, the ONF strategic plan recognizes that invasive species often become established in small, treatable patches, and are best addressed at early stages of invasion. Although designed for other problems like invasives, it is also appropriate for climate change because it could allow managers to respond quickly to the impacts of extreme events (disturbances, floods, windstorms) with an eye toward adaptation.

Large-scale disturbance can cause sudden and major changes in ecosystems, but can be used as occasions to apply adaptation strategies. ONF is currently climatically buffered from chronic disturbance complexes already evident in drier forests, but age-class studies and paleoproxy evidence indicate that large-scale disturbances occurred in the past. For comparison, fire suppression and harvest practices in British Columbia played a role in the current pine beetle outbreak by homogenizing forest structure over very large areas. In ONF, the amount of young forest (as a result of 20th century harvest) is both a risk (hence ONF's "restoration" status) and an opportunity. Large disturbances that may occur in the future could be used to influence the future structure and function of forests. Carefully designed management experiments for adapting to climatic change could be implemented. There is a clear need to have concepts and plans in place in anticipation of large fire and wind events, so that maximum benefit can be realized.

Information and tools needed to assist adaptation are primarily a long-term, management-science partnership with decision-specific scientific information. ONF relayed a critical request of scientists: natural resource managers need a manager's guide with important scientific concepts and techniques. Critical gaps in scientific information hinder adaptation by limiting assessment of risks, efficacy, and sustainability of actions. Managers would also like assistance and consultation on interpreting climate and ecosystem model output so that the context and relevance of model predictions can be reconciled with managers' priorities for adaptation. Managers identified a need to determine effectiveness of prevention and control efforts for invasive species; monitoring is critical (and expensive). There is a strong need for data on genetic variability of key species, as well as recent results of hydrologic modeling relative to water supply, seasonal patterns, and temperature. In contrast, managers pointed out that ONF collects data on a large array of different topics, many of them important, but new data collection should be implemented only if it will be highly relevant, scientifically robust, and inform key decisions.

3.5.5 Opportunities and Barriers to Proactive Management for Climate Change on the ONF

An important opportunity for adapting to climatic change at the regional scale is the coordinated development of forest plans among ONF, Mt. Baker-Snoqualmie National Forest, and Gifford Pinchot National Forest. The target date for beginning this forest planning effort is 2012. The effort would facilitate further cooperation and planning for adaptation in similar ecosystems subject to similar stressors. ONF has implemented a strategic plan that has similar capacity for guiding prioritization and can incorporate climatic change elements now, rather than waiting for the multi-forest plan effort. However, by explicitly addressing resilience to climatic change (and simultaneously developing any science needed to do so) in the ONFP, ONF can formalize the use of climate change information in management actions.

A second, related opportunity is to integrate climatic change into region-wide NWFP guidelines that amended Pacific Northwest forest plans. The legacy of the 20th century timber economy in the Pacific Northwest has created ecological problems, but also opportunities (Fig. 3.17). Landscapes predominately in early seral stages are more easily influenced by management actions, such as targeted thinning and planting, than are late seral forests, so there is an opportunity to anticipate climate change and prepare for its impacts with carefully considered management actions. By recognizing the likely future impacts of climatic change on forest ecosystems (such as shifts in disturbance regimes), the revised forest plans can become an evolving set of guidelines for forest managers. Specifically, will the NWFP network of late successional reserves remain resilient to climatic change and its influence on disturbance regimes? Are there specific management practices in adaptive management areas that would change given the likely impacts of climatic change?

Sometimes, collaboration among multiple organizations is an underutilized opportunity. ONF staff believe that the "stage is set" for continued and future collaboration among organizations and agencies on the Olympic Peninsula. Climatic change and ecosystems do not recognize political boundaries, and significant adaptive leverage can be gained by cooperation. Initiatives by coalitions and partnerships can include climatic change (*e.g.*, the Puget Sound Partnership) and are conducive to an environment in which adaptation actions are well supported. In some cases, working with other agencies can improve the likelihood of success by increasing overall land base and resources for addressing problems.

Major barriers to adaptation are (1) limited resources, (2) policies that do not recognize climate change as a significant problem or stressor, and (3) the lack of a strong management-science partnership. National and regional budget policies and processes are significant barriers to adaptation, and represent a constraint on the potential for altering or supplementing current management practices to enable adaptation to climate change. Current emphasis on fire and fuel treatments in dry forest systems has greatly reduced resources for stand density management, pathogen management, etc. in forests that do not have as much fire on the ground but may, in the future, be equally vulnerable. Multiple agency collaboration can be difficult because of conflicting legislation, mandates, and cultures, but such collaboration is likely to be a hallmark of successful adaptation to climatic change. Certainly increased collaboration between scientists and managers could streamline the process of proposing testable scientific questions and applying knowledge to management decisions and actions.

Policies, laws, and regulations that are based on a more static view of the environment do not consider the flexibility required to adapt to changing conditions outside historical observations. The NFMA puts limitations on management actions, and NEPA delays implementation of actions. The ESA requires fine-scale management for many imperiled species, which may be unrealistic in a rapidly changing climate. Given the projected future rate of climate change and the resource limitations for land management agencies, it may be more sustainable and a more efficient use of funding to protect systems and landscape diversity than to plan for and protect many individual species. The NWFP partially embraces this strategy, but does not focus specifically on climate change. The Clean Water Act could become an important barrier in the future as stream temperatures increase; this may result in unattainable standards that constrain management actions. NEPA, the ESA, the Clean Water Act, and the NWFP all focus on historical reference points in comparatively static environments, but climate change warrants looking to future impacts and the need for preparation.

Future barriers to adaptation may arise with the interaction of current policy restrictions and the potential need to adapt to climatically mediated changes in ecosystem processes. One example is the potential for using wildland fire for the benefit of forest ecosystems, which is not currently an authorized management tool on ONF. The benefits of wildland fire use (likely limited in ONF to natural ignitions within wilderness areas) would need to be weighed against the cost of authorization. Authorization to use this tool in the short term would require a Forest Plan amendment and associated NEPA process. A less costly but longer-horizon alternative is to include wildland fire use in the 2012 Forest Plan revision effort. Benefits would be limited to wildland fire use that could be approved within the confines of the ESA and other regulations.

Olympic National Park recently completed a fire management plan that authorizes wildland fire use, but has restrictions related to ESA requirements. For ONF the role of wildland fire use in management would also be limited by the ESA and the adjacency of non-federal land concerns.

3.5.6 Increasing the Adaptive Capacity to Respond to Climate Change

The ecosystem stressors ONF manages for currently (Table 3.2) are likely to be exacerbated by climatic change, but little work has focused on quantifying the direct linkages between the climate system and future ecosystem services on the Olympic Peninsula. Resilience to climate change is therefore only describable qualitatively. Past timber harvest has resulted in a very large area of lower-elevation forest consisting of second growth, in an ecosystem that was characterized by resilient old growth. This landscape homogenization has occurred in other forest types, and, at least in theory, results in less resilience to climate-mediated disturbances. However, such characterization is at the moment speculative. Aquatic ecosystems are probably less resilient, and measuring resilience there is similarly underdeveloped.

The primary conclusions of this case study are:

1. Climate change and its impacts are identifiable regionally, and adaptation to climate change is necessary to ensure the sustainability of ecosystem services.
2. ONF management priorities (Table 3.2) are consistent with adaptation to climatic change and promoting resilience to the impacts of climate change. However, available resources do not allow adaptation at sufficient scale. Moreover, scientific uncertainty remains about the best adaptation strategies and practices.
3. The current political and regulatory contexts limit adaptive capacity to current and future climatic changes by:
    a. failing to incorporate climatic change into policy, regulations, and guidelines;
    b. requiring lengthy planning processes for management actions, regardless of scope; and
    c. adopting priorities and guidelines that are not clear in intent and/or consistently applicable at national, regional, and forest levels.
4. These limitations can be overcome by:
    a. developing a manager’s guide to climate impacts and adaptation;
    b. developing an ongoing science-management partnership focused on climate change;
    c. incorporating climatic change explicitly into national, regional, and forest-level policy;
    d. re-examining the appropriateness of, and regulations on, management actions in the context of adaptation to climatic change;
    e. creating clear, consistent priorities and regulations that provide guidance but allow for local/forest level strategies and management actions that increase resilience and reduce vulnerability to climatic change;
    f. allocating resources sufficient for adaptation; and
    g. increasing educational and outreach efforts to promote awareness of climate change impacts on ecosystem services.

ONF is at a crossroads. The effects of climatic change on forest ecosystems and natural resources are already detectable. Adapting to those changes and sustaining ecosystem services is an obvious and urgent priority, yet adaptive capacity is limited by the policy environment, current allocation of scarce resources, and lack of relevant scientific information on the effects of climate change and, more crucially, on the likely outcomes of adaptive strategies. Adaptive management is one potential strategy for learning how to predict, act on, and mitigate the impacts of climatic change on a forest ecosystem, but if there is no leeway for management actions or those actions must occur quickly, then adaptation options are limited in the current environment. ONF staff indicated that if they were managing for climate change, given what they know now and their current levels of funding and personnel, they would continue to emphasize management for biodiversity. It is possible, for example, that they might further increase their current emphasis on restoration and diversity. Another possible change, reminiscent of the earlier Forest Service priorities, would be to emphasize the role of forests as producers of hydrological commodities.

Key components of adaptation will be to (1) develop a vision of what is needed and remove as many barriers as possible; (2) increase collaboration among agencies, managers, and scientists at multiple scales; and (3) facilitate strategies (such as early detection/rapid response) that are proven to work. A functional forest ecosystem is most likely to persist if managers prioritize landscape diversity and biological diversity. Equally certain is that management actions should not, in aggregate, lead to the extirpation of rare species. Clear and consistent mandates, priorities, and policies are needed to support sustainability of ecosystem services in the face of a warmer climate and changing biophysical conditions.

We envision a future in which the policy, planning, and scientific aspects of ecosystem-based management co-evolve with changes in climate and ecosystems. This vision requires trust, collaboration, and education among policy makers, land managers, and scientists as well as the publics they serve. Climate will continue to change, effects on ecosystems will be complex, and land managers will struggle to adapt to those changes with limited resources. Collaboration with scientists is certain to produce information that relates directly to on-the-ground decision making. Less certain is how opportunities for adaptation will be realized while retaining public support for resource management actions. ONF has already transitioned from producing a few commodities to producing a broad array of ecosystem services, but the more ambitious vision of coevolution must progress rapidly in order for adaptation to keep pace with anticipated effects of climatic change.

3.6 Case study: Uwharrie National Forest

3.6.1 Setting and Context of the Uwharrie National Forest

Uwharrie National Forest (UNF) is a relatively small (20,383 ha) and new (established in 1961) national forest covering three counties in the Piedmont region of North Carolina (Fig. 3.18). Much of UNF's acreage was previously owned as either private industrial forest or private agricultural land. Therefore, much of UNF has been modified from a natural to a managed ecological condition. UNF has a rolling topography, with elevation ranging from 122 to 305 m above sea level. The forest is fragmented into 61 separate parcels, which pose unique forest management challenges (Fig. 3.18). UNF is within a two-hour drive of North Carolina's largest population centers, including Winston-Salem, Greensboro, Charlotte, Raleigh, and Durham. This close proximity to major cities creates opportunities for outdoor recreation in the form of hunting, all-terrain vehicle (ATV) and horseback riding, picnicking, bird watching, hiking and fishing within the forest.

3.6.2 Current Uwharrie NF Planning Context, Forest Plan Revision and Climate Change

The National Forest Management Act of 1976 requires that all NFs periodically revise their forest management plan (U.S. Congress, 1976). Existing environmental and economic situations within the forest are examined. Then plans are revised to move the forest closer to a desired future condition. The current UNF forest management plan was originally developed in 1986, and UNF is now undergoing a Forest Plan Revision (FPR).

The revised forest plan focuses on three themes. Two of the themes—restoring the forest to a more natural ecological condition, and providing outstanding and environmentally friendly outdoor recreation opportunities—will likely be affected by a changing climate. The third theme of the FPR (*i.e.*, better managing heritage (historical and archeological) resources) will likely not be significantly affected by climate change. Thus, this case study examines potential impacts on the first two UNF FPR themes.

The revised forest plan will suggest management strategies that help reduce risks to the health and sustainability of UNF associated with projected impacts of a changing climate. Therefore, the UNF case study focuses on specific recommended modifications to the forest plan. This level of specificity was not possible with either the Tahoe or Olympic National Forest case studies because neither has recently undergone a forest plan revision that incorporates climate change impacts into forest management decision making.

3.6.2.1 Revised Forest Plan Theme 1: Restoring the Forest to a More Natural Ecological Condition

Prior to the 1940s, fires were a regular occurrence in southern U.S. ecosystems (Whitney, 1994). The reoccurrence interval varied among vegetation types, with more frequent fires being less intense than less frequent fires (Wear and Greis, 2002). Upland oak (*Quercus* sp.) and hickory (*Carya* sp.) forests would burn at an interval of 7–20 years with flame heights of less than one m. These fires would kill thin-barked tree species such as red maple (*Acer rubrum*), sweetgum (*Liquidambar styraciflua*), and tulip poplar (*Liriodendron tulipifera*), while leaving the more fire-resistant oaks and hickories alive. Pine ecosystems had a shorter fire return interval of 3–5 years, with flame heights reaching 1–2 m, thus favoring fire- and drought-resistant longleaf (*Pinus palustris*) and shortleaf (*Pinus echinata*) pines more than loblolly pines. The fires also removed much of the mid-canopy vegetation and promoted light-tolerant grasses and herbs (Uwharrie National Forest, 2007). Deciduous and coniferous tree species are equally represented in UNF. However, a higher percent of the conifers are in loblolly pine (*Pinus taeda*) plantations than would have historically occurred, because of the planting emphasis of this species over the past 40 years (Uwharrie National Forest, 2007).

Climate change is projected to increase the number and severity of wildfires across the southern United States in the coming years (Bachelet *et al.*, 2001). As part of its FPR, UNF plans to convert approximately 120 ha of loblolly pine plantation to more fire-resistant ecosystem types (*e.g.*, longleaf pine) each year (Uwharrie National Forest, 2007). This management shift will restore UNF to a more historically natural condition and reduce catastrophic wildfire risk associated with an increase in fuel loading (Stanturf *et al.*, 2002; Busenberg, 2004) and hotter climate (Bachelet *et al.*, 2001).

3.6.2.2 Revised Forest Plan Theme 2: Provide Outstanding and Environmentally Friendly Outdoor Recreation Opportunities

Recreation opportunities provided by UNF are an important ecosystem service to the local and regional communities. The proximity to large population centers and diverse interest in outdoor activities make UNF a destination for many groups that use the trails and water bodies located within the forest. The continued quality of these trails, streams, and lakes are of very high importance to UNF's mission.

During the 20th century the frequency of extreme precipitation events has increased, and climate models suggest that rainfall intensity will continue to increase during the 21st century (Nearing, 2001). Soil erosion occurs when the surface soil is exposed to rainfall and surface runoff. Soil erosion is affected by many factors, including rainfall intensity, land cover, soil texture and structure (soil erodibility), and land topography (slope) (Toy, Foster, and Renard, 2002). Because soil erosion increases linearly with rainfall-runoff erosivity, it would be expected to increase over the next 50 years in the UNF region if no management measures are taken to control the current soil erosion problems. Soil erosion is limited to exposed (*i.e.*, without vegetative cover) soil surfaces (Pimentel and Kounang, 1998). Hiking, ATV, and logging trails and forest harvest areas represent the major types of exposed soil surface in UNF and all other NFs (Uwharrie National Forest, 2007). Increased soil erosion would degrade both trail and water quality.

In response to current and projected increases in soil erosion potential, the UNF FPR proposes to repair authorized roads and trails, close unauthorized roads and trails, minimize new road construction, and reroute needed roads that could produce excessive soil erosion. In total, these measures should effectively reduce the potential impact of increased precipitation intensity on soil erosion in UNF.

3.6.3 Long-Term Natural Resource Services

In addition to the objectives outlined in the UNF plan revision, NFs in the United States provide valuable natural resources of clean water and wood products. While the demand for U.S. pulp and paper products has decreased in recent years, it is important to assess the long-term ability of the NFs to supply wood resources if a future need should arise. The demand for clean, dependable water is increasing within the southern United States as population pressure on water resources increase. Therefore, climate change impacts on UNF water yield and timber supply were also assessed in the UNF Watershed Analysis Document of the FPR.

3.6.3.1 Water Yield

Clean water is one of the most valuable commodities that our NFs provide. National forest lands are the largest single source of water in the United States and the original reason that the NFS was established in 1891 (USDA Forest Service, 2000d). There is concern that climate change could reduce water yield from our NFs, including UNF. Currently, about 1,590 mm of precipitation falls in UNF every year, with close to 70% (or 1,100 mm) of it evapotranspiring back to the atmosphere. The other 30% (or 490 mm) leaves the forest as stream runoff and percolates downward becoming a part of the groundwater (Uwharrie National Forest, 2007). Climate change models suggest that precipitation may increase to 1,780 mm per year. Air temperature is also expected to increase, which will, in turn, increase forest evapotranspiration. In total, stream water flow is projected to decrease by approximately 10% by the middle of the 21st century if there is no change in forest management (Sun *et al.*, 2005a; Sun *et al.*, 2005b).

Forest water use increases with increased tree stocking density and leaf area (Hatton *et al.*, 1998; Cook *et al.*, 2002). The use of controlled fire and other forest management activities that will increase tree spacing and shift the forest toward more fire- and drought-tolerant tree species will also help to reduce forest water use (Heyward, 1939). Based on this line of research, most of the climate change-caused reductions in water yield can be compensated through this proposed change in forest management.

3.6.3.2 Timber and Pulpwood Productivity

The southern United States has long been a major supplier of pulpwood and timber. But because an increasing amount of timber and pulpwood is being supplied to the United States by Canada, Europe, and countries in the Southern Hemisphere (USDA Forest Service, 2003), national forest managers have moved away from an emphasis on timber supply toward recreational opportunities and sustainable water (Apple, 1997).

Climate change will have variable impacts globally. Timber production in some countries, such as Canada, may benefit from warmer climate, while countries closer to the Equator may experience significant reductions in productivity (Melillo *et al.*, 1993). Although NFs are not currently major sources of wood products, this situation could change as timber production from other parts of the world shifts. Therefore, it is important to assess the impact of climate change on forest productivity in UNF. Forest productivity models suggest that although pine productivity may decrease, hardwood productivity is projected to increase and the net loss of total forest productivity would be small for the UNF over the next 40 years (National Assessment Synthesis Team, 2000). However, the analysis did not account for the potential for increased fire occurrence, which could significantly reduce overall forest volume and growth (Bachelet *et al.*, 2001). The proposed shift in forest tree types to more drought-tolerant and fire-resistant species should also help to assure that UNF remains a timber resource for future generations (Smith, Ragland, and Pitts, 1996).

3.7 Conclusions and Recommendations

3.7.1 Climate Change and National Forests

The mission of the NFs has broadened over time, from water and timber to multiple resources to one of sustaining the health, diversity, and productivity of the nation’s forests and grasslands to meet the needs of present and future generations. Increasingly the concepts of ecosystem management, ecological integrity, resilience, and sustainability have become important concepts and goals of national forest management. The Forest Service's 2005 planning rule specifically directs that forest plans "must guide sustainable management of NFS lands."

The management of national forest lands has broadened to include involvement by EPA and consultation with the Fish and Wildlife Service, as well as coordination on management of lands within NFs by national systems such as the Wilderness Preservation System, National Trails, National Monuments, and Wild and Scenic Rivers. The checkerboard ownership patterns of many of the western forests, the scattered private in-holdings of many NFs, and the scattered land parcels of the eastern forests result in the important need to coordinate with other agencies (in the case of state lands) and with private land owners. Public involvement has increased through law (*e.g.,* NEPA) since the establishment of the NFs. This broader level of participation by the public and other federal and state agencies, as well as the assortment of different management units, can be a challenge for coordinating and responding to novel situations such as climate change.

Over the last 30 years, the rapid expansion of the urban environment toward rural and remote areas has altered many aspects of the large landscape. With world travel and increasing accessibility within the United States, invasive species have many opportunities to spread and establish themselves across the landscape. The total area of fires burned has also increased across the western United States. These stressors are likely to interact with climate change in both known and surprising ways.

One of the challenges to the Forest Service, as an agency in responding to climate change, will be the diversity of climatic changes experienced by NFs that are spread across the country. Not only will each national forest experience regional and site-specific changes in temperature and precipitation, but the forests are likely to experience changes in weather events such as the occurrence of ice storms; straight-line wind events such as derechos, tornados, and hurricanes; and flooding associated with high-intensity rainfall events or with shifts between rain and snow events. Local land management goals differ greatly by national forest and grassland, and by management units within NFs (*e.g.,* wilderness, matrix working forest, ski areas, campgrounds, etc). Further, climate effects and climate change will vary by geography and ecosystem, and thus no single climate solution will fit all. This diversity of climatic changes will interact with the diversity of stressors and the diversity of management goals across the NFs—responding to climate change will need to reflect local and regional differences in climate, ecosystems, and the social and economic settings.

The NFs have, in many aspects, begun to address many of the challenges of climate variability and change—changes to historic disturbance regimes, historically unprecedented epidemics of native insects, spread of non-native invasive species, drought, fuels accumulation, and ecosystem fragmentation. Current management approaches include landscape-scale planning and coordinated agency planning for fire suppression, and coordinated agency efforts for invasive species, among others. Still, more resources, awareness, skill, and maybe even new policies, may be needed to deal with the growing risks with climate change as it accelerates.

Adaptation options for climate-sensitive ecosystems encompass three approaches: no active planning, reaction to a changing disturbance, and anticipatory adaptations. The rationale for choice involves the costs and benefits associated with the ecological, social, and economic components under the changing climate. In some cases, the choice of no active planning could reflect short-term goals on landscapes where the risk of climate change impacts may be minimal on the short term, for ecosystems with low sensitivity to climate change, where the uncertainty is great (climate variability large, potential impacts low), or where the resource is jeopardized by climate change and the decision is to triage. In situations where the choice is to respond to a climate-induced changing disturbance, the rationale here could be that adjustments to historical management approaches are needed eventually, but are best made during or after a major climatic or disturbance event; adaptive actions are incorporated after the disturbance occurs. The third option involves anticipating climate change opportunities and impacts, and preparing for those opportunities and impacts now. The choice involves using the best available information about future climate and environmental conditions, and the best available information about the societal context of forest management, to begin making changes to policy and on-the-ground management now as well as when future windows of opportunity open.

3.7.2 Management Response Recommendations

3.7.2.1 Integrate Consideration of Climate Change Across All Agency Planning Levels

The integration of climate change and climate change impacts on ecosystem services into the policy development and planning across the levels of the agency (Forest Service strategic goals, RPA Assessment, national forest plans, multi-forest plans, project planning) could facilitate a cohesive identification of opportunities and barriers (institutional, ecological, social). The current approach responds to the legislative requirement to address climate change analyses within the strategic national level through the RPA Assessment. The ecological and the economic analyses conducted as part of the RPA Assessment may provide a framework and context for regional-and-finer-scale analyses on impacts and opportunities. More quantitative approaches may be available at the national/regional scales, providing strategic guidance for broad consideration of climate change opportunities and impacts to management activities at finer scales.

3.7.2.2 Reframe the Role of Uncertainty in Land Management: Manage for Change

Current ecological, social, and economic conditions of NFs are projected to change under a changing climate, including vegetation type shifts, changes in wood production, water quantity, etc. The challenge for the Forest Service will be to determine which ecosystem services and which attributes and components of biodiversity can be managed for under a changing climate and all that it entails. Climate change and the many anthropogenic land use, atmospheric, and fragmentation effects may result in a future where historical ecosystem dynamics may not be a good guide to future ecosystem conditions and dynamics. There will be a need to anticipate and plan for surprise and threshold effects for climate change and these other stressors.

There may also be a need to shift focus to managing for change, setting a goal of desired future function (processes, ecosystem services) and managing current and future conditions (structure, outputs), which may be quite dynamic, through a changing climate. The 2005 planning rule describes desired conditions as “the social, economic, and ecological attributes toward which management of the land and resources of the plan are to be directed.” Defining a goal as an ecosystem condition, such as old growth habitat for protection of a threatened and endangered species, could be undermined with the arrival of an invasive species that out-competes the native species, or by an invasive species that alters the fire regime irrevocably.

Under a changing climate, embracing uncertainty will necessitate a careful examination of various underlying assumptions about climate, climate change, ecological processes, and disturbances. Specifically, the Forest Service will need to re-evaluate (1) the dynamics of ecosystems under disturbances influenced by climate; (2) current management options as influenced by climate; and (3) important premises about the nature of disturbances (*e.g.*, fire, insect outbreaks, diseases, extreme climate-related events, and the interactions among these disturbances) that influence management philosophy and approaches. These premises include: (1) historical range of natural variability as a reference condition and goal for restoration; (2) the determination of "100 year flood" events and the relationship between weather events and erosion; (3) the role of natural regeneration versus artificial regeneration; and (4) seed transfer guidelines. These premises have implications for terrestrial and aquatic habitats, water balance, water runoff and in-stream flows, and other ecological attributes of NFs as well as for management approaches. The climate sensitivity of best management practices, genetic diversity guidelines, restoration treatments, and regeneration guidelines may need to be revisited. Opportunities to test these assumptions through management activities and research experiments may be valuable. Current management strategies offer a good platform to reframe these strategies to address uncertain and varying climates and environments of the future.

3.7.2.3 Nurture and Cultivate Human Capital Within the Agency

The Forest Service has a long tradition of attracting and retaining highly qualified employees. The capacity of the agency to address climate change may require the staff within NFs to have a more technical understanding of climate change. Specifically, the Forest Service could provide opportunities to develop a better technical understanding of climate and its impacts, as well as options for adaptation and mitigation in NFs. This requirement could be integrated into the many training opportunities that currently exist within the Forest Service, including the silvicultural certification program, regional integrated resource training workshops, and regional training sessions for resource staffs. New opportunities to share training of resource managers with other natural resource agencies could also enhance the ability of the Forest Service to address climate change in resource management. Additionally, increased awareness and knowledge of climate change could be transferred through the development of managers' guides, climate primers, management toolkits, a Web clearinghouse, and video presentations.

Resource management is challenging in today's environment, and climate change will increase that challenge. Line officers and resource staffs are faced with—and will continue to be faced with—the challenge of making decisions in an uncertain environment. Facilitation of a learning environment, where novel approaches to addressing climate change impacts and ecosystem adaptation are supported by the agency, will support Forest Service employees as they attempt to maintain management goals in the face of climate uncertainty. Mistakes are seen as opportunities to learn the conditions for such approaches.

3.7.2.4 Engage Stakeholders and Partners on the Role of Climate in Natural Resource Management

The Forest Service, perhaps more than any other federal land management agency, actively involves the public through its planning process and through volunteers and partnerships. Appeals and litigation have restricted implementation of adaptive management practices and in some cases research experiments. Appeals or litigation on the climate change question are inevitable.

Urgent need exists to inform policy makers, managers, stakeholders, and the public about the specific evidence of global climate change and its projected consequences on ecosystems to enhance public understanding of the choices, future opportunities, and risks. Education on the scale necessary will require new funding and educational initiatives. Effective efforts must involve diverse suites of educational media, including information delivery on evolving platforms.

The Forest Service should work with current partners to engage the public in understanding the changing climate and the potential impacts of climate on disturbances and ecosystems, so that the dialogue on adaptation and mitigation can begin with stakeholders. If ecosystem services, biodiversity, and the outcomes of interest to partners are changed under a changing climate then climate change will have an impact on the relationships among current partners. Opportunities for new partnerships must also be considered.

There will also be a need to educate landowners in the wildland-urban interface about the potential for increased disturbances or changing patterns of disturbances in these areas, as well as the challenges of land ownership and protection of valued resources within this environment.

3.7.2.5 Increase Collaboration Across Federally Managed Landscapes

Where federally managed land encompasses large landscapes, the Forest Service should increase collaboration to facilitate the accomplishment of common goals (*e.g.,* the conservation of threatened and endangered species), as well as adaptation and mitigation, that can only be attained on larger landscapes. The 2005 planning rule specifically directs the Responsible Official to look at the larger landscape including across ownerships.

When plans are developed or revised, Responsible Officials must evaluate social, economic, and ecological elements of sustainability and (1) conduct sustainability evaluations within an area large enough to consider broad-scale social, economic, and ecological factors and trends over large landscapes. Selection of the area included in these evaluations must be guided by the issues being addressed; the extent of relevant ecosystems and their composition, structure and function; the ranges and habitats of individual species; and key social and economic patterns and processes. These landscapes may include several NFs and should consider non-NFS lands. Evaluations for sustainability must extend to this larger area of analysis to understand the environmental context and opportunities and limitations for NFS lands to contribute to the sustainability of social, economic, and ecological systems (FSM 1920.3).

Common goals might include mitigation of threatened and endangered species habitats, integrated treatment of fuels or insect and disease conditions that place adjacent ownerships at risk, and developing effective strategies to minimize loss of life and property at the wildland-urban interface.

While collaboration makes sense logically, and seems conceptually like the only way to manage complex ownerships, large landscapes, and across multiple jurisdictions, there are many challenges to such an approach. Attempting to collaborate multi-institutionally across large landscape scales can produce unexpected institutional and societal emergent properties. For example, large multi-forest landscapes have high investment stakes—with resulting political pressure from many different directions. Further, if collaboration is taken to mean equal participation and that each collaborator has an effective voice, then laws, regulations, resources and staffing can lead to situations in which collaboration by different groups is uneven and possibly unsuccessful. For example, the Forest Service, EPA, and the U.S. Fish and Wildlife Service each must obey its particular governing laws, and thus agency oversight can overrule attempts at equal participation and collaboration. Careful consideration of the challenges to managing across large landscapes will be an important aspect of adaptation to climate change.

3.7.2.6 Establish Priorities for Addressing Potential Changes in Populations, Species, and Community Abundances, Structures, Compositions, and Ranges, Including Potential Species Extirpation and Extinction under Climate Change

The Forest Service should develop a common framework to prioritize management responses in situations where the magnitude and scope of anticipated needs, combined with diminishing available human resources, dictate that priorities be evaluated swiftly, strictly, and definitely.

This evaluation of priorities could be addressed jointly by neighboring landowners, or regionally to guide the management of currently rare or threatened and endangered species as well as populations, species, communities and ecosystems that expand and retreat across the larger landscape. Such an approach could capitalize on the respective strengths of the various local, state and federal land management agencies.

3.7.2.7 Develop Early Detection and Rapid Response Systems for Post-Disturbance Management

Early detection and rapid response systems are a component in the current invasive species strategy of the Forest Service. Such an approach may have value for a broader suite of climate-induced stressors, for example using the current network of experimental forests and sites to early detection and response system. Consideration of post-disturbance management for short-term restoration and for long-term restoration under climate change prior to the disturbance (fire, invasives, flooding, hurricanes, ice storms) may identify opportunities and barriers. Large system-resetting disturbances offer the opportunity to influence the future structure and function of ecosystems through carefully designed management experiments in adapting to climatic change. Currently restricted management practices (barriers) may need to be revisited and permitted in areas where such management is currently restricted.

3.7.3 Research priorities

3.7.3.1 Conceptual (Research Gaps)

Climate change will interact with current stressors—air quality, native insects and diseases, non-native invasives, and fragmentation—in potentially surprising ways. Greater understanding of the potential interactions is needed through field experiments, modeling exercises, and data mining and analysis of past forest history or even recent geological records. Given the numerous stressors facing all nature resource managers, these research priorities could promote syntheses of disciplinary research related to climate and other stressors, and integrate the efforts of the research communities at universities, non-governmental organizations, state agencies, tribal organizations, and other federal agencies.

There is great need for socioeconomic research and monitoring of how social and economic variables and systems are changing, and likely to change further, as climate change influences the opportunities and impacts within and surrounding NFs. The expansion of the urban and suburban environment into remote areas could also be influenced by climate change—potentially shifting this expansion to higher elevations or to more northerly regions where winters may not be as historically severe. Recreational choices could also be influenced by climate changes, shifting outdoor activities across a spectrum of options from land-based to water-based, from lower/warmer regions to cooler regions.

The need currently exists to develop tradeoff analyses for situations in which management actions taken now potentially could alter more serious impacts later, such as the tradeoffs of planned prescribed fire/air quality versus unplanned wildfire/smoke/air quality. Habitat restoration for threatened and endangered species under a changing climate might involve social, economic, and ecological impacts and opportunities on national forest land, adjacent ownerships, or private land. Tradeoffs involve ecological consequences as well as social and economic consequences. Similarly, the tradeoffs between mitigation and adaptation at present cannot be addressed in the available suite of decision-making and management tools.

These research priorities will be most useful to managers if they explicitly incorporate evaluations of uncertainty. Toward that end, new approaches to quantifying uncertainty in quantitative and qualitative management methods are needed.

3.7.3.2 Data Gaps (Monitoring/Mapping)

Information on the status of ecosystem services as climate changes will be important in ascertaining whether management goals are being attained under the changing climate. Determining the baseline for monitoring, what to monitor and evaluating whether current monitoring approaches will be adequate under a changing climate are critical research needs. Experimental forests and sites, and the network of research natural areas on NFs could serve as early detectors of change associated with climate.

Regional analyses could identify the relative condition and contribution that an entire landscape makes—or that components of the landscape (vegetation type, or land ownerships) make—with respect to habitats under a changing climate and such information could inform options for optimizing management decisions about habitat management within NFs.

The Forest Inventory and Analysis data have informed historical analyses of productivity shifts as affected by recent climate variability and change at large spatial scales. The data have also contributed to national accounting analyses of carbon in U.S. forests. Other potential analyses with these inventory data could include exploring the response of ecosystems to changing fire regimes and insect outbreaks, along with the network of experimental forests and sites, develop a consistent early detection and rapid response program to climate change. The Montreal Process Criteria and Indicators for Boreal and Temperate forests have been used to describe sustainability of forests and rangelands by managers at several spatial scales. The use of Montreal Process Criteria and Indicators may also have value in assessing the opportunities and impacts on sustainability under a changing climate.

3.7.3.3 Tool Gaps (Models and Decisions Support Tools)

There is a need to develop techniques, methods, and information to assess the consequences of climate change and variability on physical, biological, and socioeconomic systems at varying spatial scales, including regional, multi-forest, and national forest scales. The analyses at the national scale in the RPA Assessment, particularly if extended beyond forest dynamics, could provide national-level information and set a larger context for the forest opportunities and impacts under climate change. Fine-scale analyses of the ecological and economic impacts of climate change may be within reach, and offer projections at the spatial scale of importance to managers.

There is a need to develop a tool box for resource managers that can be used to quantify effects of climate change on natural resources as a component of land management planning. This tool box would have a suite of science-based products that deliver state-of-the-art information derived from data, qualitative models, and quantitative models in accessible formats, including a Web-based portal on climate-change science. Technology transfer through training packages on climate change that can be delivered through workshops and online tutorials would be valuable to internal staff and potentially to stakeholders.

Forest-scale Decision Support Applications that incorporate the dynamics of climate, climate variability, and climate change into natural resource management planning would enhance the information about climate used in management analyses. At present, most established planning and operational tools do not directly incorporate climate variability and change. These tools need to be informed by recent scientific data on climate trends and the relationship between climate and the resource of interest. Research can contribute immediately to the revision of popular tools such as the Forest Vegetation Simulator, thereby improving their accuracy for a variety of applications. A Web-based portal on climate change, customized for the needs of Forest Service users, will be an important component of the tool box, providing one-stop shopping for scientific information, key publications, and climate-smart models. A training curriculum and tutorials will ensure that Forest Service managers receive current, consistent information on climate change issues.

3.7.3.4 Management Adjustments or Realignments

The development of management alternatives for adapting to and mitigating the effects of an uncertain and variable climate and other stressors on natural resource outputs and ecosystem services will require experimentation under the changing climate. Many proposed management alternatives may need to be established as small-scale pilot efforts to determine the efficacy of such pro-active approaches to adapting to climate change in various ecosystems and climates. Protocols for ‘assisted migration’ of species need to be tested and established before approaches are implemented.

Assumptions about the dynamics of ecosystems under climate change and alternative treatments may need to be revisited in field experiments. Regeneration and seedling establishment studies under a variety of vegetation management treatments under the changing climate may suggest new approaches are needed to ensure ecosystem establishment and restoration. The Forest Service should test and develop a range of science-based management alternatives for adapting to and mitigating the effects of climate change on major resource values (water, vegetation, wildlife, recreation, etc.).

Additionally, current protocols about restoration may need further experimentation to determine the role and assumptions of climate in the current techniques.

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3.9 Acknowledgements

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Workshop Participants

- Chris Bernabo, National Council on Science for the Environment
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- Jeff Sorkin, U.S.D.A. Forest Service
- John Townsley, Okanogan and Wenatchee National Forests
- Chris Weaver, U.S. Environmental Protection Agency

3.10 Boxes

Box 3.1. Strategic Plan Goals of the Forest Service, 2004–2008

1. Reduce the risk from catastrophic wildland fire. Restore the health of the nation's forests and grasslands to increase resilience to the effects of wildland fire.
2. Reduce the impacts from invasive species. Restore the health of the nation's forests and grasslands to be resilient to the effects of invasive insects, pathogens, plants, and pests.
3. Provide outdoor recreational opportunities. Provide high-quality outdoor recreational opportunities on forests and grasslands, while sustaining natural resources, to meet the nation's recreational demands.
4. Help meet energy resource needs. Contribute to meeting the nation's need for energy.
5. Improve watershed condition. Increase the number of forest and grassland watersheds that are in fully functional hydrologic condition.
6. Conduct mission-related work in addition to that which supports the agency goals. Conduct research and other mission-related work to fulfill statutory stewardship and assistance requirements.

Box 3.2. Ecosystem services described by the Millennium Ecosystem Assessment (2005)

Provisioning services—fiber, fuel, food, other non-wood products, fresh water, and genetic resources

Regulating services — air quality, climate regulation, water regulation, erosion regulation, water purification and waste treatment, disease regulation, pest regulation, pollination, and natural hazard regulation

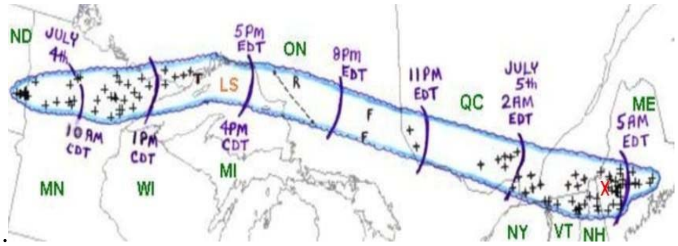
Cultural services—cultural diversity, spiritual/religious values, knowledge systems, educational values, inspiration, aesthetic values, social relations, sense of place, cultural heritage values, recreation and ecotourism

Supporting services—primary production, soil formation, pollination, nutrient cycling, water cycling

Box 3.3. The “Boundary Waters – Canadian Derecho”, a straight line wind event in the central US and Canada.

During the pre-dawn hours on Sunday, July 4, 1999 thunderstorms were occurring over portions of the Dakotas. By 6 AM CDT some of the storms formed into a bow echo and began moving into the Fargo, North Dakota area with damaging winds. Thus, would begin the "Boundary Waters-Canadian Derecho" which would last for over 22 hours, travel over 1300 miles at an average speed almost 60 mph, and result in widespread devastation and many casualties in both Canada and the United States

In the Boundary Waters Canoe Area (BWCA), winds estimated at 80 to 100 mph moved rapidly causing serious damage to 600 square miles of forest in the area. Tens of millions of trees were blown down. Sixty people in the BWCA were injured by falling trees, some seriously. Twenty of those injured were rescued by floatplanes flying to lakes within the forest.



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Area affected by the July 4-5, 1999 derecho event (outlined in blue). Curved purple lines represent the approximate locations of the "gust front" at three hourly intervals. "+" symbols indicate the locations of wind damage or estimated wind gusts above severe limits (58 mph or greater) (NOAA's National Weather Service, 2007).

Box 3.4. Insects and drought in piñon-juniper woodlands in the southwest USA.

Between 2002 and 2003, the southwestern US experienced a sub-continental scale dieback of piñon pines (*Pinus edulis)*, Ponderosa pines (*P. ponderosa*) and juniper (*Juniperus monosperma*), the dominant tree species in the region (Breshears *et al.*, 2005). Piñon pines were hit hardest, and suffered 40-80% mortality across an area spanning 12,000 km^2 of Colorado, Utah, Arizona, and New Mexico. Beetles (*Ips confuses* LeConte) were the proximate cause of death of the piñons, but the beetle infestation was triggered by a major "global-change type drought" that depleted soil water content for at least 15 months (Breshears *et al.*, 2005). Although a major drought occurred in the same region in the 1950s, mortality was less extensive—mostly Ponderosa pine stems > 100 years old and on the driest sites died (Allen and Breshears, 1998). In contrast, the more recent drought killed piñons across all size classes and elevations. It also killed 2–26% of the more drought-tolerant junipers and reduced by about half the live basal cover of *Boutelua gracilis*, a dominant grass in the piñon-juniper woodlands (Breshears *et al.*, 2005). The more recent drought also was characterized by warmer temperatures, which increased the water stress on the trees. This increased water stress was probably exacerbated by the increased densities of piñons that resulted from anomalously high precipitation in the region from about 1978–1995 (Breshears *et al.*, 2005).

The scale of this dieback will greatly affect carbon stores and dynamics, runoff and erosion, and other ecosystem processes, and may also lead to an ecosystem type conversion (Breshears *et al.*, 2005). The possibility that vegetation diebacks at the scale observed in this example may become more common under climate change presents a major management challenge.

These photos—taken from similar vantages near Los Alamos, NM—show the large-scale dieback of piñon pines in 2002–2003 that resulted from a protracted drought and associated beetle infestation. In 2002, the pines had already turned brown from water stress, and by 2004, they had lost all their needles.

Photo credit: CD Allen, USGS

Box 3.5. Bark Beetles in Western North American Forests

Bark beetles are native insects and important disturbance agents in western North American forests (Carroll *et al.*, 2003). Beetle outbreaks occur periodically when otherwise healthy trees are weakened from drought, injury, fire damage, and other stresses. Since 1996, bark beetles have infested and killed millions of pines, spruce, and fir trees over vast areas from Arizona to British Columbia. This outbreak, which is considered to be more extensive and damaging than any previously recorded in the west, is expected to continue without active management (Western Forestry Leadership Coalition, 2007).

The most "aggressive, persistent, and destructive bark beetle in the US and western Canada" is the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (The Bugwood Network, 2007), which will attack and kill most western pine species. The mountain pine beetle (MPB) infested 425,000 acres of Colorado's lodgepole pine (LP) forests in 2005 (Colorado Department of Natural Resources, 2005) and 660,000 acres (~40% of Colorado's LP forests) by 2006 (Erickson, 2006). The large scale of this outbreak in Colorado is attributable to a combination of factors, including large areas with even-age, monospecific stands (a result of fire suppression and other management practices), drought, and climate change (Colorado State Forest Service cited in Paulson, 2007).

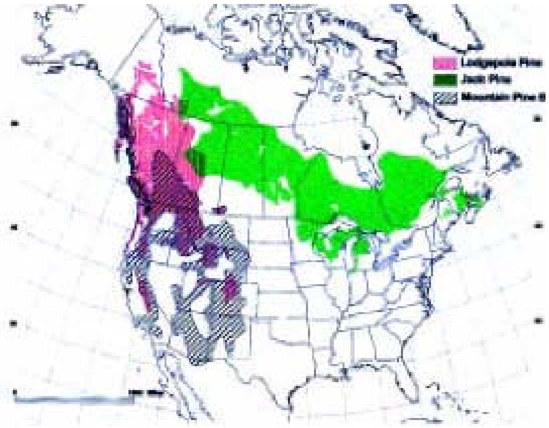
Warmer winters have spurred extensive mountain pine beetle damage in the US and Canadian Rockies. Left photo is courtesy of Jerald E. Dewey, USDA Forest Service; photo below is reprinted with permission from Colorado State University Extension, fact sheet no. 5.528, Mountain Pine Beetle, by D.A. Leatherman. and I. Aguayo.

Despite the historic scale of the recent MPB outbreak in Colorado's lodgepole pine forests, periodic outbreaks, albeit on a smaller spatial scale, are considered normative (Logan and Powell, 2001). Lodgepole pine and MPB are co-evolved, and lodgepole pine is the MPB's most important host (Logan and Powell, 2001). Lodgepole pine has serotinous cones and is maintained by stand replacing fires that are facilitated by MPB-induced mortality. Dead needles from outbreaks are an important fuel, standing dead trees serve as fire ladders, and falling limbs and stems provide high fuel loads for high intensity crown fires. Without such fires, more shade-tolerant species would eventually replace lodgepole pine in much of its range (Logan and Powell, 2001).

Other western pines, especially those growing at higher elevations such as whitebark pine, are not similarly co-evolved with MPB. Until recently, high elevation and high latitude habitats typically have been too harsh for MPB to complete its life cycle in one season. Because the ability to complete its life cycle in one season is central to the MPB's success (Amman, 1973; Safranyik, 1978), MPB activity has historically been restricted to lower elevation pines, which are separated from high-elevation (3,000 m or 10,000 ft in CO) pines by non-host species.

Climate change will not only spur further MPB outbreaks, but will also likely facilitate the invasion of species currently restricted to more benign environments into whitebark pine and other high-elevation pine stands in the wake of MPB infestations (Logan and Powell, 2001). The fact that all aspects of the MPB's seasonality are controlled by seasonal temperature patterns (Logan and Bentz, 1999) supports this forecast. It is further supported by the finding that both the timing and synchrony of the beetle's life cycle are responsive to climate change (Logan and Powell, 2001). Specifically, Logan and Powell (2001) showed that a 2^{o}C increase in annual average temperature allows MPB populations to synchronously complete their life cycle in a single season. Such a shift from a two season, asynchronous life cycle confers the greatest chance for population success. Because the response of the MPB's life cycle to temperature is nonlinear, climate change-induced MPB outbreaks are likely to occur in high elevation pine ecosystems without warning.

In addition to creating ideal conditions for populations of MPB to reach epidemic levels, climate change has allowed the MPB to expand its range northward and eastward in recent decades (Carroll *et al.*, 2003). The current MPB range extends from northern Mexico through the American Rockies west and into British Columbia, Alberta & Saskatchewan (Carroll *et al.*, 2003). The range of the MPB is principally constrained by climate rather than the availability of suitable hosts; lodgepole pine exists beyond the range of MPB (Logan and Powell, 2001; Carroll *et al.*, 2003). Evidence for the range expansion of MPB includes accelerating rates of infestation since 1970 into previously unsuitable habitats. Further range expansion is likely with additional warming (Carroll *et al.*, 2003). Logan and Powell (2001) predict a 7^o northward shift in the range of MPB with a doubling of CO_2 and an associated temperature increase of 2.5^{o}C. Such a shift would allow MPB to occupy previously unoccupied lodgepole pine habitat and allow an invasion into jack pine ecosystems in both the US and Canada, which have not been previously attacked by MPB (see map at right). The continuous habitat provided by lodgepole pine will facilitate this range shift. Although cold snaps and depletion of hosts caused previous large-scale MPB outbreaks to collapse, the current outbreak may not collapse because there is no shortage of host trees, and temperatures are expected to continue warming (Carroll *et al.*, 2003).



Geographic ranges of lodgepole pine (pink), mountain pine beetle (hatched), and jack pine (green). Source Logan and Powell (2001).

Box 3.6. Introduction to the National Forest Case Studies

Case studies were developed for three National Forests:

the Tahoe National Forest in California,
the Olympic National Forest in Washington, and
the Uwharrie National Forest in North Carolina.

Just as the forests are unique, these case studies are unique in their approaches, reflecting the diversity of ecosystem services as well as the current context for their management and planning activities. The Tahoe National Forest plan dates from 1990 and has been amended by the Sierra Nevada Forest Plan Amendment (USDA Forest Service, 2004b) and the Herger-Feinstein Quincy Library Group Forest Recover Act (U.S. Congress, 1998). The ONF is a 'restoration forest' charged with managing large, contiguous areas of second-growth forest, objectives from the Northwest Forest Plan. The Uwharrie National Forest is in the process of revising its forest plan.

Workshops were held on the Tahoe and the Olympic, involving National Forest line officers and resources staff, and members of the National Forest chapter writing team with presentations and discussions. For both the Tahoe and the Olympic, there existed several studies to draw from for recent and anticipated regional climate changes and ecological impacts On the Uwharrie National Forest, a member of the writing team worked with local resource staff to explore the implications of climate change to the current forest plan themes and long-term natural resource services produced on the Uwharrie National Forest

Each case study starts with the setting and context for each forest, the current planning and management environment. For the Tahoe and the ONF, a description of current planning and management approaches on the forest are followed with options for proactive management actions anticipating climate change For the Uwharrie, the proposed forest management changes in the plan (e.g., relocation of trails, forest conversion) are examined in light of possible climate change stresses and whether or how these would help reduce climate change impacts

Box 3.7. Forest Planning Assumptions to Consider Regarding Climate Change (West, 2005).

<u>Historic Conditions</u> - We assume that historical conditions are a useful reference or point of comparison for current or future trends, in accord with the Healthy Forest Restoration Act, the 2005 planning rule, and LANDFIRE (and other national fire-related projects). However, we recognize that this assumption is likely to face substantial challenges as the effects of climate change on vegetation and disturbance regimes play out over the next several decades. Accordingly, an adaptive management approach can be used to test this assumption and make adjustments in the desired future condition and plan goals and objectives as the local effects of climate change become apparent.

<u>Flexibility & considerations</u> - Although climate and ecosystem forecast models have significantly improved, they cannot produce highly accurate local projections. Flexibility to address the inherent uncertainty about local effects of climate change could be achieved through enhancing the resiliency of forests by considering that:

- Diverse plantings will likely be more adaptable to changing conditions than will single species stands.
- Prescribed fire and thinning could be used to keep tree densities low to improve resistance to drought and pest infestations.
- Nitrogen-fixing species, intermixed in a stand, may facilitate re-growth after disturbance in a rapidly changing environment, although they may compete for water on droughty sites.
- Encouraging local industries that can adapt to or cope with variable kinds of forest products because of the uncertainty in which tree species will prosper under changed climate.
- Some vegetation types in vulnerable environments (*e.g.*, ecotonal, narrow distribution, reliant on specific climate combinations, situations sensitive to insect/pathogens) will be highly sensitive to changes in climate and may undergo type conversions despite attempts at maintaining them (meadow to forest, treeline shifts, wetland loss). Some of these changes are likely to be inevitable.
- Reforestation after wildfire may require different species (*i.e.* diverse plantings, as mentioned above) than were present on the site pre-fire to better match site-type changes due to climate effects.
- Genetic diversity of planting stock may require different mixes than traditionally prescribed by seed zone guidelines.
- Massive forest diebacks may be clues to site transition issues.
- Behavior of invasive species is likely to be different as climates shift.
- Increasing interannual climate variability (*e.g.*, dry periods followed by wet, as in alternating ENSO patterns) may set up increasingly severe fuels situations.
- Non-linear, non-equilibrium, abrupt changes in vegetation types and wildlife behavior may be more likely than linear, equilibrium, and gradual changes.
- Water supply and water quality issues might become critical, particularly if increased or prolonged drought or water quality changes are the local consequences of climate change.
- Carbon storage to reduce greenhouse gas and other effects might be important.

<u>Adaptive Management</u> - Effects due to climate change (*e.g.*, wildfire severity/acreage trends, vegetation trends, insect and disease trends) may become more apparent as new information becomes available to Forests through regional or sub-regional inventories, data collection, and research. This information may be useful for adjusting desired conditions and guidelines as plans are implemented. Information of interest might include:

- The frequency, severity, and area trends of wildfire and insect/disease disturbances, stratified by environment
- The distribution of major forest types. For example, the lower and upper elevational limits of forests and woodlands might change as precipitation, temperature, and other factors change. These trends might be detected through a combination of permanent plots (*e.g.*, FIA) and remotely sensed vegetation data (*e.g.*, gradient nearest neighbor analyses).
- Stream flow and other indicators of the forests’ ability to produce water of particular quality and quantity.

Box 3.8. National Forests: Adaptation Options for Resource Managers

✓ Maintain species with strategies such as supplying needed nutrients and water, removing competing understory, fertilizing young plantations, and developing cover species.

✓ Where warranted, conduct thinning and fuels abatement treatments to reduce crown fire potential and risk of insect epidemics.

✓ Identify high value areas and take special measures to protect them.

✓ Monitor non-native species to be able to take early, proactive, and aggressive action against them.

✓ Proactively promote stand resilience with silvicultural techniques (e.g., widely-spaced thinnings or shelterwood cuttings).

✓ Promote connected landscapes to facilitate migration.

✓ Identify environments “buffered” against climate change and consider them as sites for new plantations or long-term conservation.

✓ Protect populations that currently exist in climatically buffered, cooler, or unusually mesic environments.

✓ Spread risks by increasing ecosystem redundancy and buffers in both natural environments and plantations.

✓ Hedge against change by modifying genetic diversity guidelines to increase the range of species, maintain high effective population sizes, and favor genotypes known for broad tolerance ranges in forest ecosystems.

✓ Use disturbances as opportunities (e.g., reforest with species tolerant to low soil moisture and high temperatures, move species into the disturbed area from other seed zones).

✓ Have ready deliberate and immediate plans to encourage the return of desired species to a site post-disturbance.

3.11 Tables

Table 3.1. Current Stressors and their impacts on ecosystems in National Forests

Current Stressors	**Effects**	**References**
Loss of Open Space and Habitat Fragmentation	Increase in "perforated" forest affected by anthropogenic edges	(Riitters and Wickham, 2003; Wickham *et al.*, 2007)
	Increased predation and parasitism near forest edges	(King, Griffin, and DeGraaf, 1998; Lahti, 2001; Howell, Dijak, and Thompson, 2007)
	Impeded pollination/plant reproduction near edges	(Aguilar *et al.*, 2006)
	Increase spread of non-native, invasive species near edges	(Brothers and Spingarn, 1992; Tyser and Worley, 1992; Wein *et al.*, 1992; Pitelka, 1997; Mooney and Hobbs, 2000; Clout and Lowe, 2000; Sutherst, 2000; Thompson *et al.*, 2001; Chornesky *et al.*, 2005; Rentch *et al.*, 2005)
	Loss of biodiversity	(Noss, 1990; Vitousek, 1994; Vitousek *et al.*, 1997; Trombulak and Frissell, 2000; Novacek and Cleland, 2001; Lindenmayer and Franklin, 2002; Bradshaw, Marquet, and Ronnenberg, 2003; Hilty, Lidicker, Jr., and Merenlender, 2006; Hawbaker *et al.*, 2006)
Non-native Invasive Species	Loss of native species	(Vitousek, 1994; Ellison *et al.*, 2005)
	Altered energy, nutrient fluxes, hydrology, food webs, forest dynamics, biodiversity, plant community homogenization, changes in species interactions, availability of pollinators, shifts in community types	(Ellison *et al.*, 2005; Hale *et al.*, 2005; Frelich *et al.*, 2006; Hale, Frelich, and Reich, 2006)
Air Pollution	Acidic deposition; reduced pH in lakes, rivers and soils	(Driscoll *et al.*, 2001; National Acid Precipitation Assessment Program, 2003)
	Changes in Nitrogen saturation	(Johnson and Lindberg, 1992; Aber *et al.*, 1998; Driscoll *et al.*, 2003)
	Ozone exposure	(Ollinger, Aber, and Reich, 1997; Karnosky, Zak, and Pregitzer, 2003; Felzer *et al.*, 2004; Hanson *et al.*, 2005; Karnosky *et al.*, 2005; King *et al.*, 2005)
	Mercury deposition	(Chen *et al.*, 2005; Ottawa National Forest, 2006b; Driscoll *et al.*, 2007; Peterson *et al.*, 2007)
Altered Fire Regimes	Driver of forest dynamics	(Frelich, 2002; Seymour, White, and deMaynadier, 2002; Radeloff *et al.*, 2005)
	Invasion by nonnative species	(Mooney and Hobbs, 2000; D'Antonio, 2000; Glasgow and Matlack, 2007)
Unmanaged Recreation	– Vegetation and habitat loss from	(Leung and Marion, 2000)

	trampling; – Soil compaction and erosion; – Soil and water pollution; – Occurrence of wildfires – Spread of invasives	
Wind	Windthrow, gap formation	(Canham, Papaik, and Latty, 2001; Frelich, 2002; Seymour, White, and deMaynadier, 2002)
	Stand replacement by high-intensity storms	(Canham, Papaik, and Latty, 2001; Frelich, 2002; Seymour, White, and deMaynadier, 2002)
Ice Storms	Ice related stress,	(Bruederle and Stearns, 1985; De Steven, Kline, and Matthiae, 1991; Rhoads *et al.*, 2002; Yorks and Adams, 2005)
	Shifts in successional trajectory	(Rhoads *et al.*, 2002)
	Altered N cycling	(Houlton *et al.*, 2003)
Drought	Moisture stress	(Running, 2006)

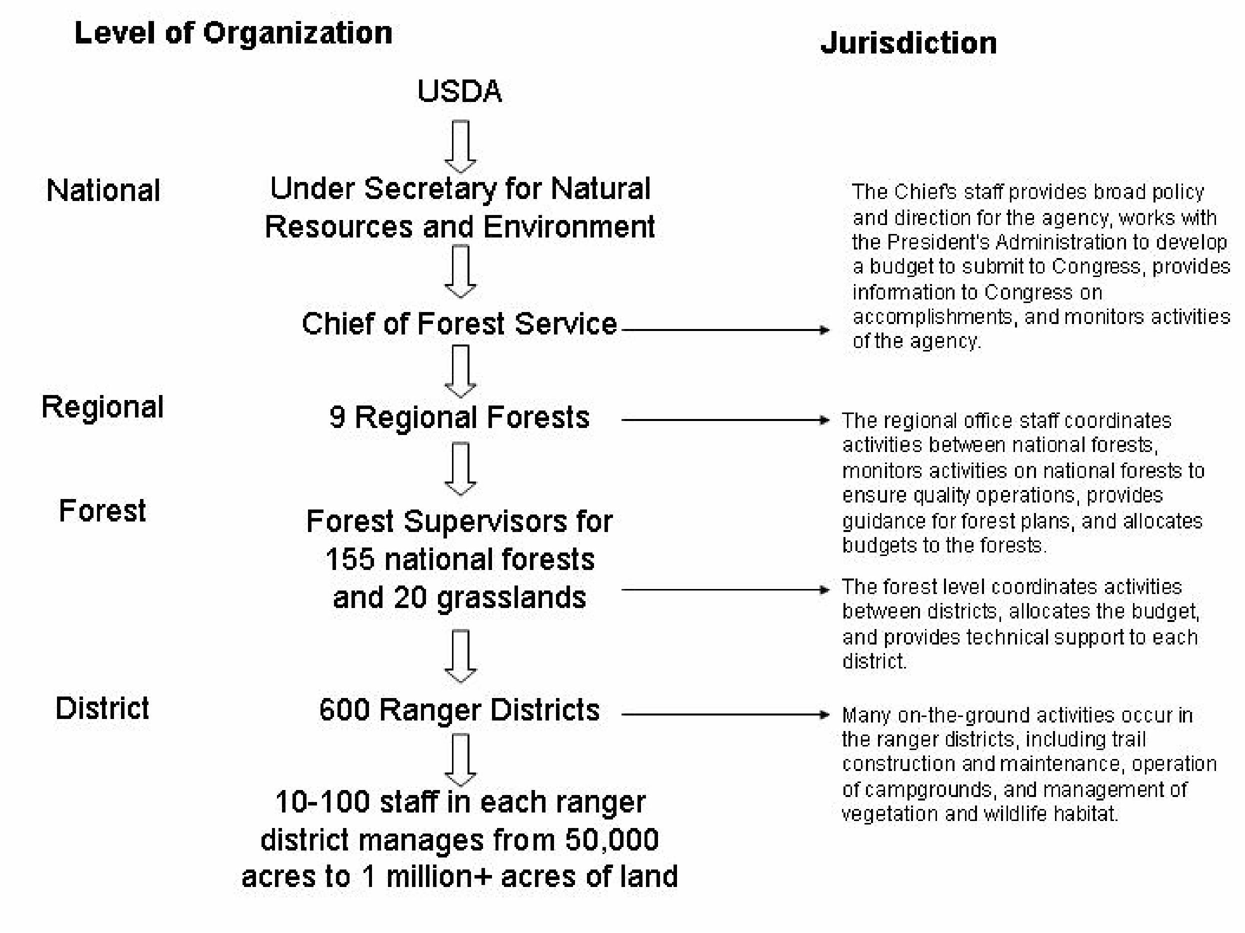
Table 3.2. Case Study Outline Foci for the ONF: current ecosystem stresses, management goals, current management methods, and climate change impacts

Current ecosystem stresses	Management goal(s)	Current methods	Climate impacts on ecosystems and management practices
Historical timber harvest impacts on landscape	Promote species and landscape biodiversity Increase late seral habitat Protect old-growth dependent species	Silvicultural treatment to achieve a broad range of habitats for native species Silvicultural treatments to increase rate of “old growth” structure development Same as above	Depends on how area and frequency of disturbances changes (windthrow, fire, endemic/exotic insect/pathogen outbreaks). Increases in the above, and their interactions, in ONF per se are understudied because they have not been large problems. All are climate mediated, and could become so, but unknown impact on management practices. Currently, the main disturbance legacy on ONF is 20th century logging.
Aquatic ecosystem degradation	Restore aquatic ecosystems to conditions that support endangered species	Riparian restoration, culvert rehabilitation	Warming waters, changes in timing of seasonal snow/rain/runoff will increase need for restoration, but potentially limit its success rate as well.
Impacts of unmaintained, closed roads	Remove potential effects of unmaintained roads	Road restoration / rehabilitation; occasionally removal	If intense storms, flooding, or rain-on-snow events increase in frequency, closed road failures will likely increase in frequency. Multiple failures on the same road limit response/access. This will require substantial investment in new management efforts.
Invasive exotic species	Limit spread of new invasives Treat established invasive species	Preventative educ./strategies Treatment limited to hand pulling in most locations; herbicide where permitted.	If disturbances or recreational travel increase or if climate changes the competitive balance between natives and exotics , efficacy of current strategies uncertain
Endemic Insects	Currently none	Monitoring	Uncertain
Fire	Currently none	Suppression (rare)	Depends on interplay between climate-mediated fire and climate-mediated regeneration

3.12 Figures

Figure 3.1. Timeline of National Forest System formation and the legislative influences on the mission of the national forests.

Figure 3.2. Jurisdiction and organizational levels within the National Forest System.



The Chief's staff provides broad policy and direction for the agency, works with the President's Administration to develop a budget to submit to Congress, provides information to Congress on accomplishments, and monitors activities of the agency.

The regional office staff coordinates activities between national forests, monitors activities on national forests to ensure quality operations, provides guidance for forest plans, and allocates budgets to the forests.

The forest level coordinates activities between districts, allocates the budget, and provides technical support to each district.

Many on-the-ground activities occur in the ranger districts, including trail construction and maintenance, operation of campgrounds, and management of vegetation and wildlife habitat.

Figure 3.3. One hundred fifty-five National Forests and 20 National Grasslands across the United States provide a multitude of goods and ecosystems services, including biodiversity (USDA Forest Service Geodata Clearinghouse, 2007).

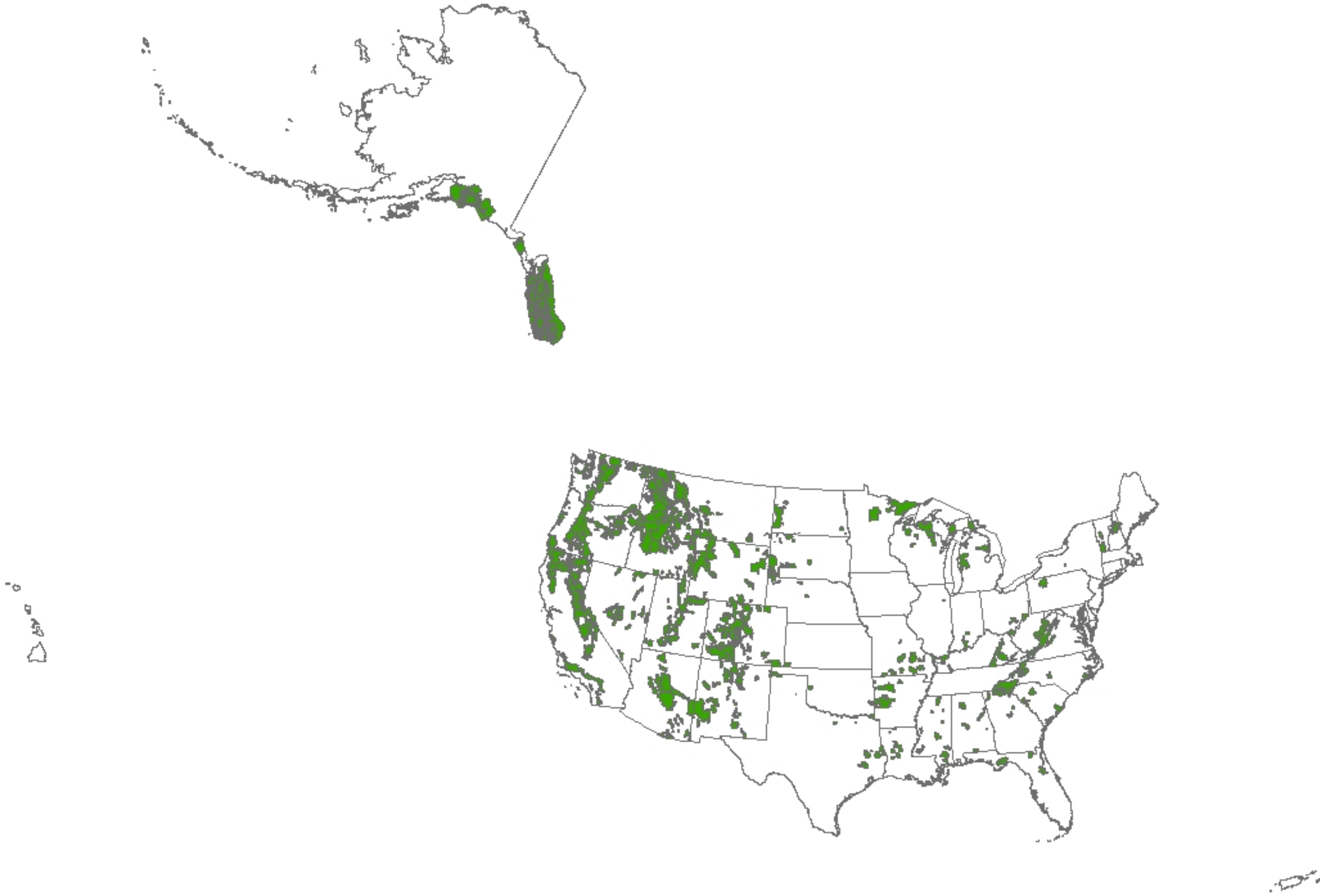


Figure 3.4. Historical harvest levels and grazing across the National Forests (USDA FS Forest Management; Mitchell, 2000).

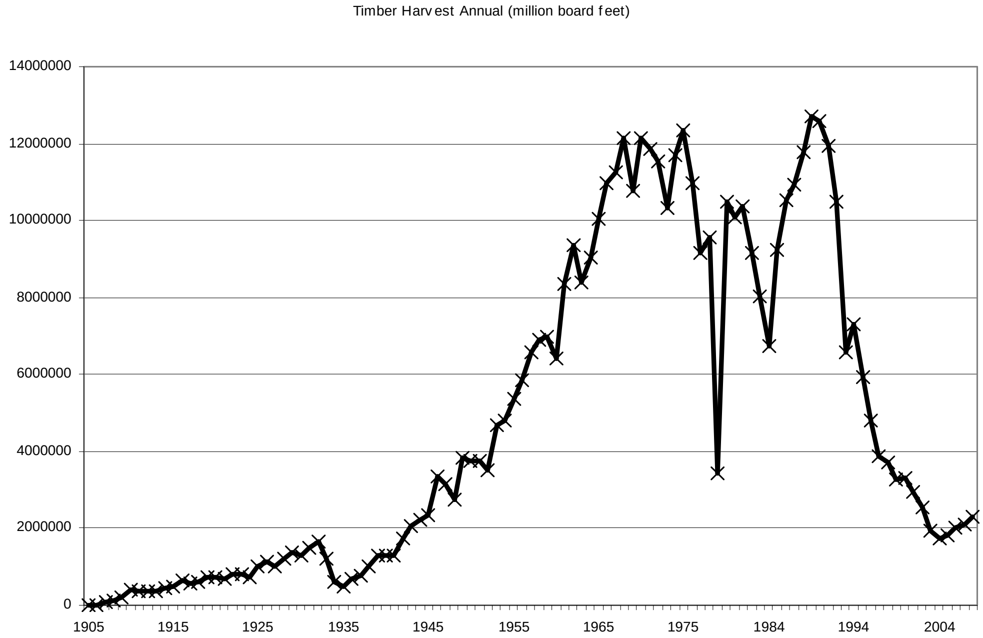
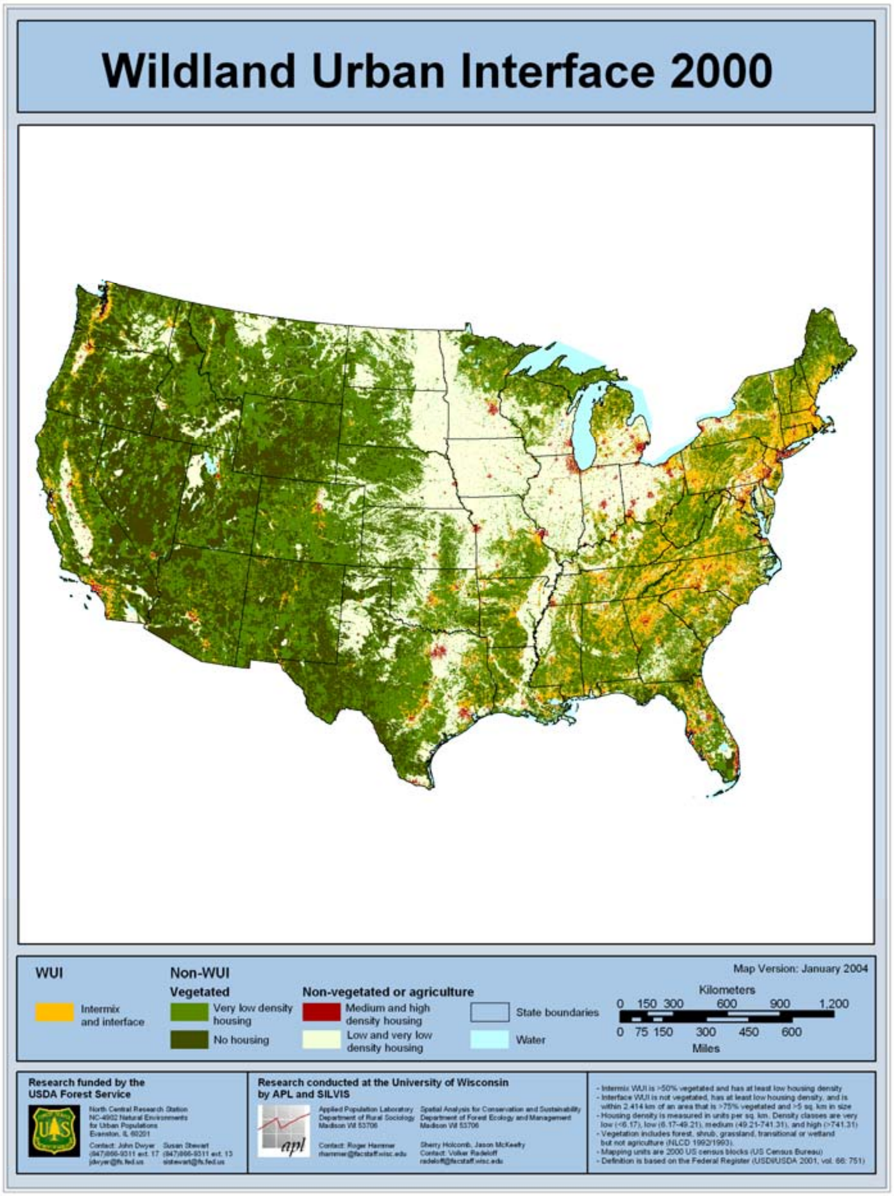


Figure 3.5. Wildland Urban Interface across the United States (Radeloff et al., 2005).



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Research conducted at the University of Wisconsin by APL and SILVIS

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- Intermix WUI is >50% vegetated and has at least low housing density
- Interface WUI is not vegetated, has at least low housing density, and is within 2.414 km of an area that is >75% vegetated and >5 sq. km in size
- Housing density is measured in units per sq. km. Density classes are very low (<6.17), low (6.17-49.21), medium (49.21-741.31), and high (>741.31)
- Vegetation includes forest, shrub, grassland, transitional or wetland but not agriculture (NLCD 1992/1993).
- Mapping units are 2000 US census blocks (US Census Bureau)
- Definition is based on the Federal Register (USDI/USDA 2001, vol. 66: 751)

Figure 3.6. Influence of non-native earthworms on eastern forest floor dynamics (Frelich *et al.*, 2006). Forest floor and plant community at base of trees before (a, left-hand photo) and after (b) European earthworm invasion in a sugar maple-dominated forest on the Chippewa National Forest, Minnesota, USA. Photo credit: Dave Hansen, University of Minnesota Agricultural Experimental Station.

Figure 3.7. Conceptual model of the relative time scales for disturbance vs. climatic change alone to alter ecosystems. Times are approximate. From McKenzie *et al.* (2004).

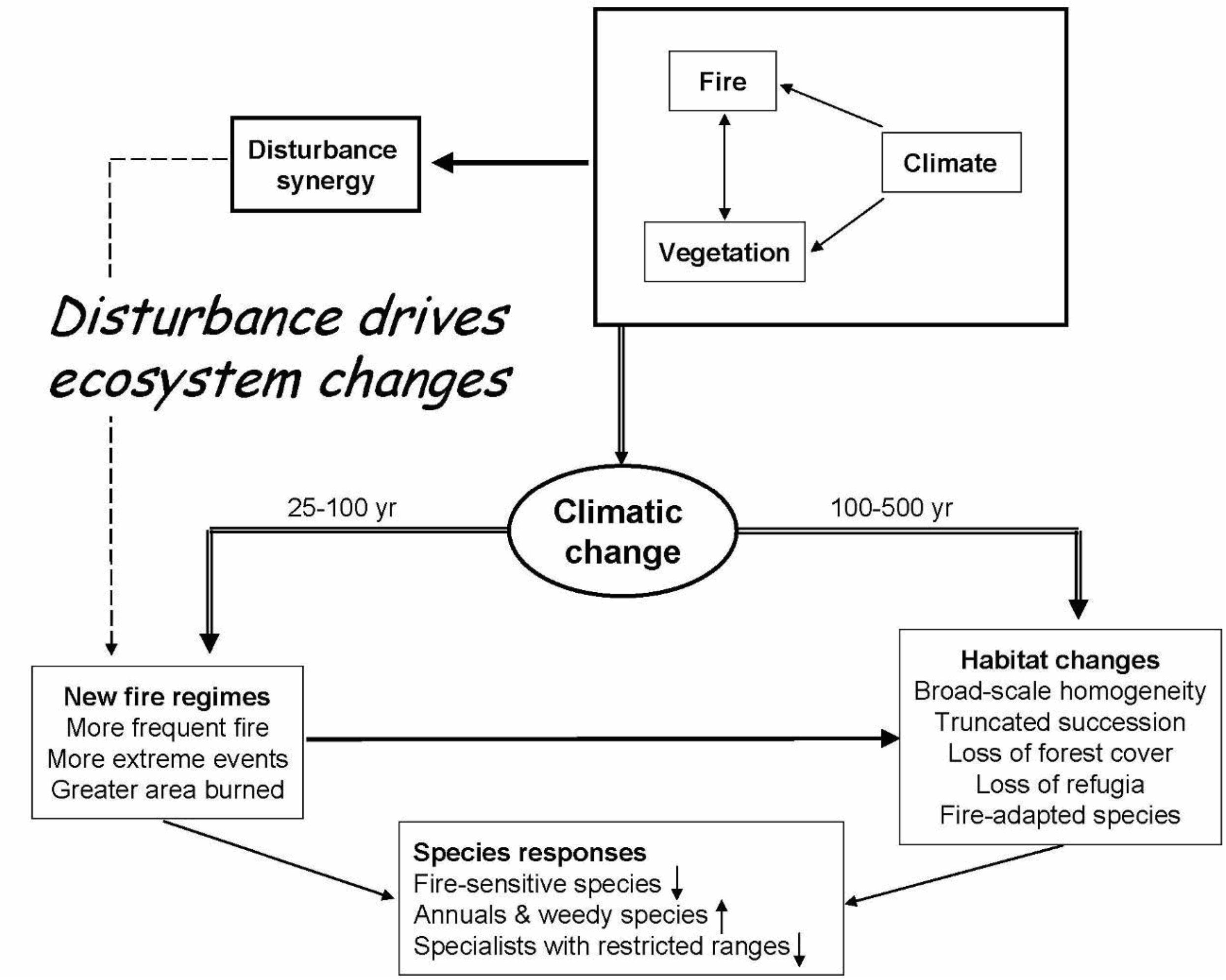


Figure 3.8. Stress complex in pinyon-juniper woodlands of the American Southwest. Adapted from McKenzie *et al.* (2004).

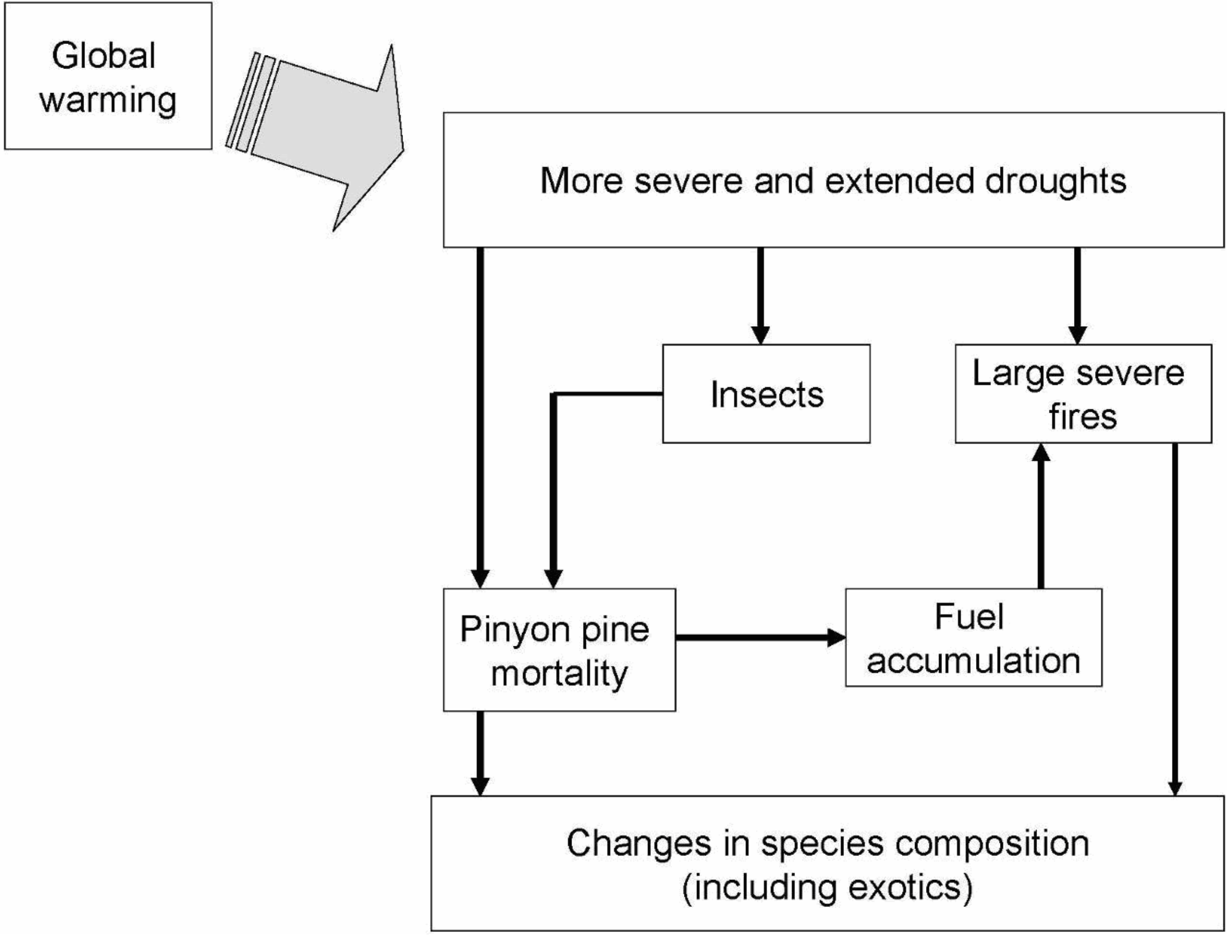


Figure 3.9. Stress complex in Sierra Nevada and southern Californian mixed-conifer forests. From McKenzie, Peterson, and Littell (In Press).

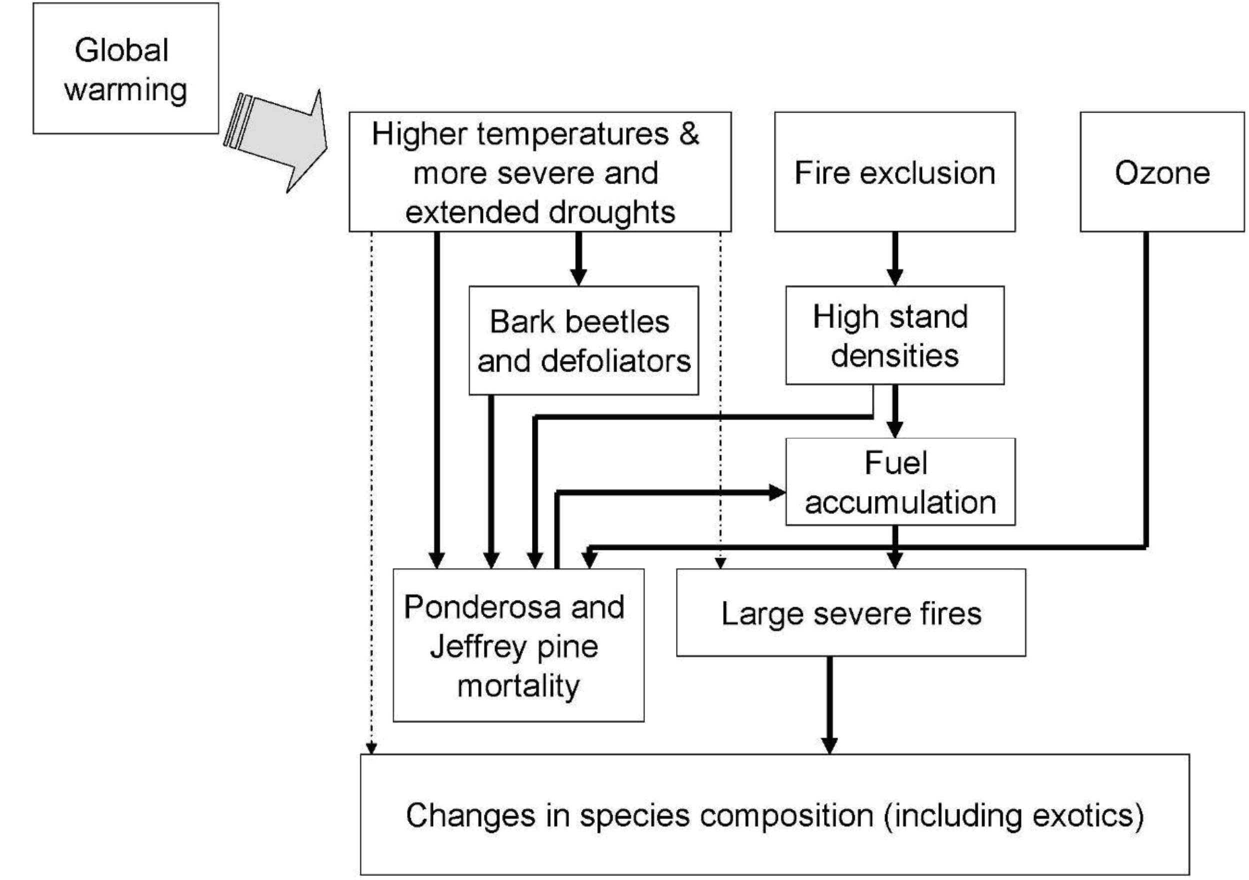


Figure 3.10. Stress complex in interior (BC and USA) lodgepole pine forests. From McKenzie, Peterson, and Littell (In Press).

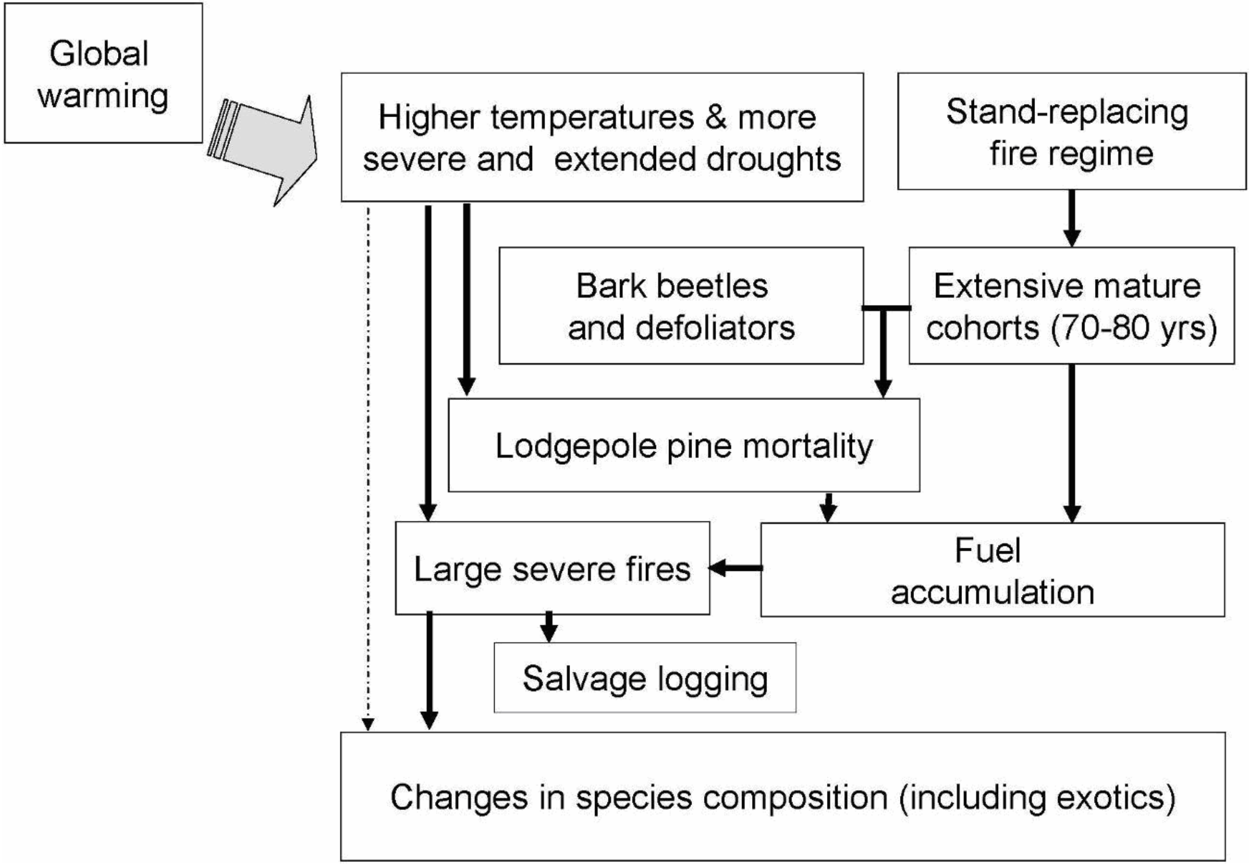


Figure 3.11. Stress complex in the interior and coastal forests of Alaska. From McKenzie, Peterson, and Littell (In Press).

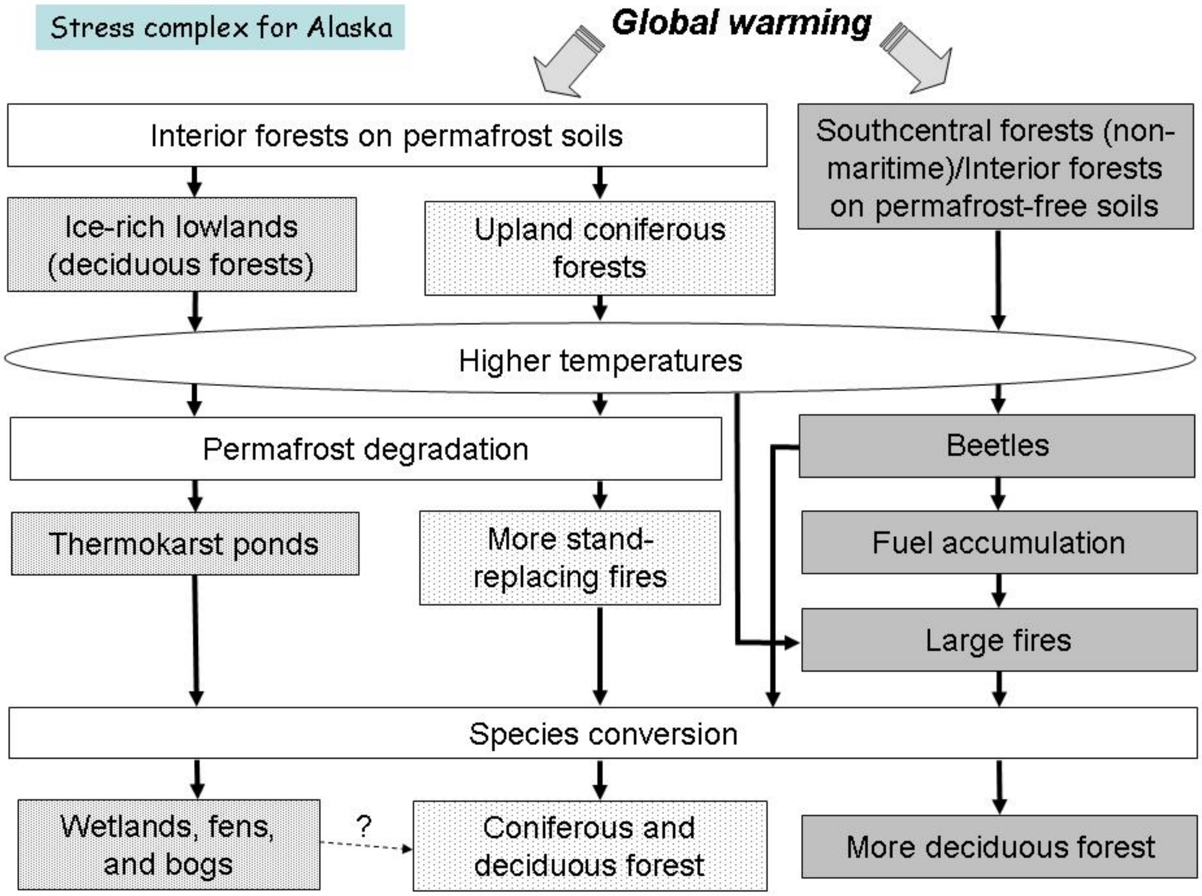
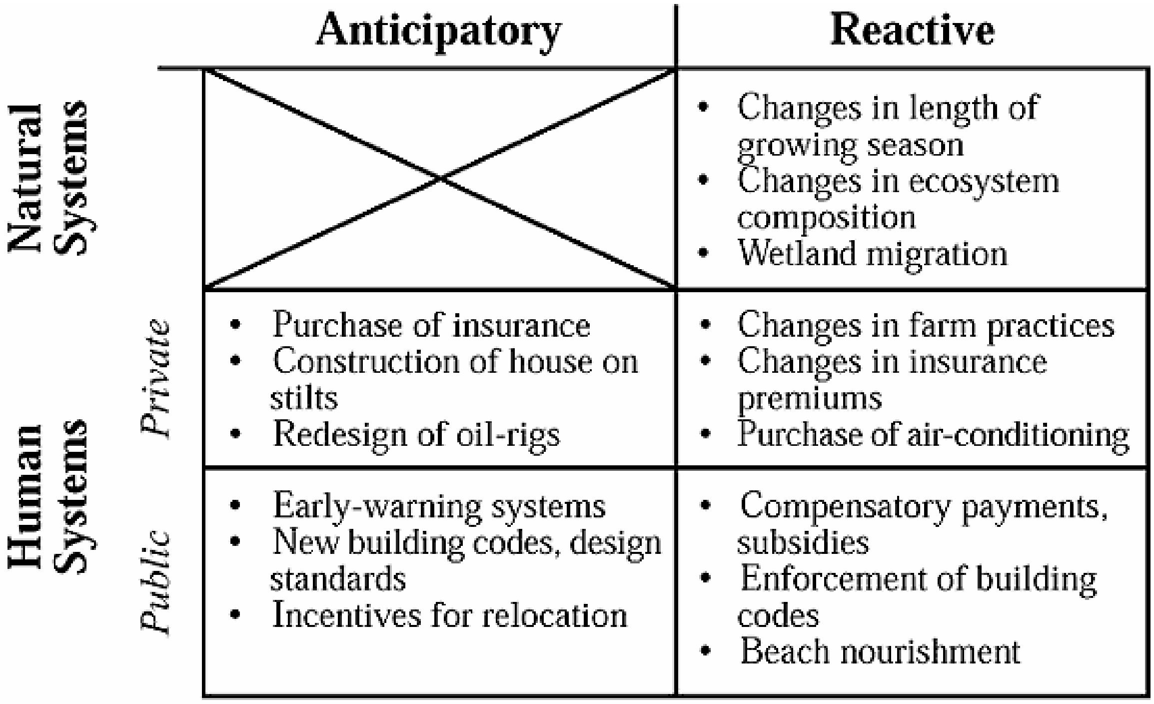


Figure 3.12. Anticipatory and reactive adaptation for natural and human systems (IPCC, 2001b).



		Anticipatory	Reactive
Natural Systems			• Changes in length of growing season • Changes in ecosystem composition • Wetland migration
Human Systems	Private	• Purchase of insurance • Construction of house on stilts • Redesign of oil-rigs	• Changes in farm practices • Changes in insurance premiums • Purchase of air-conditioning
	Public	• Early-warning systems • New building codes, design standards • Incentives for relocation	• Compensatory payments, subsidies • Enforcement of building codes • Beach nourishment

Figure 3.13. Map and location of the Tahoe National Forest, within California (a) and the Forest boundaries (b) (USDA Forest Service, 2007b; USDA Forest Service, 2007d).

a)

b)


Tahoe NF
District Boundary
Major Road
Pacific Crest Trail
Ranger Station
Visitor Center
Sierraville
Camptonville
Yuba River District
Sierraville District
Truckee
Nevada City
Big Bend
Truckee District
American River District
Foresthill

Figure 3.14. Thinned stands for fuel reduction and resilience management, part of the Herger-Feinstein Quincy Library Pilot Project. Photo courtesy of Tahoe National Forest.

Figure 3.15. Former salmon habitat (rivers marked in bold black) of the Sierra Nevada. Tahoe National Forest (TNF) rivers are scheduled to have salmon restored to them in current national forest planning. Adaptive approaches suggest that future waters may be too warm on the TNF for salmon to survive, and thus, restoration may be inappropriate to begin. Map adapted from (Sierra Nevada Ecosystem Project Science Team, 1996).

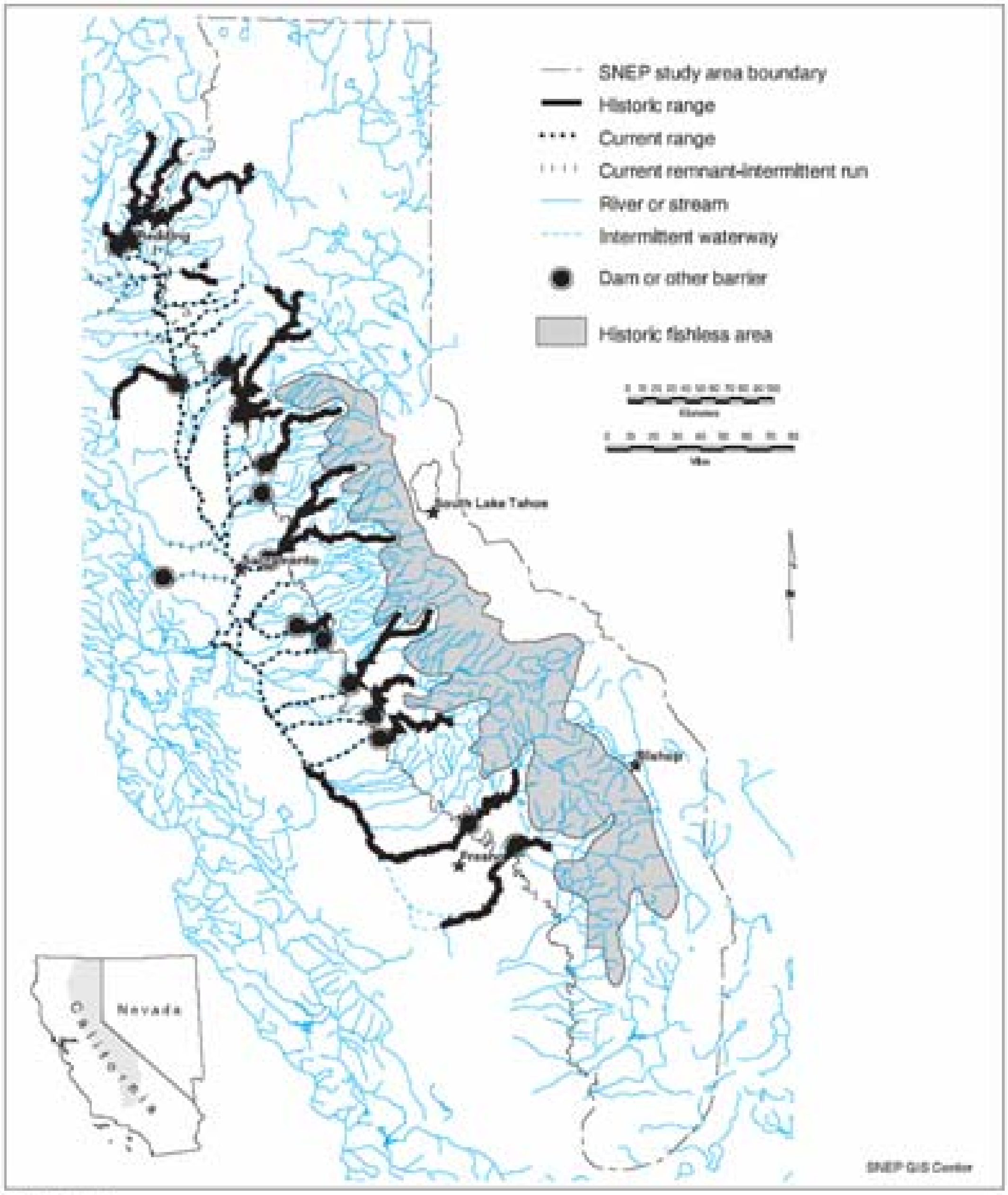


FIGURE 33.1

Figure 3.16. Olympic Peninsula land ownership and Northwest Forest Plan allocation map. Olympic National Forest contains lands (dark boundary) with different land use mandates and regulations. These include adaptive management areas, late-successional reserves, and Wilderness areas. Map courtesy of Robert Norheim, Climate Impacts Group, University of Washington.

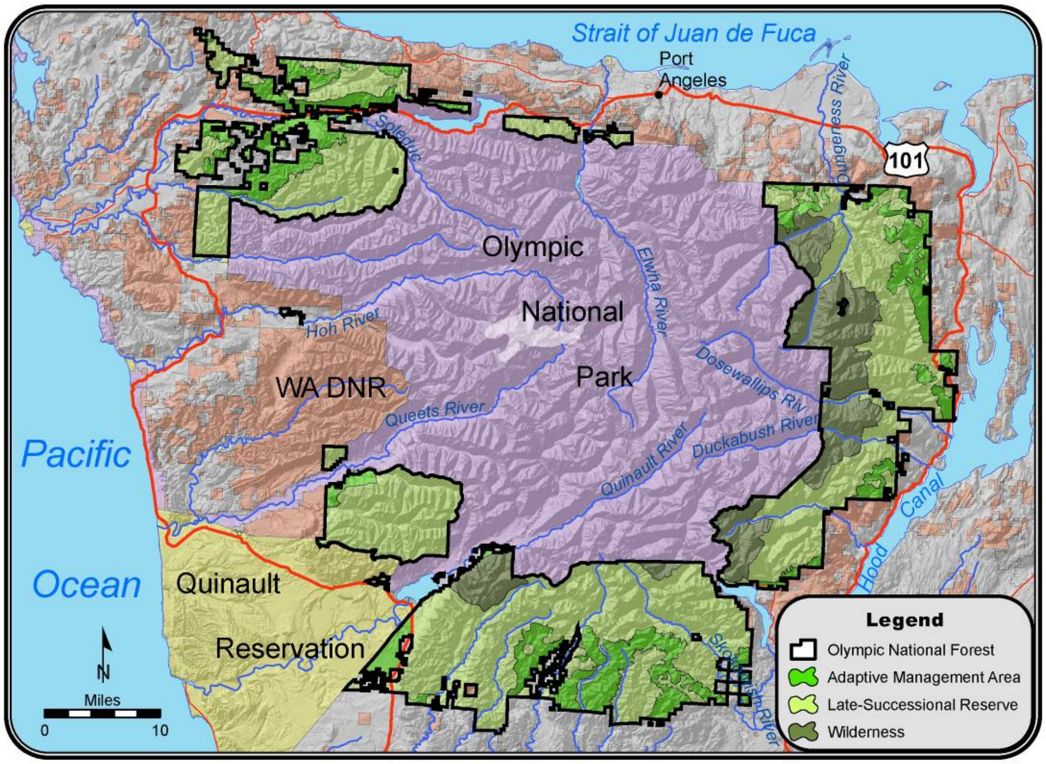
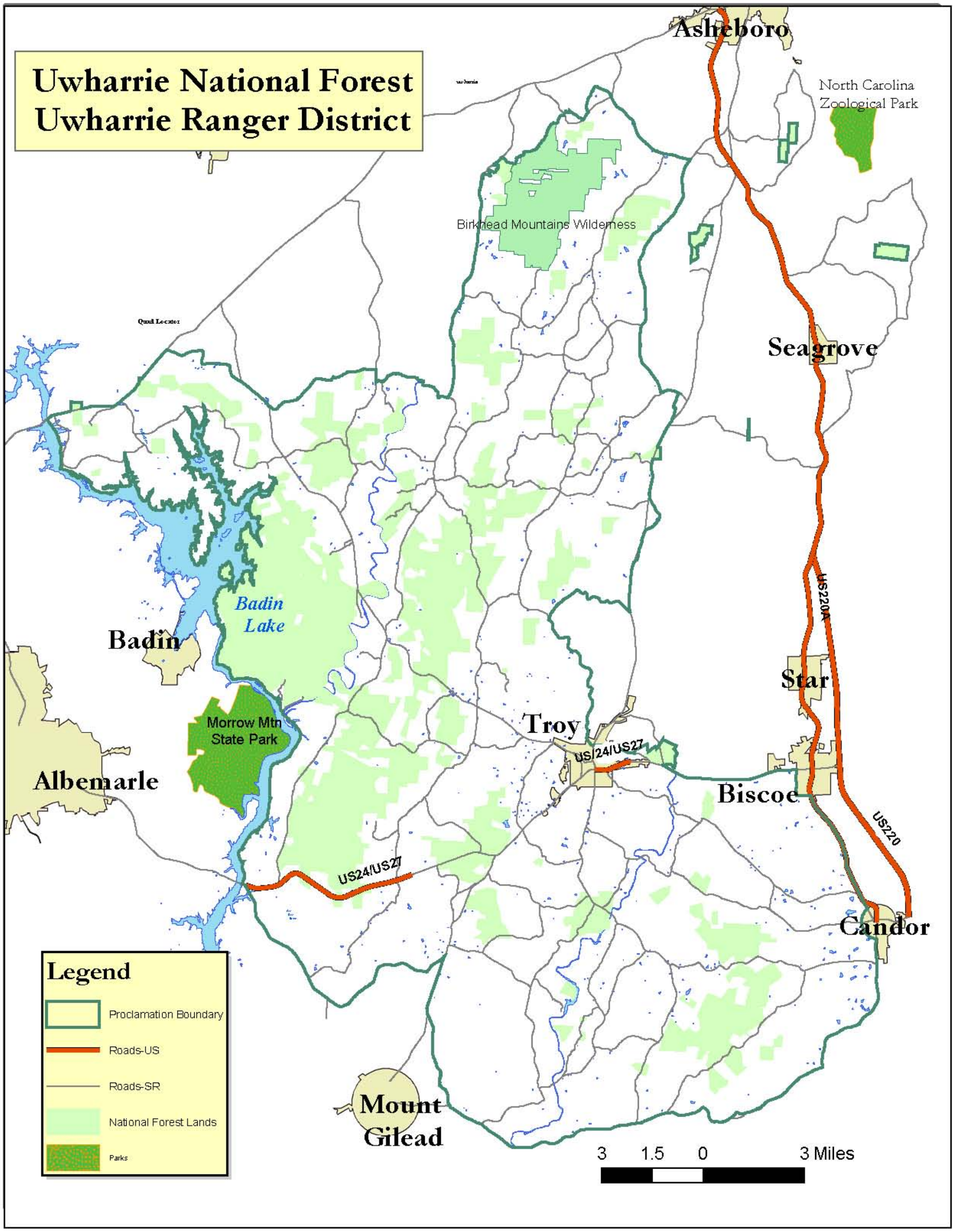


Figure 3.17. Olympic National Forest is charged with mitigating the legacy of 20th century timber harvest. Landscape fragmentation and extensive road networks (upper left) are consequences of this legacy that influence strategies for adaptation to climate change. The old-growth forest dependent northern spotted owl (upper right) is one focus of the NWFP, which prescribes forest practices but does not address climatic change. Changes in the timing and intensity of runoff expected with climate change are likely to interact with this legacy to have negative impacts on unmaintained roads (lower left) that in turn will impact water quality for five threatened or endangered species of anadromous and resident fish. Photo Credits: All photos courtesy Olympic National Forest.

1 **Figure 3.18.** Map of the Uwharrie National Forest in North Carolina (USDA Forest Service,
2 2007e).



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