TOWARD A SHARED UNDERSTANDING OF CLIMATE-SMART RESTORATION ON AMERICA'S NATIONAL FORESTS

A Science Review and Synthesis

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Cover image: Ensuring the sustainability and resilience of national forests in the face of rapid climate change will require a dramatic increase in the pace, scale, and quality of ecologically appropriate and climate-smart forest restoration (Shasta-Trinity National Forest, California). Photo: Rick Hanover/USFS.

Toward a Shared Understanding of Climate-Smart Restoration on America's National Forests is available online at www.nwf.org/ClimateSmartRestoration

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Assuring a sustainable and resilient future for America's national forests requires that restoration practices look to the future while learning from the past (Deschutes National Forest, Oregon). Photo: Buddy Mays/Alamy.

EXECUTIVE SUMMARY

A rapidly changing climate, including rising temperatures, changing precipitation patterns, and more extreme storms, is having profound consequences for America's national forests. Climate-related impacts on forest systems include larger and more severe disturbances (e.g., wildfires, drought, and insect outbreaks), shifts in tree species ranges and forest composition, and changes in forest dynamics and regeneration capacity.

Many of our national forests have been significantly modified by past management and land use, and forest managers are contending with ongoing threats from invasive species, disease outbreaks, and other challenges. With the added impacts on forest systems from climate change, an enormous mismatch exists between the level of restoration work currently underway and the scale of the challenge. As a result, there is a need to substantially increase the pace, scale, and quality of restoration on our national forests, and to ensure that this restoration is carried out in an ecologically appropriate and climate-smart manner.

Continuing and accelerating climatic changes, and their associated impacts, have significant implications for the effectiveness of traditional forest restoration efforts, including reliance on historical conditions as benchmarks for restoration outcomes. Drawing on a growing body of evidence, research, and experimentation, this science review and synthesis looks at how climate change is inspiring an important evolution in approaches for national forest restoration and management. Over the past decade, the U.S. Forest Service has made considerable progress in understanding the effects of a changing climate on forest ecosystems and working to incorporate climate considerations into its planning and management. Nonetheless, varying perspectives on what climate change means for ecological restoration in practice and how to navigate potential trade-offs continue to pose challenges to integrating climate adaptation and mitigation in national forest planning and management.

Addressing this challenge would benefit from a shared understanding among agency staff and stakeholders of what constitutes a forward-looking and climate-smart approach to national forest restoration. To this end, this report reviews and summarizes recent advances and ongoing evolution in how the concepts and principles of climate adaptation and mitigation can help promote the development and application of climate-smart forest restoration.

To inform further discussion and help advance such a shared understanding, we propose the following overarching principles for climate-smart restoration on America's national forests.

- ***Look to the future while learning from the past.*** Forest planners and their partners should develop forward-looking goals for management that build on an understanding of the historical range of variability and past responses to disturbance, but account for and anticipate future climate-related changes.

- ***Embrace functional restoration of ecological integrity.*** As climatic conditions continue to change, it will become increasingly difficult to restore the ecological integrity of forest systems based on historical species compositions and structures. Rather, goals for ecological integrity should emphasize the capacity of forest systems to adapt and adjust, including through enhancing functional diversity and habitat complexity.

- ***Restore and manage forests in the context of larger landscapes and longer time frames.*** Climate change necessitates that planners and managers consider larger spatial scales (e.g., watersheds, landscapes, and regions) and longer time frames to ensure that localized and near-term actions do not compromise the capacity of forests to accommodate and adjust to changing conditions.

- ***Adopt agile planning and management approaches that accommodate and address uncertainty.*** Restoring and managing forests in the face of continuous climatic change requires decision-making under uncertainty, underscoring the importance of adaptive planning and management, including the consideration of multiple plausible scenarios of future conditions.

- ***Address climate risks by linking adaptation strategies to key climate-related impacts.*** Understanding climate vulnerabilities and risks to priority forest resources and values serves as the

This report reviews and summarizes recent advances and ongoing evolution in how the concepts and principles of climate adaptation and mitigation can help promote the development and application of climate-smart forest restoration.

In designing restoration projects forest managers will need to determine when and where to manage for persistence—as in this boreal conifer stronghold—and when to facilitate forest transitions (Superior National Forest, Minnesota). Photo: Eli Sagor/UMN.

basis for developing and implementing adaptation strategies that are capable of reducing risks and sustaining the ecological, social, and economic systems associated with national forests.

- ***Manage for change, not just persistence.*** As climatic conditions exceed historical ranges of variability, national forest planners will need to consider how to reconcile "desired" future conditions with climatically achievable future conditions. Planners and managers increasingly will need to determine when and where it may be possible to manage for the persistence of current/historical forest conditions, and when it may be necessary to manage for change by accepting or even facilitating ecological transitions.

- ***Optimize, rather than maximize, carbon sequestration opportunities.*** National forests will play an increasingly important role in achieving the nation's climate mitigation goals. Attempting to maximize carbon sequestration and storage, however, can undermine other important ecosystem services and national forest values. Managers should instead seek to optimize sequestration opportunities by balancing carbon goals with other important forest restoration, management, and resilience outcomes.

- ***Enhance collaboration to identify shared values, navigate trade-offs, and maximize synergies in the context of changing conditions.*** Managing forests for multiple, sustained ecosystem services will necessarily entail trade-offs, particularly given the challenges and uncertainties associated with changing climatic conditions. Engaging local communities and diverse constituencies as early as possible in the forest planning process helps gain buy-in and identify opportunities to minimize trade-offs and maximize synergies, including acknowledgment and discussion of the potential for fundamental changes in national forest conditions.

Restoring our national forests in the face of rapid climate change increasingly will require the deployment of climate-smart approaches to planning and management. This report—and the above principles—are intended to advance development of a shared understanding of climate-smart forest restoration and to promote dialogue among national forest managers and their partners about how to ensure a sustainable and resilient future for America's national forests.

Covering 193 million acres across the United States, the National Forest System provides a wide array of ecosystem services, such as clean water, wildlife habitat, and recreational opportunities (White Mountain National Forest, New Hampshire). Photo: Mattia Panciroli/Flickr.

1. INTRODUCTION

America's national forests, which represent approximately 20% of all U.S. forest lands, are a treasured resource (Oswalt et al. 2019). From the rain-drenched evergreens of the Pacific Northwest to the brilliant fall displays of New England's deciduous trees, national forests are a core element of our regional identities and economies. Administered by the U.S. Forest Service, the National Forest System includes 175 national forests and grasslands spread across 193 million acres. These lands and waters offer a wide array of ecological services and economic benefits, including provision of timber and fiber, clean water, wildlife habitat, and recreational opportunities. As society grapples with the challenge of a rapidly changing climate, our national forests are increasingly recognized as providing yet another key service: carbon uptake and storage.

Yet, national forests themselves are being profoundly affected by climate change (Millar and Stephenson 2015, Vose et al. 2018, Anderegg et al. 2020). Rising temperatures, increasingly erratic precipitation patterns, and more powerful storms are exacerbating the impacts of existing forest threats and disrupting key ecological processes. Climatic changes are increasing the frequency and/or severity of droughts, wildfires, insect epidemics and other forest disturbances, and climate-induced tree mortality events are becoming widespread, especially in the West (van Mantgem et al. 2013, Millar and Stephenson 2015, Vose et al. 2018, Anderegg et al. 2019). Further, changing climatic conditions can complicate—or even prevent—the recovery and regeneration of forests following such disturbances (e.g., Coop et al. 2020, Rodman et al. 2020, Meyer et al. 2021).

Many of our national forests have been modified by past management and land use, including timber harvest, livestock grazing, long-term fire suppression, energy development, and expansion of housing in nearby wildland areas (e.g., Naficy et al. 2010, Radeloff et al. 2010, Haugo et al. 2015, Battaglia et al. 2018, BLM 2018, D'Amato et al. 2018, Franklin et al. 2018). National forest managers are also contending with ongoing threats from invasive species, disease outbreaks, and other challenges (e.g., Poland et al. 2021). Given the added impacts on forest systems from a rapidly changing climate, an enormous mismatch exists between the current level of forest restoration work and the scale of the challenge (USFS 2012a). The Forest Service estimates that 65–82 million acres in the National Forest System need proactive restoration and management to reduce the risks from these multiple and interconnected stressors (Buford et al. 2015).

To address these growing concerns, there is a need to substantially increase the pace, scale, and quality of restoration on our national forests, an endeavor that will require significant additional funding and capacity (Gandhi et al. 2019). To ensure that the benefits of those investments will endure for generations to come, restoration must account for current and future climatic conditions, taking into consideration both *climate adaptation,* which seeks to reduce climate-

There is a need to substantially increase the pace, scale, and quality of restoration on our national forests, an endeavor that will require significant additional funding and capacity.

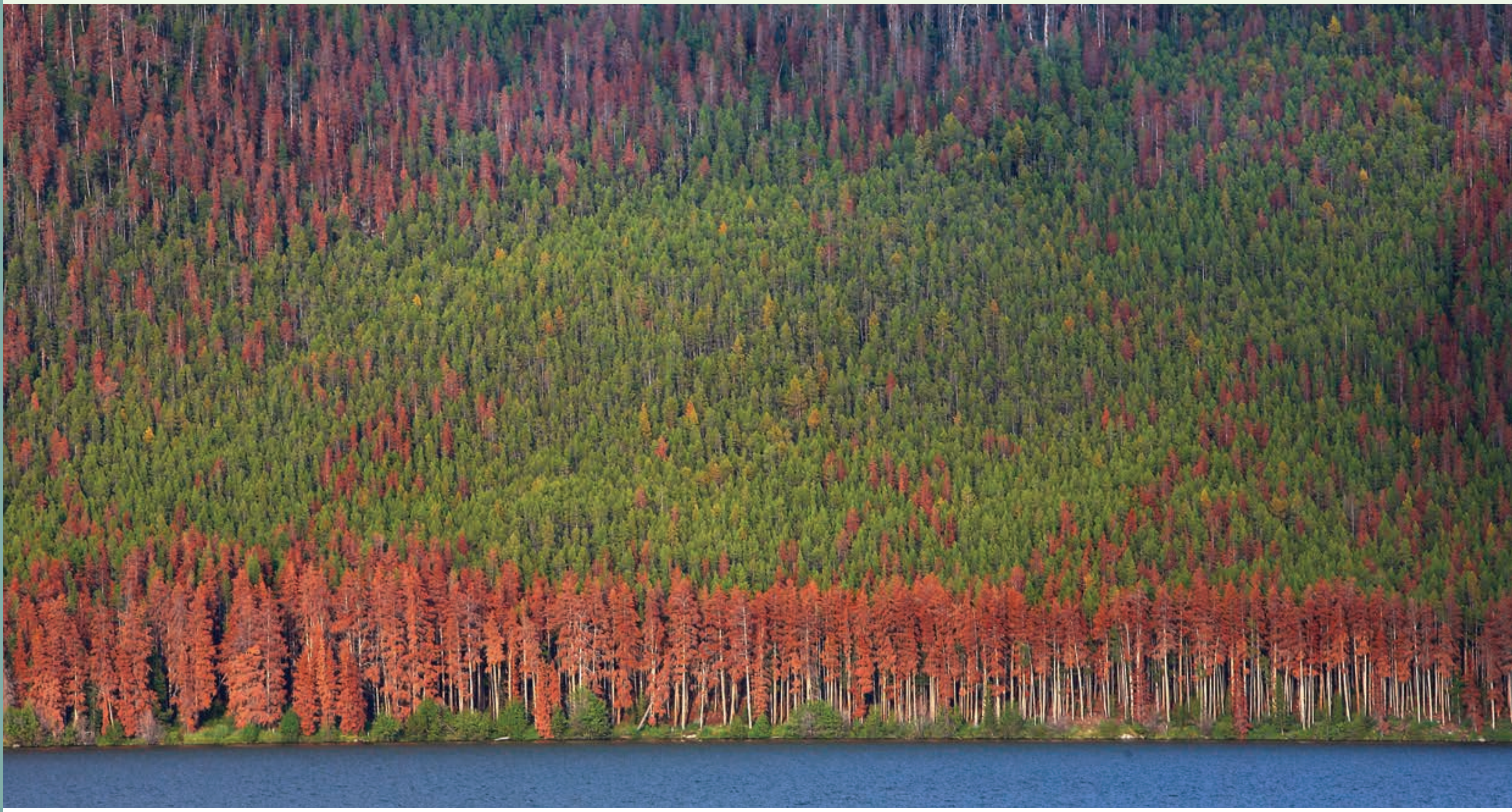
For much of its history, the Forest Service sought to suppress virtually all wildland fires, a legacy that has contributed to increasingly dense forests and higher fuel loads. Photo: laffertyryan/Flickr.

related impacts on forest systems, as well as *climate mitigation,* which focuses on stabilizing the climate through improved carbon management. National forest restoration and management must also be carried out in ways that support the broad array of environmental benefits and services that Americans now expect from these landscapes—a challenge that necessitates engaging diverse stakeholders that may have divergent and sometimes conflicting values. Thus, in addition to requiring the application of the best available ecological and climate science, restoring America's forests will depend on strengthening societal understanding, engagement, and support for action. Despite the considerable challenges facing the National Forest System, we can help ensure a sustainable and resilient future for our national forests by embracing ecologically appropriate and climate-smart approaches to restoration.

1.1. PURPOSE OF THIS REVIEW

Key to realizing this vision is the development of a collective, science-based understanding of what it means to do forest "restoration" in an era of accelerating climate change. This review and synthesis of the science underlying climate-smart forest restoration is intended to help advance such a shared understanding. In particular, it is designed to help organizations and individuals who are engaged in national forest–related conservation and restoration understand the implications of rapid climatic changes for achieving desired forest restoration outcomes and enhance their ability to productively collaborate with the Forest Service in achieving common goals.

Indeed, the Forest Service has made considerable progress over the past decade in understanding the impacts of climate change on forest ecosystems and identifying approaches for better incorporating climate adaptation and mitigation principles into its work. To scale up the application of these practices, federal land managers need committed, informed, and climate-savvy partners in the state, tribal, nonprofit, and private sectors. Drawing on a growing body of evidence, research, and experimentation, this review looks at how rapid and accelerating climate change is inspiring an important evolution in policies and approaches for national forest restoration and management. It is intended to serve as a foundation for continued dialogue and collaboration to enhance the application of such approaches in practice.



Warming winter temperatures have contributed to increases in mountain pine beetle outbreaks and associated tree mortality across much of the Rocky Mountains (Arapaho National Recreation Area, Colorado). Photo: A.J. Schroetlin/Flickr.

2. AMERICA'S FORESTS FACE A CHANGING FUTURE

As Gifford Pinchot, the first chief of the Forest Service, wrote, "Next to the earth itself the forest is the most useful servant of man. Not only does it sustain and regulate the streams, moderate the winds, and beautify the land, but it also supplies wood, the most widely used of all materials … The object of practical forestry is precisely to make the forest render its best service to man in such a way as to increase rather than to diminish its usefulness in the future" (Pinchot 1905). Nevertheless, for much of the 20th century, timber harvest was the primary emphasis of national forest management (D'Amato et al. 2018, Franklin et al. 2018), and activities such as roadbuilding, logging, and fire suppression resulted in considerable alteration of natural forest conditions.

By the middle of the 20th century, concerns about the continued sustainability of timber resources, along with growing public interest in ecological and noneconomic social values, led to enactment of the Multiple-Use Sustained-Yield Act, which explicitly called for national forests and grasslands to be managed for a range of purposes, including "outdoor recreation, range, timber, watershed, wildlife and fish" (MUSYA 1960). Subsequent laws and policies, including the National Environmental Policy Act, the Endangered Species Act, and especially the National Forest Management Act of 1976, have further guided the agency's planning and management toward the broader goal of sustaining ecosystem health and diversity. By the turn of the 21st century, the concepts of ecosystem management and ecological restoration had gained prominence, with a view toward achieving a mosaic of forest conditions on the landscape, often benchmarked by estimates of the historical (or “natural”) range of variability (Millar 2014). This shift reflected a recognition of the key role of natural processes like succession and disturbance in supporting forest health and biodiversity goals.

Yet, on top of pervasive threats from invasive species, land use change, and other major stressors, the growing risks from a rapidly changing climate have compelled updated forest planning and management approaches across all of the nation’s forest systems, including those managed by the Forest Service (USFS 2011a, Vose et al. 2018). Indeed, the impacts and risks from climate change were explicitly addressed in the 2012 Forest Service Planning Rule (2012 Planning Rule), which reflects the first substantive update to National Forest System planning in 30 years (USFS 2012b).

2.1. UNDERSTANDING CLIMATE CHANGE AND ITS IMPACTS ON FOREST ECOSYSTEMS

The relationship between atmospheric carbon dioxide (CO_2) levels and warming of the Earth through the “greenhouse effect” has been well established scientifically since the late 1800s, based on fundamental principles of physics and chemistry (Anderson et al. 2016). Human activities, especially the burning of fossil fuels, have increased atmospheric concentrations of CO_2 from about 280 parts per million (ppm) in the mid-1800s to about 410 ppm today—far higher than at any time in at least the last 800,000 years (Lüthi et al. 2008, Kopp et al. 2017) (see Figure 1). Higher atmospheric CO_2 has already contributed to a notable increase in the observed temperature in the

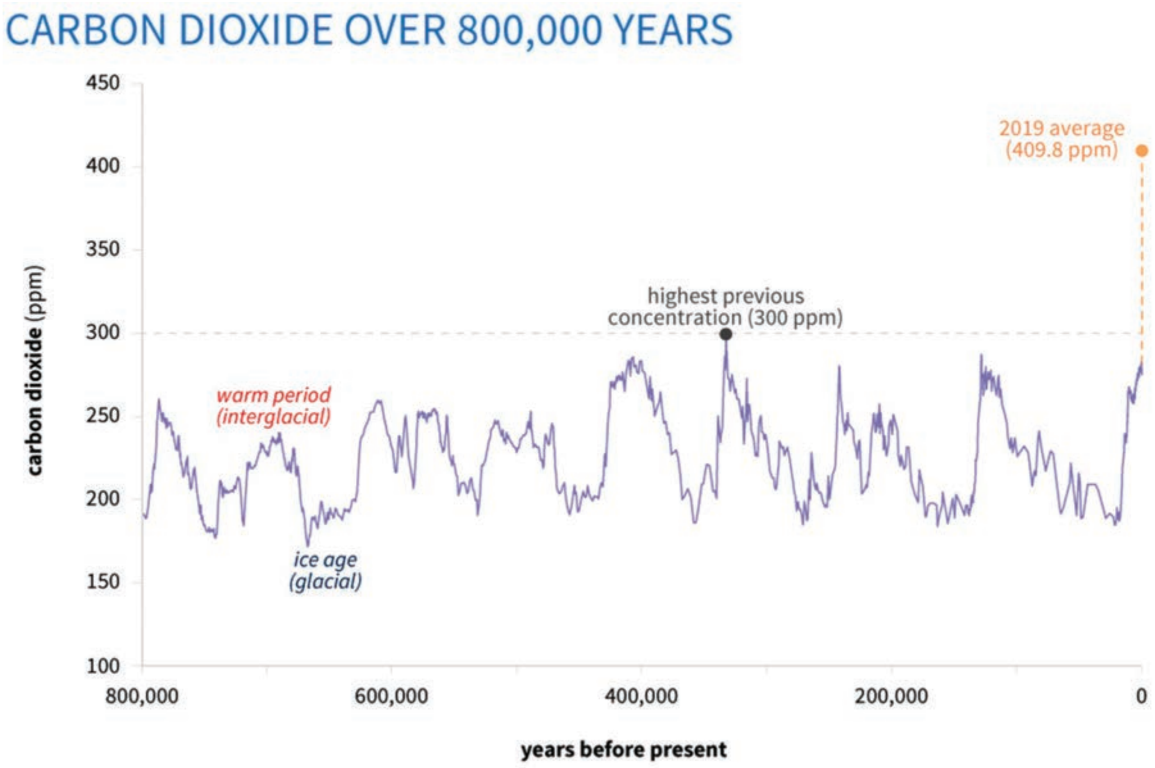


Figure 1. Atmospheric carbon dioxide. *Atmospheric carbon dioxide (CO_2) concentrations (in parts per million [ppm]) are now higher than at any point in the past 800,000 years. On a geologic timescale, the increase since 1850 (shown in orange) looks virtually instantaneous. Source: NOAA (2020).*

United States. Nationally, average air temperatures are now more than 1.8°F warmer than the historical record, with Alaska warming at about twice the rate of the lower 48 states (Vose et al. 2017).

Further demonstrating this warming trend, the past decade (2011–2020) was the warmest on record, and the world's seven hottest years have occurred since 2014 (NOAA 2021). These temperature increases are evidence of rapid climate change, and without substantial reductions in atmospheric CO_2 concentrations, average temperatures, and the frequency of multiday heat waves, will continue to rise. The annual average temperature over the contiguous United States is projected to increase by about 2.5°F by mid-century relative to 1976–2005, which suggests that recent record-setting temperatures may become "common" within a few decades (Vose et al. 2017). Rising temperatures, of course, are just one aspect of our changing climate. We are also experiencing altered precipitation patterns across the country, including shifts in types, seasonality, intensity, and variability (Easterling et al. 2017). Of particular concern is the increasing frequency and severity of extreme weather events, including hurricanes, heavy rainstorms, and droughts.

Over the past several decades, forest managers across the country have observed escalating climate-related impacts, and scientists project significant changes to continue in the years and decades to come (Joyce et al. 2014, Vose et al. 2018). For example, warmer winters and extended growing seasons are promoting insect outbreaks and facilitating the establishment and spread of invasive species. Temperature increases coupled with drought are associated with larger wildfires and a longer fire season. Warmer, wetter conditions favor more extreme flooding and can promote the establishment of certain forest pathogens. As plant and animal species across the country experience these and other changing conditions, many are responding through shifts in phenology (timing of key life-cycle events like leaf emergence or flowering), changes in growth, reproduction, and mortality rates, and altered abundance patterns and distributional ranges. These species-level responses are also leading to ecosystem-level shifts, including changes in ecosystem composition, structure, and function.

The following overview represents just a sampling of the extensive and growing body of scientific literature on the known and potential future impacts of climate change on North America's forests, including those within the National Forest System.

2.1.1. More Severe Drought and Heat Waves

Increasing temperatures and altered precipitation patterns are contributing to changes in drought conditions across the United States, and scientists project that the frequency and severity of drought in many areas will increase as the climate continues to change (Strzepek et al. 2010, Chiang et al. 2018, Vose et al. 2018). Although droughts have been an important factor shaping forest characteristics and fire regimes over millennia, as temperatures continue to rise and human water use modifies hydrologic

Low water levels and warmer temperatures are putting additional stress on salmon in the Pacific Northwest and Alaska (Chinook salmon, Ketchikan Creek, Alaska). Photo: VC Images/Alamy.

systems, scientists are seeing shifts in key drought characteristics, such as faster onset (flash drought), higher drought intensities, and impacts in new locations (Crausbay et al. 2017, 2020; Vose et al. 2018).

The specific causes, types, and impacts of drought on forest ecosystems vary considerably, both between and within ecological system types (Hanson and Weltzin 2000, Klos et al. 2009, Seager et al. 2009, Anderegg et al. 2013, Vose et al. 2016). A key challenge in anticipating the location and intensity of drought impacts now and in the future is that climate change and human water use are influencing many different drought drivers at the same time (e.g., precipitation, temperature, storage of water as snow, and hydrologic influences of vegetation and water withdrawals). In addition, factors like soil types, topography, and certain management practices (e.g., thinning of forest stands) can also influence the water available for ecosystems (Van Loon et al. 2016; Crausbay et al. 2017, 2020; Cartwright 2018).

In the western United States, many forest systems are adapted to annual, seasonal droughts. However, warmer conditions have contributed to an increase in the duration and severity of droughts in parts of the region over the last two decades, affecting both terrestrial and aquatic systems (e.g., van Mantgem et al. 2009, Hicke et al. 2016, Mote et al. 2016, Young et al. 2017, VerWey et al. 2018, Elias et al. 2021). For example, extreme drought associated with low snowpack has significantly altered hydrologic conditions across much of the West, contributing to higher winter streamflow, earlier and reduced peak spring flow, reduced summer flow, and, in combination with higher air temperatures, increased stream temperatures (Mote et al. 2018, Peterson et al. 2019). In addition to affecting fish and other aquatic species, shifts in river hydrographs due to reduced snowpack can have a significant impact on riparian areas and the diverse plants and animals they support (Dwire et al. 2018, Elias et al. 2021). In the coming decades, average annual snowpack across much of the West is projected to decline considerably, with broad implications for forest ecosystems and the services they provide, including provision of water resources to human communities (Fyfe et al. 2017, Gergel et al. 2017).

In the Midwest and East, where drought historically has been more sporadic and less intense than in the West, there is limited current scientific understanding of how forest systems will respond to what are projected to be uncharacteristically severe drought conditions in the future (Hanson and Weltzin 2000, Brooks 2009, Asbjornsen et al. 2019, Druckenbrod et al. 2019). Given that some tree species are known to be more tolerant of drought conditions than others, however, research suggests that more prolonged and frequent drought resulting from a changing climate could lead to a change in forest composition and structure in some areas (Klos et al. 2009, Vose et al. 2016). Further, many eastern forests have embedded wetlands or support species that are highly adapted to waterlogged soils. In those systems, changes in moisture regimes are likely to drive loss of species and contribute to forest type transitions, even without water becoming limiting for plant growth (Brooks 2009, Vose et al. 2018).

An increase in the occurrence of compound extreme events (e.g., extreme heat and drought) has the potential for even greater impacts on terrestrial and aquatic forest systems than individual events (Kopp et al. 2017). Over the past 50 years, there has been a substantial increase in concurrence between heat waves and low precipitation across much of the country, leading to hotter droughts and increases in evaporative demand (i.e., low moisture levels in the air pulls moisture from soils and vegetation) (Mazdiyasni and AghaKouchak 2015). Such combined extreme events can have significant social and ecological

Average annual snowpack across much of the West is projected to decline considerably, with broad implications for forest ecosystems and the services they provide, including provision of water resources to human communities.

Long-term drought is affecting even large, mature trees. In 2020, up to 10% of the world's giant sequoias died from the combined stress of drought and an exceptionally severe wildfire (Sequoia National Forest, California). Photo: Nathan Stephenson/USGS.

implications (Kopp et al. 2017). For example, the 2011–2016 drought in California, which was characterized by both low precipitation and high temperatures, killed more than 125 million trees (AghaKouchak et al. 2015, Diffenbaugh et al. 2015, USFS 2019). Further, a combination of extreme heat and drought has had a significant impact on salmon and other cold-water fish across much of the West, contributing to extensive die-offs in some areas (e.g., Crozier et al. 2020, Westley et al. 2020, Bowerman et al. 2021). As temperatures continue to rise, the impacts of drought are likely to worsen (Herrera-Estrada and Sheffield 2017). For instance, scientists project a significant increase in the risk of drought-induced stress and tree mortality in many areas over the coming decades, which is likely to significantly affect forest structure, composition, and function, potentially driving transformation of existing forested systems to other ecological types (Anderegg et al. 2015, Batllori et al. 2020).

2.1.2. Worsening Insect and Pathogen Outbreaks

How climate change will affect forest insect and pathogen outbreaks in the future is uncertain, in part due to variability in species-specific responses to climate change (Pureswaran et al. 2018). However, recent climatic changes have been exacerbating outbreaks of both native and introduced insects and pathogens across the country (Dukes et al. 2009, Weed et al. 2013, Hatfield et al. 2015, Berner et al. 2017, Loehman et al. 2017, Swanston et al. 2018). For example, higher temperatures are accelerating the development of some insects, such as the hemlock woolly adelgid, whose eggs have been hatching up to 3 months ahead of their normal emergence in parts of the Southeast (Leppanen and Simberloff 2017). Warmer winters have also enabled the establishment of cold-limited insects and diseases, such as southern pine beetle (Trân et al. 2007), spruce budworm (Régnière et al. 2012), and beech bark disease (Stephanson and Ribarik Coe 2017).

Longer growing seasons can also mean more generations of insects in a season, increasing the duration and magnitude of insect damage (DeLucia et al. 2012). Mountain pine beetle in the western United States, for instance, has become a dominant disturbance agent as changing climatic conditions have altered the life cycle of some broods to two generations per year (Mitton and Ferrenberg 2012). Recent pine beetle outbreaks have resulted in tree die-offs across more than 240,000 acres per year (Breshears et al. 2005, Klapwijk et al. 2012, Hicke et al. 2016). Climate change may also affect the severity of outbreaks via changes in host species, such as through shifts in host distribution and a decline in tree health (Dukes et al. 2009, Weed et al. 2013). For example, drought stress has been found to make pinyon pines more susceptible to outbreaks of the pinyon ips bark beetle (Kleinman et al. 2012). Together, these stressors have contributed to significant declines in certain types of pinyon–juniper woodlands in the Southwest (Friggens et al. 2020). On the whole, insect outbreaks have killed hundreds of millions of trees across the United States over the past 20 years (Hicke et al. 2016). As noted by Vose et al. (2018), this appears to be far outside of the historical context, and it is likely associated with a changing climate.

Outbreaks of forest diseases are also projected to increase under warmer and wetter conditions in some areas (Sturrock et al. 2011, Weed et al. 2013). For example, epidemics of certain foliar, vascular, and root pathogens, such as Swiss needle cast and sudden oak death, have been liked to higher temperatures and increasing precipitation (Weed et al. 2013). In the Coast Range of the Pacific Northwest, Swiss needle cast has been a persistent disease of Douglas-fir since the discovery of the fungal pathogen in the mid-1990s. Research suggests that the disease will increase at higher elevations and higher latitudes under a scenario of warmer winters and wetter summers (Lee et al. 2017). Higher temperatures and an increase in spring precipitation are also projected to increase the prevalence and range of the pathogen responsible for sudden oak death across California, Oregon, and Washington (Kliejunas 2011).

2.1.3. Larger Wildfires and a Longer Fire Season

Climate change is increasing wildfire potential across much of the United States (e.g., Cattau et al. 2020, Goss et al. 2020, Parks and Abatzoglou 2020, Higuera and Abatzoglou 2021). In the West, for instance, higher temperatures, earlier snowmelt, and reduced summer precipitation have contributed to a longer wildfire season and an increase in the total area burned, including the size of patches burned by high-severity fire (McKenzie et al. 2004, Running 2006, Westerling et al. 2006, Miller and Safford 2012, Hicke et al. 2016, Westerling 2016, Singleton et al. 2019). Extreme drought has exacerbated fire conditions across much of the region, and the occurrence of so-

Wildfire season has been lengthening across the western United States, and forest managers are documenting an increase in the acreage burned by high-severity fires (2016 Roaring Lion Fire, Bitterroot National Forest, Montana). Photo: USDA.

called "megafires"—those with areal extent greater than 100,000 acres—has risen significantly (Davis and Weber 2018). In addition to posing risks to human communities, these fires can emit considerable amounts of carbon into the atmosphere (e.g., Sommers et al. 2014, Urbanski 2014), and they have the potential to permanently transform forest ecosystems that are not adapted to high-severity fire regimes (Hicke et al. 2016, Jones et al. 2016, Berner et al. 2017, Heyck-Williams et al. 2017, Haffey et al. 2018, Halofsky et al. 2020).

In interior Alaska, record-breaking heat and drought in recent years have led to a significant increase in both the severity of wildfires and the total area burned. This has altered dynamics between vegetation and permafrost and is contributing to a shift in boreal forest composition from spruce-dominated to deciduous-dominated systems (Johnstone et al. 2010, Wolken et al. 2011, Sanford et al. 2015, Foster et al. 2019). Within the next few decades, climate change is projected to lead to functional and structural changes in Alaska's boreal forest that are unprecedented in the last 6,000 years (Chapin et al. 2010). Indeed, a number of studies suggest that the western United States will experience even larger, more frequent wildfires and a longer fire season as the climate continues to change. For example, scientists project that by mid-century total annual area burned across the West could increase by 2-6 times from the present (Litschert et al. 2012, Ojima et al. 2014, Vose et al. 2018).

Drought has also exacerbated wildfires in the East. In the Southern Appalachian region, for example, an exceptional drought in 2016 contributed to an above-normal fall wildfire season, resulting in loss of life and property (Vose et al. 2018, James et al. 2020). As in the West, many southeastern forest systems are adapted to specific fire regimes. Longleaf pine forests, for instance, rely on relatively frequent, low-intensity fires. Changing climatic conditions are projected to increase both the intensity and severity of wildfires across much of the region (Liu et al. 2013, Terando et al. 2016). This could lead to tree mortality as well as limit the window of opportunity for management options such as prescribed burns (Mitchell et al. 2014, Kupfer et al. 2020).

Scientists project that by mid-century total annual area burned across the West could increase by 2-6 times from the present.

2.1.4. Heavier Rainstorms and More Extreme Flooding

Floods are another important ecological disturbance factor that promote a mosaic of forest conditions on the landscape and help sustain biodiversity associated with all stages of forest succession (Hayes et al. 2018). However, an increase in the frequency and intensity of heavy rainfall events, changes in the timing and extent of snowmelt, and other climate-related factors are exacerbating flooding in forests across the country, affecting aquatic and terrestrial systems as well as roads and other built infrastructure. In the Pacific Northwest, for example, intense and persistent rainfall and associated flooding have led to erosion and landslides in the Mt. Baker-Snoqualmie National Forest in Washington, destroying roads and disrupting access (Raymond et al. 2014). A combination of higher average temperatures and increased precipitation in fall, winter, and spring are projected to contribute to increased flooding for most of the region's river basins toward the latter half of this century, particularly in areas where precipitation has been historically dominated by rain or mixed rain and snow (Tohver et al. 2014).

In the eastern United States, the frequency of extreme precipitation events has increased since the mid-1990s, and further increases are projected to contribute to higher total runoff and peak streamflow across much of the region (Easterling et al. 2017, Swanston et al. 2018). In addition to posing risks to downstream communities, an increase in the magnitude and frequency of flooding associated with such events could have significant implications for the composition and function of ecosystems not adapted to the altered hydrologic regime. For example, studies suggest that an increase in the depth and duration of early-season flooding in some areas could reduce the success of seedling regeneration within bottomland hardwood forests (e.g., McCurry et al. 2010, Kabrick et al. 2012).

Extreme rainfall associated with tropical storms and hurricanes (tropical cyclones) has also become more common over the past few decades, and recent storms have contributed to significant flooding and oversaturation of soil in areas of the Atlantic and Gulf coasts and U.S. Caribbean (e.g., Risser and Wehner 2017, Patricola and Wehner 2018, Keellings and Alaya 2019, Case et al. 2021a). Although hurricane-strength winds can cause significant damage to forests, research suggests that climate-induced increases in the duration and intensity of rainfall associated with tropical cyclones are also of concern (Van Beusekom et al. 2018, Keellings and Alaya 2019, Gang et al. 2020). In Puerto Rico, for instance, heavy rain during Hurricanes María and Irma in 2017 was found to have caused greater damage to the island's tropical forests than did wind (Hall et al. 2020).

2.1.5. Altered Phenology and Growth Rates

Studies suggest that changes in temperatures and precipitation patterns and a continued rise in atmospheric CO_2 will affect the growing environment of many tree species throughout the United States, altering processes such as tree phenology, water use, primary productivity, recruitment, and mortality (Vose et al. 2012, Fisichelli et al. 2014, Harvey et al. 2020). Responses among species will vary both spatially and temporally and will depend on factors such as age class, competition, and other biotic and abiotic conditions (Restaino et al. 2016, Ford et al. 2017, Dixit et al. 2020).

One of the primary ways that climate change affects forests is through changes in the timing of life-cycle events (phenology) of trees and other species. Indeed, a trend toward earlier leaf emergence in the spring and shifts in leaf senescence among a number of plant species in fall has been an important indicator of the effects of recent climatic changes (Gill et al. 2015, Panchen et al. 2015, Monahan et al. 2016). For example, Melaas et al. (2018) found that leaf emergence has trended earlier in the eastern temperate forests of

More extreme rainfall events and flooding are causing damage to roads and other infrastructure on national forests (Umatilla National Forest, Oregon). Photo: USFS.

North America over the 30-year period between 1984 and 2013. Research suggests that earlier spring warm-up, later fall cooldown, and an associated increase in the length of the growing season in the Northeast in the coming decades are likely to affect productivity of a number of tree species (Rustad et al. 2012). These changes, in turn, can affect nutrient proficiency, photosynthesis, and other physiological processes, as well as ecological processes such as water fluxes and carbon uptake (see section 2.1.1.7, below) (Richardson et al. 2013, Keenan et al. 2014, Estiarte and Peñuelas 2015, Way and Montgomery 2015, Fang et al. 2020).

A trend toward earlier spring budburst is also occurring among some tree species in the West, which is attributed in part to higher average temperatures (Ault et al. 2011). As the climate continues to warm, scientists expect further changes in the timing of budburst, although differences will vary by species and location of a population within its range (Harrington and Gould 2015). For example, some tree species, such as Douglas-fir, require a period of chilling before warmer spring temperatures force budburst, although the required chilling period varies across different genotypes. Projections for temperature-induced changes in budburst among Douglas-fir across parts of its range in western North America suggest that a 3.2–5.5°C increase in average winter temperatures by 2080 could result in significantly earlier budburst for the trees across much of the study area, but later budburst in some southern portions due to a lack of chilling (Harrington and Gould 2015). Delayed budburst could lead to poor growth, particularly if climate change also leads to earlier drought in those areas.

In addition to contributing to a warmer climate, a higher concentration of atmospheric CO_2 can have a direct effect on plant growth. Experimental studies have shown that trees grow faster when exposed to enriched CO_2 levels (e.g., Norby et al. 2005, Kim et al. 2020). Evidence suggests that higher levels of CO_2 have also contributed to an increase in forest water use efficiency in some areas (Keenan et al. 2013, Fernández-de-Uña et al. 2016). In addition, the combination of a reduction in acidic deposition, warmer springs, and an increase in atmospheric CO_2 was found to contribute to recent increases in the growth of red spruce trees in the Central Appalachian Mountains (Mathias and Thomas 2018). However, the net effect of CO_2 fertilization on forest ecosystems remains uncertain, as potential benefits may be offset by water stress and other climate-related impacts (e.g., Morin et al. 2018, Belmecheri et al. 2021).

2.1.6. Shifts in Species' Ranges

A number of trees and other forest plant and animal species (both native and nonnative) are shifting their distributions in response to changing climatic conditions (e.g., Mamet et al. 2019; Knott et al. 2019, 2020; Terskaia et al. 2020). In some instances, species have moved to higher elevations or latitudes, largely in response to changing temperatures; in others, species have shifted longitudinally or to lower elevations, tracking shifts in precipitation patterns and moisture availability (e.g., Crimmins et al. 2011, Bell et al. 2014, Lenoir and Svenning 2015, Fei et al. 2017). Taking a variety of factors into consideration, model-based projections suggest that further range shifts among tree species are likely in forests across North America (e.g., Iverson et al. 2008, 2019; Woodall et al. 2009; Iverson and McKenzie 2013; Clark et al. 2014; Matthews et al. 2014; Prasad et al. 2020; Rehfeldt et al. 2020; Toot et al. 2020).

Importantly, range shifts may result from a variety of site- and species-specific processes, and the potential for and rate of such shifts depend on factors such as reproduction, dispersal, and establishment. For example, a geographic shift in species may occur

Given the considerable variability in the rates and degree to which tree range shifts will occur over time, the composition of many forest systems in the future will differ from both historical and current conditions.

because of increased recruitment at the leading edge of a species' range, reproductive failure or die-off at the trailing edge, or a combination of the two (Lenoir and Svenning 2015, Boisvert-Marsh et al. 2019). However, the ability of trees to expand into newly suitable habitat in the future will depend on whether they can keep pace with the increasing velocity of climate change (Zhu et al. 2012, Sittaro et al. 2017, Liang et al. 2018, Solarik et al. 2018). Further, successful establishment in new areas depends not just on a favorable climate, but also on whether other, site-specific biotic and abiotic conditions (e.g., soil type) will support recruitment and survival (Etterson et al. 2020, MacKenzie and Mahony 2021). Given the considerable variability in the rates and degree to which tree range shifts will occur over time, and the high rates of land conversion in many parts of the United States that limit tree species dispersal, the composition of many forest systems in the future will differ from both historical and current conditions (Fei et al. 2017).

Another potential concern for national forest management is the potential for climate change to contribute to shifts in the range of invasive species (i.e., introduced, nonnative plants and other organisms that do or can cause environmental or economic harm to humans) (Iannone et al. 2020). As noted in the discussion on insect and pathogen outbreaks (which may include both native and nonnative species), studies suggest that climate change may enable invasive species with established populations to move into new areas as constraints such as temperature thresholds are removed (Hellmann et al. 2008, Poland et al. 2021). Further, climate-related changes in disturbances, such as uncharacteristically severe or frequent fires, drought, or increased flooding and erosion, may enable invasive species to gain a foothold in disturbed areas (Hellmann et al. 2008, Poland et al. 2021). Although climate may become less suitable for invasive species in some areas (e.g., Bradley 2009), some of the very characteristics that make some species "invasive," such as broad habitat requirements, high dispersal ability, and short time to maturity, are likely to put many invasive species at a competitive advantage (Hellmann et al. 2008, Dukes et al. 2009).

2.1.7. Changes in Ecosystem Composition, Structure, and Function

Both direct and indirect effects of climate change can alter the composition, structure, and function of forest ecosystems (Vose et al. 2018). For example, changes in tree species composition, which can occur rapidly following disturbances or more gradually through changes in recruitment or survival, can lead to disruption of interspecific relationships, such as competition, predator–prey interactions, and pollinator–plant associations. In some forests of the Northeast, for instance, wildflower leaf-out and bloom times in the understory are strongly limited by light availability. Higher temperatures have contributed to earlier leaf-out among the overstory trees compared

Freshwater swamp forests, such as these bald cypresses in Louisiana, are suffering widespread die-offs as sea-level rise increases salinity in estuaries, coastal wetlands, and tidal rivers. Photo: Southern Forests/Flickr.

The impacts of climate change could lead some forest systems to reach critical ecological thresholds, where conversion to different forest types, or even to non-forested systems, is possible.

to the understory vegetation, which has resulted in a shorter period of light availability for understory herbs (Heberling et al. 2019). If this trend continues, the region could see a decline in wildflower species abundances and a shift in community composition, which could alter forest energy flow and nutrient cycling (Gilliam 2007), as well as affect pollinator visitation (Cho et al. 2017).

In addition, shorter and warmer winters are creating significant changes in winter belowground processes, which can have a wide range of cascading impacts. In the Northern Forest region, for example, a decline in the duration and depth of insulating snowpack has, paradoxically, contributed to freezing soils, which can lead to reductions in soil microbial biomass and affect the ability of trees to retain nutrients and carbon (Sorensen et al. 2018, Contosta et al. 2019, Harrison et al. 2020, Wilson et al. 2020). And in parts of coastal Alaska, milder winter conditions and an associated decline in snowpack has contributed to significant mortality among yellow-cedar due to freeze damage to fine roots, particularly in areas with poorly draining soils (Hennon et al. 2016).

Lastly, the impacts of climate change could lead some forest systems to reach critical ecological thresholds, where conversion to different forest types (e.g., the conversion of black spruce to deciduous forest in interior Alaska following severe wildfire [Hansen et al. 2020]), or even to non-forested systems, is possible (Koch et al. 2009, Adams 2013, Anderson-Teixeira et al. 2013, Allen et al. 2015, Teskey et al. 2015, Walker et al. 2018, Busby et al. 2020, Harris and Taylor 2020). Research by Parks et al. (2019a), for instance, suggests that a significant percentage of forest systems at the trailing edge of their distribution (i.e., those areas expected to experience a range contraction under changing climatic conditions) in the intermountain western United States are at risk of fire-facilitated conversion to non-forest conditions by mid-21st century. And along the Atlantic and Gulf coasts, accelerating sea-level rise has contributed to the conversion of coastal forests to intertidal vegetation, affecting both the composition and function of coastal systems (Kirwan and Geden 2019). For example, Ury et al. (2021) calculated that more than 21,000 acres of trees on North Carolina's Alligator River National Wildlife Refuge were converted to "ghost forest" (i.e., areas characterized by standing dead trees and fallen tree trunks) between 1985 and 2019 due to rising sea levels and increasing salinity.

2.2. ADDRESSING CLIMATE-RELATED UNCERTAINTY

Despite tremendous progress in scientific understanding of known and potential climate-related impacts on forest ecosystems, it is important to recognize that key areas of uncertainty remain regarding how the climate may change in the future, how species and ecological systems may respond to those changes, and how people may react to those climatic and ecological shifts (Park et al. 2014). Although some of these uncertainties can be reduced over time—for instance, through the development of new research and modeling techniques and ongoing monitoring—other forms of uncertainty may never be resolved. National forest managers, however, have always confronted uncertainty in their work, and managing in the face of such uncertainty is not

Key areas of uncertainty remain regarding how the climate may change in the future, how species and ecological systems may respond to those changes, and how people may react to those climatic and ecological shifts.

Adaptive management has long been recognized as essential to effective forest restoration, as has the importance of promoting landscape heterogeneity. The uncertainties of future climatic conditions and ecological responses make these approaches even more imperative (Willamette National Forest, Oregon). Photo: Matthew Tharp/USFS.

new. Thus, existing experience and approaches for managing dynamic and unpredictable systems can be brought to bear on the new challenges of climate change-related uncertainty. For example, adopting a more agile, learning-based approach to management (i.e., *adaptive management*) has been recognized by the Forest Service as an important principle for addressing climate change (Millar et al. 2007; Joyce et al. 2008, 2009). The 2012 Planning Rule (USFS 2012b) provides for an "adaptive planning cycle" that allows the Forest Service to "adapt to changing conditions and improve management based on new information." In addition, the Forest Service has embraced tools such as scenario planning to identify robust management strategies (i.e., those that are likely to be effective across a range of potential future conditions) and facilitate long-term decision-making under uncertain future conditions (e.g., Nydick and Sydoriak 2011, Joyce and Coulson 2020).

Nevertheless, concerns about the inherent uncertainties and complexity associated with climate change remain a barrier to implementation of climate adaptation among some forest practitioners (Halofsky et al. 2018). Enhancing engagement between scientists and practitioners through workshops, trainings, collaborative working groups, and other means will be essential to address the considerable additional challenges that the complexities and uncertainties of a changing climate bring to national forest management.

Over the past two decades, Forest Service spending on wildfire suppression grew from under 20% of total budget to more than 50%, eroding the agency's ability to fund needed forest restoration and management activities. Photo: Kari Greer/USFS.

3. IMPLICATIONS OF CLIMATE CHANGE FOR NATIONAL FOREST MANAGEMENT

Climate change will challenge the ability of the Forest Service to achieve its mission of sustaining the health, diversity, and productivity of our national forests and grasslands to meet the needs of present and future generations. Indeed, the impacts of climate change have already had significant implications for Forest Service activities. For instance, the increasing cost of fighting worsening wildfires has stressed the agency's budget and contributed to the massive backlog in forest restoration (USFS 2017, Dumroese et al. 2019, Nave et al. 2019). Over the last two decades, Forest Service spending on wildfire suppression grew from under 20% of total budget to more than 50%, eroding the agency's ability to fund restoration and management activities to improve forest health and resilience, despite the growing need for such activities (USFS 2015b).

Fortunately, recent policies provide an opportunity to accelerate ecologically appropriate and climate-smart forest restoration. New authorities included in the 2018 Consolidated Appropriations Act, for instance, creates a disaster fund separate from the agency's operating budget that can be tapped for extraordinary wildfire suppression activities. This has the potential to free up much needed funding for restoration and reforestation activities and enable the Forest Service to expand work on collaborative, landscape-scale approaches to fire management (Taylor 2019). Recent Forest Service directives have also encouraged forest planners and managers to place greater emphasis on fostering forest resilience under current and future climatic conditions, rather than requiring strict adherence to historical ranges of variation (USFS 2015a, Bone et al. 2016).

Addressing the growing threats from climate change on the nation's forests requires a two-pronged approach. *Climate adaptation* refers to efforts designed to prepare for and address the impacts of climate change, with an emphasis on reducing key climate-related vulnerabilities and risks (Stein et al. 2013). *Climate mitigation,* in contrast, focuses on efforts to reduce the atmospheric concentrations of carbon dioxide and other greenhouse gases that are the underlying drivers of rapid climate change (IPCC 2014). Over the past two decades there has been considerable progress in developing the science and practice of both climate adaptation and mitigation in the United States and globally, although there is an urgent need for much broader adoption and deployment of these approaches. The Forest Service has been an early adopter and leader among the nation's resource management agencies in recognizing the importance of integrating consideration of climate change into its planning and management activities, including both adaptation and mitigation (e.g., USFS 2008, 2011a, 2011b, 2012b, 2015a, 2016, 2018).

However, recent studies suggest that broad-scale progress on climate-related activities at the Forest Service has often been hampered by several factors, including: 1) uncertainties about future climatic conditions, the potential ecological response to those changes, and appropriate management and adaptation options (e.g., Archie et al. 2014; Janowiak et al. 2017, 2020; Halofsky et al. 2018; Scheller and Parajuli 2018); 2) inconsistencies in agency guidance and adaptation-related terminology (e.g., Kemp et al. 2015, Bone et al. 2016, Timberlake and Schultz 2017, Greiner et al. 2020); and 3) barriers to planning and implementation of climate adaptation and mitigation strategies, including limited staff and funding capacity, jurisdictional complexities, and political and economic concerns (e.g., Jantarasami et al. 2010, Kemp et al. 2015, Timberlake and Schultz 2017, Halofsky et al. 2018, Gandhi et al. 2019). Progress has also been hampered by continuing challenges in reconciling science and information needs among researchers, managers, and other stakeholders (Kemp et al. 2015, Rodriguez-Franco and Haan 2015, Timberlake and Schultz 2017).

This science review and synthesis is intended to help inform efforts to address many of these challenges. The information presented here draws from and builds on the extensive research, expertise, and experience of the Forest Service and its partners, as well as researchers from the academic and nonprofit sectors. We fully recognize that there is no one-size-fits-all approach to climate-smart forest restoration and stewardship given the wide range of forest types, natural disturbance regimes, and current forest and watershed conditions; inconsistencies in scientific assessment and management approaches; and the unique needs and concerns of local communities, industry, and other stakeholders. Nevertheless, by advancing a shared understanding of key science-based concepts and practices, we hope to provide an informational foundation for promoting multi-scale collaborations to further climate-smart restoration on our national forests.

Widespread tree mortality due to climate change-enhanced drought, insect outbreaks, and other disturbances poses an enormous challenge for managing national forests across much of the West (Sierra National Forest, California). Photo: USFS.

3.1. U.S. FOREST SERVICE RESPONSE TO CLIMATE CHANGE

As described in its *National Roadmap for Responding to Climate Change* (USFS 2011a), the Forest Service has adopted a three-pronged strategy to confront climate change, including: 1) assessment of current risks, vulnerabilities, policies, and gaps in knowledge; 2) engagement of internal and external partners in seeking solutions; and 3) management for resilience, in ecosystems as well as in human communities, through adaptation, mitigation, and sustainable consumption strategies. These activities are not mutually exclusive—they are intended to be both dynamic and synergistic. The development of a Climate Change Performance Scorecard (USFS 2011b) enabled national forest managers to begin tracking progress in each of these areas and helped the agency increase its awareness and capacity to respond to climate change. This tracking system has more recently been replaced by a Sustainability Scorecard that retains core elements from the previous scorecard (e.g., vulnerability, adaptation, monitoring, carbon, and sustainable operations), but adds watershed stewardship as an additional element (USFS 2020).

The commitment to address climate change was reinforced with formalization of the 2012 Planning Rule (USFS 2012b) and issuance of subsequent management directives (USFS 2015a). Over the past decade, the Forest Service has made considerable progress in addressing climate change through scientific assessment and partner engagement, and some national forest units have begun incorporating climate considerations into their land management plan revisions under the new planning rule. To date, climate change vulnerability assessments have been completed for nearly the entire National Forest System, using a variety of approaches and for a wide range of forest types, geographies, spatial scales and resolutions, and time frames (Brandt et al. 2017, Timberlake and Schultz 2019). There has also been progress in understanding carbon stocks on federal forest lands, with data regularly compiled, maintained, and made publicly available under the Forest Service's Forest Inventory and Analysis (FIA) Program (Radtke et al. 2017, Smith et al. 2019, Wurtzebach et al. 2020).

To help integrate climate change science and local management knowledge and needs, the agency has championed the development of science–management partnerships (Peterson et al. 2011, Littell et al. 2012, Halofsky and Peterson 2016, Ontl et al. 2018, Timberlake and Schultz 2019). In addition, the U.S. Department of Agriculture (USDA) has established a network of regional "Climate Hubs" that represent a collaboration across the department's agencies to develop and deliver science-based information and technologies to agricultural and natural resource managers (USDA, n.d.). This includes efforts such as the Climate Change Response Framework, which helps forest planners and managers integrate climate considerations into their work through tools like the Adaptation Workbook (CCRF, n.d.), and the Adaptive Silviculture for Climate Change (ASCC) project, which is carrying out experimental trials designed to identify measures that might be effective in preparing forest ecosystems for climatic changes (Nagel et al. 2017). Together, these programs and activities play a critical role in advancing the Forest Service's commitment to managing for resilience through climate adaptation and mitigation efforts, which are at the heart of climate-smart restoration and management (Solomon et al. 2009).

However, there remains a disconnect between the progress at the institutional and research levels and implementation of climate-smart forest restoration and management in practice (Laatsch and Ma 2015). As noted by Hart et al. (2015), this is due, in part, to differing perspectives between restoration scientists, restoration practitioners, and stakeholders about whether, and the degree to which, restoration represents a return to historical conditions or one that explicitly incorporates the potential for new stresses and novel forest conditions. Addressing this challenge underscores the need for a more forward-looking, collaborative approach to national forest management. Building a shared, science-based understanding of climate-smart forest restoration among Forest Service practitioners, their partners, and the public is critical to achieving the agency's mission (Albrich et al. 2018). Toward this, knowledge of recent advances in forest and climate science, as well as the ongoing evolution in the concepts and principles of climate-smart and ecologically appropriate restoration, can provide a strong foundation for furthering both the dialogue and actions necessary for progress.

3.2. PROPOSED PRINCIPLES FOR CLIMATE-SMART FOREST RESTORATION

To inform further discussion and help advance a shared understanding of climate-smart restoration and management of America's national forests, we propose the following overarching principles. These principles draw from the Forest Service's climate-related work, from the principles underlying the National Wildlife Federation's climate-smart conservation adaptation planning framework (Stein et al. 2014), from the climate adaptation experience of other partners and practitioners, and from the vast and growing body of scientific literature summarized in the chapters below.

- ***Look to the future while learning from the past.*** Forest planners and their partners should develop forward-looking goals for management that build on an understanding of the historical range of variability and past responses to disturbance, but account for and anticipate future climate-related changes.

- ***Embrace functional restoration of ecological integrity.*** As climatic conditions continue to change, it will become increasingly difficult to restore the ecological integrity of forest systems based on historical species compositions and structures. Rather, goals for ecological integrity should emphasize the capacity of forest systems to adapt and adjust, including through enhancing functional diversity and habitat complexity.

- ***Restore and manage forests in the context of larger landscapes and longer time frames***. Climate change necessitates that planners and managers consider larger spatial scales (e.g., watersheds, landscapes, and regions) and longer time frames to ensure that localized and near-term actions do not compromise the capacity of forests to accommodate and adjust to changing conditions.

Photo: Joseph M. de Leon/USFS.

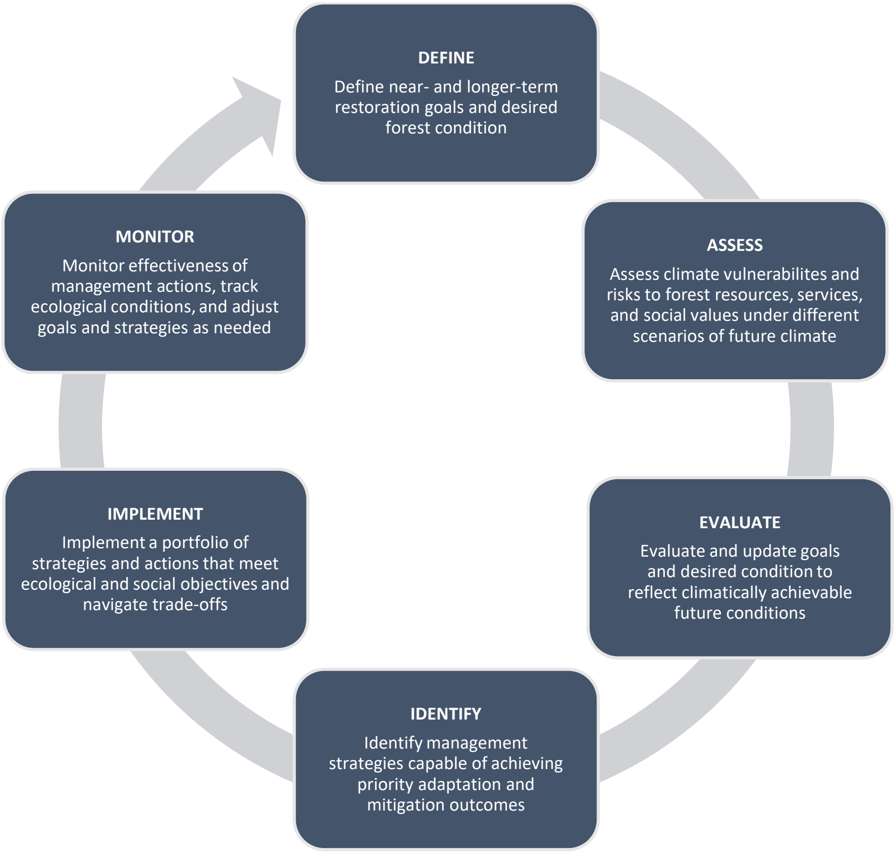


Figure 2. Climate-smart forest restoration planning cycle. *To support application of the proposed climate-smart forest restoration principles, this iterative planning process illustrates the incorporation of future climatic conditions into forest restoration planning and implementation. Adapted from Stein et al. (2014), Swanston et al. (2016), Golladay et al. (2016), Meyer et al. (2021), and NPS (2021).*

- ***Adopt agile planning and management approaches that accommodate and address uncertainty.*** Restoring and managing forests in the face of continuous climatic change requires decision-making under uncertainty, underscoring the importance of adaptive planning and management, including the consideration of multiple plausible scenarios of future conditions.

- ***Address climate risks by linking adaptation strategies to key climate-related impacts.*** Understanding climate vulnerabilities and risks to priority forest resources and values serves as the basis for developing and implementing adaptation strategies that are capable of reducing risks and sustaining the ecological, social, and economic systems associated with national forests.

- ***Manage for change, not just persistence.*** As climatic conditions exceed historical ranges of variability, national forest planners will need to consider how to reconcile "desired" future conditions with climatically achievable future conditions. Planners and managers increasingly will need to determine when and where it may be possible to manage for the persistence of current/historical forest conditions, and when it may be necessary to manage for change by accepting or even facilitating ecological transitions.

- ***Optimize, rather than maximize, carbon sequestration opportunities.*** National forests will play an increasingly important role in achieving the nation's climate mitigation goals. Attempting to maximize carbon sequestration and storage, however, can undermine other important ecosystem services and national forest values. Managers should instead seek to optimize sequestration opportunities by balancing carbon goals with other important forest restoration, management, and resilience outcomes.

- ***Enhance collaboration to identify shared values, navigate trade-offs, and maximize synergies in the context of changing conditions.*** Managing forests for multiple, sustained ecosystem services will necessarily entail trade-offs, particularly given the challenges and uncertainties associated with changing climatic conditions. Engaging local communities and diverse constituencies as early as possible in the forest planning process helps gain buy-in and identify opportunities to minimize trade-offs and maximize synergies, including acknowledgment and discussion of the potential for fundamental changes in national forest conditions.

To help forest managers put these principles into practice, we also offer a proposed climate-smart forest restoration planning cycle (see Figure 2). This adaptive planning framework emphasizes the need to clearly define and articulate restoration goals and objectives, to understand how current and future climatic conditions may affect forest resources and the services they provide, and to reevaluate and update goals that may be climate-compromised and unachievable under projected future conditions. Based on an understanding of climate vulnerabilities and risks, targeted management strategies can be identified that are designed to enhance forest resilience and reduce key climate risks (i.e., achieve adaptation outcomes) as well as reduce greenhouse gas emissions and optimize carbon sequestration and storage capacity (i.e., achieve mitigation outcomes). A portfolio of strategies and actions can then be selected for implementation that collectively help achieve key ecological and social objectives and account for trade-offs. Monitoring the effectiveness of management actions and ecological responses is essential for understanding when and how strategies and goals may need to be adjusted to reflect changing climatic, ecological, or social/economic conditions. Indeed, this framework fundamentally represents an adaptive management loop, and assumes an iterative approach to planning, implementation, and refinement.

Changing conditions will place new strains on forest resources, such as freshwater supplies, and will require increased attention to working with diverse groups of stakeholders. Photo: Mark Doliner/Flickr.

This proposed climate-smart forest restoration cycle draws from and builds on a variety of existing climate adaptation and adaptive management planning frameworks. This includes the climate-smart conservation adaptation planning cycle that was developed by the National Wildlife Federation in collaboration with a number of U.S. federal agencies including the Forest Service (Stein et al. 2014), as well as the Forest Service's Climate Change Response Framework and Adaptation Workbook (Swanston et al. 2016).

The following sections offer a deeper exploration of the science underlying the proposed climate-smart forest restoration principles and planning cycle. Chapter 4 (Restoration in the Context of Future Change) examines the first four principles, providing an overview of the challenges associated with restoration as conditions move beyond historical ranges of variability. Chapter 5 (Managing National Forests for Adaptation and Resilience), delves more deeply into adaptation outcomes, discussing principles that focus on reducing climate risks and managing for ecological change. Chapter 6 (Managing National Forests to Achieve Natural Climate Solutions), in turn, looks at climate mitigation and the principle related to carbon sequestration. Finally, chapter 7 (Balancing Trade-offs Among Ecosystem Services) considers some of the trade-offs that may emerge in seeking to achieve adaptation and mitigation outcomes and explores how collaborative processes can help in navigating those trade-offs.

Forest ecosystems have always been dynamic, but the scale and intensity of disturbances, including hurricanes, wildfires, and pest infestations, increasingly are exceeding historical bounds (Great Dismal Swamp National Wildlife Refuge, North Carolina). Photo: Rob Wood/USFWS.

4. RESTORATION IN THE CONTEXT OF FUTURE CHANGE

Traditionally, the goal of ecological restoration has been the return of degraded systems to some chosen preexisting natural condition (Clewell et al. 2002). As management of natural resources began to place greater emphasis on ecosystem health and integrity, the development of the related concepts of *historical range of variability* (sometimes referred to as *historical range of variation*) (HRV) and *natural range of variability* (NRV) offered an important advance in identifying restoration and management benchmarks.[1] Rather than specifying a single reference condition, HRV and NRV emphasize the dynamic nature of ecosystems and account for periodic fluctuations (whether interannual or decadal) in the system driven by natural events over time and across landscapes (Swanson 1994, Landres et al. 1999).

Within the Forest Service, the concept of HRV played an important role in the agency's adoption of "ecosystem management" in the 1990s as an alternative to more resource extraction–oriented management approaches (Keane et al. 2009). More recently, NRV has become embedded in agency planning and practice, with the 2012 Forest Planning Rule requiring a determination

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[1] Because of the difficulty of defining "natural," particularly in the context of a changing climate, we find the concept of "historical range of variability" to be more appropriate for application in climate adaptation and climate-smart restoration. However, given the prominence of the term "natural range of variability" in recent U.S. Forest Service management directives, we recognize that it may be more commonly applied in the agency's work.

of NRV for a suite of ecological characteristics as a basis for measuring “ecological integrity” (USFS 2012b, Safford and Stevens 2017). Continuing and accelerating climatic changes, however, are complicating the application of these concepts in restoration, and forest practitioners increasingly will need to anticipate and manage for conditions that exceed historical ranges of variability.

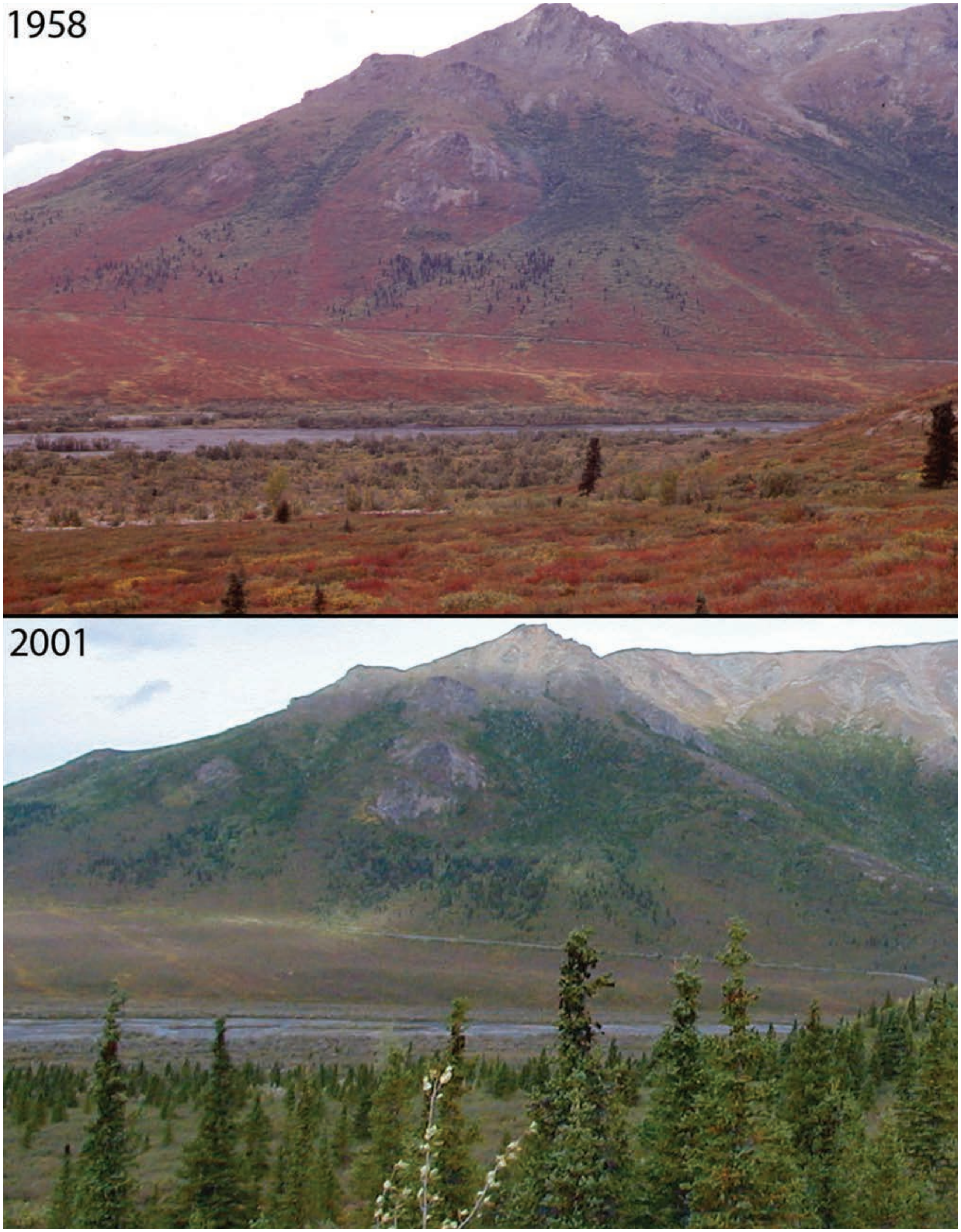
4.1. LOOKING TO THE FUTURE WHILE LEARNING FROM THE PAST

Engaging in forward-looking and climate-smart forest restoration and management does not mean that the past is no longer relevant. Indeed, evaluation of where and how forest systems have existed and evolved in the past allows for greater understanding of their ecological processes and functions under a range of environmental conditions, as well as their potential response to natural and human disturbances and long-term change (Barrett et al. 2006, Löf et al. 2019, Beller et al. 2020). It also provides important insights into cultural connections to forests over time (Higgs et al. 2014). Thus, assessment of HRV/NRV in national forest planning remains appropriate as a tool to inform management and restoration efforts. However, the 2015 *Land Management Planning Handbook (Handbook)* acknowledges that NRV does not necessarily constitute a management target or desired condition, stating that “[f]or specific areas within an ecosystem, the Responsible Official may determine that it is not appropriate, practical, possible, or desirable to contribute to restoring conditions to the natural range of variation” (USFS 2015a). It also suggests that it may be necessary to manage an ecosystem for characteristics that were either rare or never occurred in the past in order to support its ability to withstand or recover from disturbance events caused under unique circumstances (USFS 2015a). Thus, forest restoration in a changing climate must look to the future while learning from the past.

A rapidly changing climate, in particular, is compromising the idea among many managers that restoring forest conditions to those reflected by their HRV/NRV is an optimal, or even achievable, outcome (Millar et al. 2007, Millar 2014, Hanberry et al. 2015, Golladay et al. 2016, McKelvey et al. 2021). Although the concepts recognize and reflect dynamic and cyclic conditions, the general assumption has been that these variations typically revolve around a mean value (i.e., despite fluctuations, the value remains stable over the long term). Yet, as Milly et al. (2008) and Craig (2010) acknowledge, in the context of climate change, “stationarity is dead.” Directional shifts in climatic factors (e.g., long-term warming trends) will in many places eventually exceed the bounds of the historical range of variability. Additionally, for some factors (e.g., precipitation), there is also a shift toward greater extremes (Hayhoe et al. 2018). As a result, sooner or later many forests will experience conditions that are well outside the limits of historical variability.

In fact, evidence suggests this may already be occurring in some places, as forest systems are nearing or have surpassed ecological thresholds due to extreme conditions beyond what they likely have experienced in the past (e.g., Young et al. 2019, Hansen et al. 2020). Therefore, a growing number of scientists argue that exclusively relying on a selected set of historical conditions as benchmarks for forest restoration outcomes will be increasingly untenable (Millar et al. 2007, Alagona et al. 2012, Millar 2014, Dumroese et al. 2015, Jacobs et al. 2015, Millar and Stephenson 2015,

Look to the future while learning from the past. Forest planners and their partners should develop forward-looking goals for management that build on an understanding of the historical range of variability and past responses to disturbance, but account for and anticipate future climate-related changes.



Directional trends in climatic factors are pushing many natural systems beyond the bounds of historical variability. Warming in Alaska, for instance, is leading to a loss of permafrost and contributing to the expansion of trees in formerly treeless tundra (Denali National Park and Preserve, Alaska). Photo: L.A. Viereck.

Golladay et al. 2016, Gann et al. 2019, Prober et al. 2019, Beller et al. 2020, Donato et al. 2020, McKelvey et al. 2021, Meyer et al. 2021). Rather, information about historical ecological conditions and processes should be used to support a more forward-looking and anticipatory approach to restoration and management (e.g., Heller and Hobbs 2014, Stanturf et al. 2014, Golladay et al. 2016, Bradford et al. 2018, Timberlake et al. 2018). As noted by Meyer et al. (2021), the applicability of reference conditions identified by NRV analysis may be reduced under rapidly changing environmental conditions. They suggest that although historical ecological information is still important, NRV-based management targets may require modification, or treated as "waypoints" rather than "endpoints" (Meyer et al. 2021).

Given the challenges in applying HRV/NRV in management decisions under a rapidly changing climate, some scientists suggest augmenting the use of HRV/NRV with the concept of *future range of variability* (FRV) which incorporates projections for the species assemblages and disturbance regimes that will characterize future forest conditions (McComb and Duncan 2007; Duncan et al. 2010; Seidl et al. 2016; Keane et al. 2009, 2018, 2019; Loehman et al. 2020; Meyer et al. 2021). Such analyses can then be used to evaluate the potential effectiveness of various management decisions and help identify intended and unintended consequences of those options (see section 4.4) (Mozelewski and Scheller 2021).

4.2. EMBRACING FUNCTIONAL RESTORATION OF ECOLOGICAL INTEGRITY

The challenge of applying the concepts of HRV/NRV in national forest management in an era of climate change also requires an explicit evaluation of what restoring *ecological integrity* means (Dumroese et al. 2015, Wurtzebach and Schultz 2016, Carter et al. 2019, Rohwer and Marris 2021). Under the 2012 Planning Rule, ecological integrity is defined as "[t]he quality or condition of an ecosystem when its dominant ecological characteristics (for example, composition, structure, function, connectivity, and species composition and diversity) occur within the natural range of variation and can withstand and recover from most perturbations imposed by natural environmental dynamics or human influence" (USFS 2012b). This reflects the traditional application of ecological integrity, which is based on selecting a pre-European-influenced reference period—an approach echoed in the 2015 *Handbook* as it describes the natural range of variation (Wagner 2000, USFS 2015a, Zellmer et al. 2018).

Embrace functional restoration of ecological integrity. Goals for ecological integrity should emphasize the capacity of forest systems to adapt and adjust, including through enhancing functional diversity and habitat complexity.

Importantly, the *Handbook* suggests a longer-term perspective of the historical record than has generally been considered in national forest restoration, stating that "[t]he pre-European influenced reference period considered should be sufficiently long, often several centuries, to include the full range of variation produced by dominant natural disturbance regimes such as fire and flooding and should also include short-term variation and cycles in climate" (USFS 2015a). Drawing from the field of historical ecology, this approach builds on the idea that considering longer time horizons into the past (e.g., centuries to millennia) will help forest managers better understand the dynamics and complexities that confer ecological resilience over time (see section 5.2.1) (Swetnam et al. 1999, Millar and Brubaker 2006, Littell et al. 2016, Colombaroli et al. 2017, Zellmer et al. 2018, Beller et al. 2020, D'Amato and Palik 2021). The application of such a long-term perspective in practice depends on whether sufficient data (e.g., from paleorecords) exist to support such analysis, among other challenges (Keane et al. 2009, Safford et al. 2012). Traditional ecological knowledge can also provide valuable insights into past ecological changes and current ecosystem structure (e.g., Vinyeta and Lynn 2013, McClenachan et al. 2015).

Prescribed fire is an important tool for achieving functional restoration in many fire-adapted forest ecosystems (Oconee National Forest, Georgia). Photo: USFS.

The *Handbook* also underscores the need for a more future-oriented perspective on ecological restoration, which it describes as "[t]he process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed." Specifically, "[e]cological restoration focuses on reestablishing the composition, structure, pattern, and ecological processes necessary to facilitate terrestrial and aquatic ecosystems' sustainability, resilience, and health under current *and future conditions"* (emphasis added) (USFS 2015a). It also highlights the concept of *functional restoration,* which focuses on the underlying processes that may be degraded, acknowledging that the functionally restored system may look different from the reference condition in terms of the composition and structure of vegetation patches and/or their spatial pattern. The *Handbook's* definition of ecological restoration is an important update of previous terminology, and the concepts it espouses provide a critical underpinning for effective climate adaptation and mitigation activities throughout the National Forest System.

4.3. RESTORING AND MANAGING FORESTS IN THE CONTEXT OF LARGER LANDSCAPES AND LONGER TIME FRAMES

Forest managers have long recognized the importance of taking a large landscape approach. The emergence of ecosystem management approaches since the 1990s has helped institutionalize thinking at scales larger than a forest stand or management unit, including efforts to incorporate regional-scale processes such as gene flow, successional pathways, and disturbance regimes (e.g., Seidl et al. 2012). Nevertheless, with climate-driven range shifts among species already underway, the need for considering and managing across broader geographic scales takes on an added significance (Stein et al. 2014). From an ecological perspective, focusing on management of individual national forest units, while still necessary, may not be sufficient to meet conservation goals given the strong potential for dynamic range shifts, emergence of novel (also called *no-analog* or *emerging*) species assemblages, and changes in biotic interactions (Joyce et al. 2008, Stein et al. 2014, Olson et al. 2017, Dudley et al. 2020).

The 2012 Planning Rule recognizes the importance of considering conditions outside the boundaries of national forests and enhancing *functional connectivity,* which it defines as the "ecological conditions that exist at several spatial and temporal scales that provide landscape linkages that permit the exchange of flow, sediments, and nutrients; the daily and seasonal movement of animals within home ranges; the dispersal and genetic interchange between populations; and the long distance range shifts of species, such as in response to climate change" (USFS 2012a, Cannon et al. 2019).

From a planning perspective, broader landscape-based approaches also require coordination and collaboration across management jurisdictions and among diverse partners (Butler et al. 2013). Recognizing this, the Collaborative Forest Landscape Restoration Program (CFLRP) was established in 2009 to allow communities to work directly with Forest Service managers to

Restore and manage forests in the context of larger landscapes and longer time frames. Climate change necessitates that planners and managers consider larger spatial scales and longer time frames to ensure that localized and near-term actions do not compromise the capacity of forests to accommodate and adjust to changing conditions.

Carrying out forest restoration at landscape scales requires broad collaboration and engagement with nearby communities and other stakeholders (Four Forest Restoration Initiative, Arizona). Photo: USFS.

plan, implement, and monitor large-scale restoration programs. Effective collaboration is also exemplified by the National Cohesive Wildland Fire Management Strategy, which was developed through a partnership between federal, state, local, and tribal governments, nongovernmental partners, and public stakeholders to achieve greater social and ecological resilience to wildfire at a national scale (DOI and USDA 2014). Yet, as described further in section 7.2, the added complexities and uncertainties associated with climate change have made it especially challenging for participants in such collaborative efforts to define desired outcomes for restoration.

Another important consideration is the relevant time frame for adaptation strategies and actions. Although forest managers are accustomed to accounting for long-term implications of decisions given the long lifespan of trees, there is often a mismatch between forest planning time frames[2] and the need to consider potential climatic changes and associated impacts throughout this century and beyond (Timberlake and Schultz 2019). Further, governance challenges, such as annual budgeting and turnover among leadership and local staff, can hinder the ability of forest managers to achieve long-term ecological restoration goals (Schultz et al. 2019b).

While consideration of longer-term effects and ecological and human responses to climate change does not replace short-term operational and management planning, it provides an important strategic context for near-term decisions. Ideally, near-term management decisions and actions should align with and help advance longer-term climate adaptation and mitigation outcomes. Failure to consider the longer-term climatic changes affecting the national forest might result in decisions that will be either ineffective in meeting forest management goals, translate to lost opportunities for climate adaptation and mitigation, or, worse, compromise the capacity of forests to accommodate and adjust to changing conditions and exacerbate potential negative effects and climate risks.

4.4. ADOPTING AGILE PLANNING AND MANAGEMENT APPROACHES THAT ACCOMMODATE AND ADDRESS UNCERTAINTY

Despite considerable advances in the use of climate models and projections in forest management, ongoing concerns about uncertainty in understanding future climatic conditions and associated impacts has created some reticence about applying the concept of FRV in national forest planning (e.g., Haugo et al. 2015, DeMeo et al. 2018). To be sure, articulating goals for future conditions can be challenging. In particular, climate change may require managers to aim for moving targets (Luce et al. 2012). For instance, some impacts to forests will be gradual, such as shifts in species' ranges as temperature and precipitation patterns change. Others will be rapid, including possible transformations to non-forest ecosystem types due to exceedance of key climatic or fire tolerance thresholds (Crausbay et al. 2017), or forest regeneration failures due to loss

Adopt agile planning and management approaches that accommodate and address uncertainty. Restoring and managing forests in the face of continuous climatic change requires decision-making under uncertainty, underscoring the importance of adaptive planning and management, including the consideration of multiple plausible scenarios of future conditions.

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[2] National forest plans have an expected duration of no longer than 15 years, although project and budget planning generally are based on much shorter timelines.

The iconic coast redwood of California has been suggested as a possible candidate for assisted migration to ensure its persistence into the future (Humboldt Redwoods State Park, California). Photo: Kirt Edblom/Flickr.

of seed sources after intense fires (Coop et al. 2020). Nevertheless, climate-smart restoration necessitates managing under uncertainty.

The need to reconsider management goals, and not just strategies, is a core climate adaptation principle that acknowledges how changing climatic conditions may compromise the ability to achieve existing goals and desired future conditions (Stein et al. 2014). Recognizing this challenge, Golladay et al. (2016) suggest the adoption of risk-based approaches to incorporate uncertainty into forest management efforts, with management goals based on what they call *achievable future conditions.* Their conceptual framework involves engaging managers and scientists in collaborative, scenario-based planning and adaptive management, building on existing ecosystem management principles and best practices. The authors also emphasize that determining restoration goals is necessarily about human values. Thus, forest restoration efforts must capitalize on collaboration and development of shared goals, reflecting both desired biophysical conditions and the relevant social dimensions (Duncan et al. 2010, Stanturf et al. 2014, McKelvey et al. 2021). While science can help inform what outcomes may be achievable, society must determine what is acceptable or even desirable. As noted by Jenkins and Jenkins (2017), a critical first step toward development and success of innovative management approaches is the "inclusion of biological considerations in tandem with both social and economic concerns, for which different stakeholders have their own multi-dimensional and complex objectives, metrics, and definitions." Forest management decisions will invariably involve dealing with trade-offs, such as whether strategies should aim toward maintaining particular species, genetic resources, or biotic assemblages; production of particular resources such as timber, forage, or other non-timber forest products; whether greater emphasis should be placed on managing for ecosystem processes or functions; and whether truly novel forest conditions are acceptable, such as if they support valued ecosystem services like water production or carbon storage (Hayward et al. 2016, Rissman et al. 2018, van Kerkhoff et al. 2019). Such trade-offs in setting restoration goals and management targets are explored in more detail in chapter 7.

Managing for change, including ecological transformations, will be an increasingly important part of forest adaptation and restoration planning (ghost forest in coastal South Carolina). Photo: William Conner/Clemson University.

5. MANAGING NATIONAL FORESTS FOR ADAPTATION AND RESILIENCE

While climate adaptation has been recognized as being important for North American forest management since the 1990s and early 2000s (e.g., Duinker 1990, Wall 1992, Spittlehouse 1997, Spittlehouse and Stewart 2003), an increased scientific understanding of the climate vulnerabilities of forest ecosystems, along with evidence of the accelerating pace of climate change and associated impacts, have heightened attention to the issue in recent years (e.g., Joyce et al. 2008, 2009; Blate et al. 2009; Millar and Stephenson 2015; Halofsky et al. 2018). The Forest Service has invested in a broad range of adaptation-related activities, from developing adaptation guidance and conducting climate change vulnerability assessments at multiple scales, to engaging staff and partners in adaptation planning workshops across the country (e.g., Peterson et al. 2011, Davison et al. 2012, Furniss et al. 2013, Janowiak et al. 2014, Treasure et al. 2014, Hatfield et al. 2015, Swanston et al. 2016, Nagel et al. 2017, Halofsky et al. 2018, Timberlake and Schultz 2019).

Address climate risks by linking adaptation strategies to key climate-related impacts.

Understanding climate vulnerabilities and risks to priority forest resources and values serves as the basis for developing and implementing adaptation strategies that are capable of reducing risks and sustaining the ecological, social, and economic systems associated with national forests.

5.1. ADDRESSING CLIMATE RISKS BY LINKING ADAPTATION STRATEGIES TO KEY CLIMATE-RELATED IMPACTS

Forest adaptation strategies are necessarily highly variable and context specific, reflecting differences in both the vulnerabilities of forest ecosystems and the institutional systems and contexts in which they are managed. No single approach will be appropriate in all cases due to a number of contextual factors, including: differences in regional and localized climate change projections; the diversity of ecosystems within and across national forests; variability in management goals and approaches across different forest units; complex and dynamic interactions among multiple forest stressors; and differences in jurisdictional settings (e.g., between the eastern and western United States and between publicly and privately owned forest lands) (Blate et al. 2009, Ontl et al. 2018, Oswalt et al. 2019, Rice 2019). Thus, it is important for scientists and forest managers to work together to identify specific science needs and resources in order to inform development of appropriate and effective adaptation strategies (Peterson et al. 2011, Littell et al. 2012, Furniss et al. 2013, Joyce and Millar 2014, Timberlake and Schultz 2017).

Effective climate adaptation relies on explicitly linking adaptation strategies and actions to climate-related impacts and vulnerabilities (Stein et al. 2014). Doing so facilitates the development of appropriate adaptation and management responses that support agreed-upon (and ideally climate-informed) goals and objectives. Toward this, the USDA Climate Hubs, the Forest Service Office of Sustainability and Climate, and the Forest Service research stations play an essential role in fostering scientific understanding of climate impacts and promoting relevant adaptation strategies and actions across the diverse contexts of national forest management. The greater challenge is ensuring that such information is readily translatable to on-the-ground management and restoration, which underscores the importance of engaging national forest managers, partners, and other stakeholders early in the adaptation planning process (Stein et al. 2014, Olliff and Hansen 2016).

A comprehensive review and evaluation of specific adaptation strategies and tactics is beyond the scope of this review. Rather, we provide a general overview of conceptual and practical considerations for managing national forests to achieve adaptation goals, building on the Forest Service's approach of managing forests for both persistence and change (e.g., Janowiak et al. 2014, Swanston et al. 2016, Halofsky et al. 2018).

5.2. MANAGING FOR CHANGE, NOT JUST PERSISTENCE

As discussed previously, given the pace and magnitude of climatic changes already underway, future conditions for much of America's forests will be different from those experienced in the past, and often dramatically so. In many places, the climatic factors that helped produce the forests of the past and present have already shifted. While measuring HRV/NRV enables forest managers to understand how forests have responded to past disturbances and how much they have changed over time, ultimately, the use of historical ecosystem conditions will be less relevant—and perhaps even inappropriate—as a benchmark for

In many places, the climatic factors that helped produce the forests of the past and present have already shifted.

defining forest management and restoration goals (Millar 2014, USFS 2015a). Indeed, as the pace and scale of change increase, even managing for persistence of *current* conditions (as opposed to re-creating *historical* conditions) will become increasingly difficult (Jackson and Hobbs 2009). Thus, a growing emphasis on the development of forward-looking goals requires managers to acknowledge that ecological change, including possible transformation from one system type to another, may be inevitable. Accordingly, forest management and restoration in an era of rapid climate change will increasingly focus on managing for change (Millar et al. 2007, Joyce et al. 2008, Stein et al. 2013, Prober et al. 2019, St-Laurent et al. 2021b).

Managing forest systems under climate change can be envisioned as falling along a spectrum, from attempting to restore/maintain a historical or current desired state (i.e., persistence), to accepting or actively facilitating transitions to a new system state that, ideally, also support important ecological and social values. Management actions at various points along this spectrum could range from a hands-off (or passive) approach to active management approaches (St-Laurent et al. 2021b). Importantly, persistence and change are scale dependent. For example, facilitating a shift of a species to a new geography would likely be viewed as a change-oriented approach at the local scale, while at a regional scale this same action could be viewed as a persistence-oriented strategy for assuring the regional survival of the species (Stein et al. 2014).

The Forest Service's approach to adaptation acknowledges this continuum of change and management options and has often been organized around the following high-level approaches (Peterson et al. 2011, USFS 2011a, Swanston et al. 2016):

1. Enhance *resistance* to climate-related stressors to maintain desired states and conditions;
2. Increase ecosystem *resilience* by enhancing their capacity to withstand or absorb impacts without irreversible changes in ecological processes and functions;
3. Facilitate ecological *transitions/transformation* (sometimes referred to as *response* or *realignment*); and
4. Allow forests to change on their own (i.e., *no action* or *acceptance*).[3]

This general framework, first described by Millar et al. (2007), has been widely cited and increasingly applied in practice (e.g., Peterson et al. 2011, Duveneck and Scheller 2016, Nagel et al. 2017, Dunn and Thompson 2018, Hagerman and Pelai 2018, James et al. 2018, Long et al. 2018, Clifford et al. 2020, Frelich et al. 2020, Kershner et al. 2020). For example, the Climate Change Response Framework, which offers a menu-based approach for adaptation planning developed by the Northern Institute of Applied Climate Science—a collaborative effort among the Forest Service, universities, conservation organizations, and the forest industry—helps forest managers connect these broad conceptual approaches to specific adaptation strategies and tactics tailored to meet specific project needs (Swanston et al. 2016, Ontl et al. 2018, Shannon et al. 2019).

Manage for change, not just persistence.
As climatic conditions exceed historical ranges of variability, National Forest planners and managers increasingly will need to determine when and where it may be possible to manage for the persistence of current/historical forest conditions, and when it may be necessary to manage for change by accepting or even facilitating ecological transitions.

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[3] Recent collaborative efforts have further refined and advanced the concept of managing along a continuum of ecological change. Schuurman et al. (2020), Thompson et al. (2021), and NPS (2021) have articulated a Resist-Accept-Direct (RAD) framework that describes the decision space available to managers along the persistence to transformation continuum.

As discussed below, however, there are some notable ambiguities and inconsistencies in how these general approaches are defined and measured, which some forest managers suggest has made them challenging to apply in on-the-ground decisions (DeRose and Long 2014, Bone et al. 2016, Seidl et al. 2016). Our intent here is to highlight various ways in which these adaptation-related terms and concepts have been used in the context of natural resource management, with the hope that such understanding will help clarify the important underlying principles and, in turn, enable national forest managers and their partners to more effectively apply them in practice.

5.2.1. Managing for Persistence: Resistance and Resilience

5.2.1.1. Definitions of Resistance and Resilience

In general, both resistance- and resilience-based adaptation strategies for natural resource management have tended to focus on restoring or maintaining persistence of desired conditions (i.e., an effort to limit undesirable changes) (St-Laurent et al. 2021b). However, the nuances between the terms *resistance* and *resilience* have proved to be vexing for many resource managers, complicating their application in practice (DeRose and Long 2014, Long et al. 2018, Selles and Rissman 2020). From an ecological perspective, *resistance* is often defined as the ability of a species or ecosystem to experience stressors but not change (i.e., *ecological resistance*) (Luce et al. 2012, Parent et al. 2020). By comparison, management strategies to maintain or enhance the resistance of a focal species or system (i.e., *resistance strategies*) entail specific actions designed to forestall impacts. Such strategies may focus on enhancing ecological resistance, such as through selective thinning to increase the resistance of ponderosa pine trees to bark beetles (Kolb et al. 2007, Crotteau and Keyes 2020). They also may entail active management to prevent change, such as: maintenance of fuelbreaks around structures at risk from wildfires; use of insecticides to combat mortality from insect outbreaks; removal of juniper and other woody vegetation expanding into sagebrush or grassland systems; and maintaining or creating climate refugia (Millar et al. 2007, Morelli et al. 2016, Bottero et al. 2017, D'Amato et al. 2018, Krawchuk et al. 2020; Maestas et al. 2021).

Resistance approaches *often focus on sustaining current ecological conditions or restoring a system to a desired historical state, as in this effort to restore grasslands by clearing encroaching junipers (Kaibab National Forest, Arizona). Photo: USFS.*

Aspen declines are occurring across many parts of the West, with warming temperatures and drought conditions appearing to play a role in the onset of disease and die-backs. Photo: Jeff Sullivan/Flickr.

In its most common ecological usage, *resilience* refers to the ability of a system to return to a particular functional state after a disturbance (Holling 1973, Walker et al. 2004, Millar et al. 2007, Benson and Garmestani 2011, Swanston et al. 2016, Bryant et al. 2019, Koontz et al. 2019, Greiner et al. 2020, Gustafson et al. 2020). Based on this application, both resistance and resilience strategies are focused on sustaining persistence of the target ecological system and preventing system change or transformations. Indeed, resistance and resilience have been described by some scientists as interrelated concepts, where the capacity to resist or recover from perturbations is viewed as an essential component of system resilience (e.g., Oliver et al. 2015, Duveneck and Scheller 2016, Bryant et al. 2019, Hessburg et al. 2019, DeSoto et al. 2020). For example, techniques such as thinning and prescribed fire may enhance forest resistance to high-severity wildfire, preventing catastrophic losses. Those treatments may also facilitate forest regrowth and recovery (i.e., resilience), such as where overly dense forest cover impedes growth of shade-intolerant trees (e.g., Stevens-Rumann et al. 2013, Short et al. 2019).

One factor that makes the application of resilience challenging, however, is that the concept has also been applied where desired management outcomes suggest room for at least some amount of ecological change—a distinction sometimes termed *adaptive resilience* (Dudney et al. 2018, Gillson et al. 2019). For example, the Forest Service's 2016 Ecosystem Restoration policy describes resilient National Forest System lands as being "self-sustaining and, if subject to disturbances or environmental change, have the ability to reorganize and renew themselves" (USFS 2016). Thus, the policy recognizes the adaptive capacity of restored ecosystems. Falk et al. (2019) describe resilience as comprising the full range of possible responses: resistance, recovery, and reorganization. Indeed, this perspective highlights a key challenge in applying HRV/NRV as a sufficient benchmark for resilience if forest conditions (e.g., composition or structure) shift outside of that range in response to climate change, yet continue to support desired ecological functions. As noted by Seidl et al. (2016), "resilience is a dynamic property, and climate change might not only change the disturbance regime … but also impact the range of variability and recovery rates of an ecosystem." Thus, they suggest the need to also explicitly consider the FRV resulting from the combined effects of climate change to describe system resilience.

In the context of national forest management, adaptive resilience might also apply to the more societal elements of the agency's mandate. Hagerman and Pelai (2018), for instance, acknowledge that, particularly for socio-ecological systems, resilience is often seen as a function of both adaptation and transformation. Schoennagel et al. (2017) and McWethy et al. (2019) discuss the importance of adaptive resilience to wildfires, which includes implementing strategies to help human communities "live with fire." Similarly, McWethy et al. (2019) argue that communities in the West need to go beyond "basic resilience" (i.e., allowing and supporting ecosystem recovery from wildfires and helping individuals and communities manage the impacts and recover from fires) to consider both adaptive resilience (e.g., focusing on fuel management and community planning to improve fire preparedness and response), and *transformative resilience* (e.g., accept fire-catalyzed transitions in ecosystems, changing patterns and characteristics of social organization to reduce overlap between fire and human built environment) (see section 5.2.2).

Resilience approaches *often focus on enhancing the capacity of a system to retain key functions. Beavers act as ecosystem engineers, and restoring them to a watershed can increase the availability of water for wildlife and riparian vegetation during dry periods (Uinta-Wasatch-Cache National Forest, Utah). Photo: Tom Kelly/Flickr.*

5.2.1.2. Challenges and Opportunities in Applying Resistance and Resilience in Practice

Several studies suggest that the ambiguity in the definitions of resistance and resilience may actually be useful. For one, it provides a "common language" for resource managers to communicate adaptation-related issues across disciplines (Brand and Jax 2007, Bone et al. 2016, Selles and Rissman 2020). It also may be the case that focusing on "resilience" as an alternative to more polarizing terms, such as climate change, provides the Forest Service with "political space to act" (Bone et al. 2016, Selles and Rissman 2020).

From an on-the-ground management perspective, however, the ambiguity creates challenges (DeRose and Long 2014, Chapin and Abrams 2020, Coughlan et al. 2020). One way to more effectively apply the concepts in practice is to explicitly consider resistance or resilience *of what, to what* (Carpenter et al. 2001, Long et al. 2018, Higuera et al. 2019, Chapin and Abrams 2020). Otherwise, management efforts could be fruitless or, worse, result in maladaptive outcomes (Fisichelli et al. 2016). For example, an overemphasis on thinning to increase resistance to high-severity wildfire could leave a forest susceptible to other forms of disturbance, such as windthrow (Bone et al. 2016, Long et al. 2018). Further, if resilience is defined as having a forest rebound as quickly as possible from wildfire, then managers may choose to minimize wildfire through suppression. On the other hand, if resilience is viewed as having wildfire be "part of a healthy forest," then management might focus on ways to enhance forest composition that allows for wildfire without significantly altering the state of the forest (Bone et al. 2016).

Charnley et al. (2017) suggest that it is also important to also ask, resilience *for what benefit.* That is, managing national forests for resilience should reflect both ecological and social values, as identified and developed through collaborative forest planning efforts. For example, managing to achieve the goal of resilience of fire-prone forest ecosystems to high-severity wildfire can be important for several purposes: protection of homes and structures; protection of timber assets and production; protection of scenic quality and recreational opportunities; and protection of certain ecological values. However, potential trade-offs exist in managing for forest resilience to wildfire related to each of these purposes (see chapter 7). As Seidl et al. (2017) acknowledge, increased resilience can be viewed as a "positive" outcome of management (e.g., rapid recovery of clean water production in a watershed after a disturbance) or a "negative" outcome (e.g., persistence of an invasive species after disturbance).

Recognizing the operational challenges in managing national forests for resilience, Chapin and Abrams (2020) suggest the following "best practices" for forest practitioners:

- Establish a clear definition for resilience to increase understanding of the concept;
- Plan for disturbances, ecological change, and surprises;
- Embrace adaptive management and experimentation;
- Identify creative solutions for scientific and monitoring capacity; and
- Manage with (rather than against) change, including acknowledging trade-offs between short- and long-term goals.

Ultimately, improving metrics for measuring the various factors that confer forest resistance and resilience under changing climatic conditions will continue to be an important area for scientific research to better enable forest planners and managers to apply the concepts in practice (Rice 2019).

5.2.2. Managing for Change: Forest Transitions and Transformations

Although the Forest Service acknowledges that managing for change will be increasingly necessary for effective climate adaptation, to date, most forest adaptation strategies have focused on promoting resistance and enhancing resilience, with the intention of achieving persistence-oriented goals (e.g., maintaining forest composition, structure, or function). In a review of global literature on climate adaptation within the forest sector, Hagerman and Pelai (2018) found that recommendations for forest management tactics "overwhelmingly" focused on maintaining current ecological patterns, either through passive approaches (no direct management intervention) or active approaches (direct management, such as removal of nonnative species). Only 10% of those recommendations considered actions to achieve transitions to new species assemblages. The authors argue that this was a surprising outcome given the growing attention among resource managers and conservation researchers on transformative approaches and the potential need to manage novel ecosystems (e.g., West et al. 2009; Stein et al. 2014; Wise et al. 2014; Kueffer 2015; Prober et al. 2015, 2019; Swanston et al. 2016; Colloff et al. 2017a, 2017b; Ontl et al. 2018; Rissman et al. 2018; van Kerkhoff et al. 2019).

The Adaptive Silviculture for Climate Change project (ASCC) is a nationwide study designed to test different silvicultural approaches to climate adaptation, including resistance, resilience, and transition-oriented (shown here) approaches (Chippewa National Forest, Minnesota). Photo: USFS.

Yet, there is growing recognition that, over time, efforts to help forests resist or recover from (i.e., be resilient to) climate-related changes across the United States will become increasingly risky and costly (Millar et al. 2007, Millar and Stephenson 2015). As noted by North et al. (2009, 2019), although trying to maintain current forest structures may be futile in the face of long-term climate change, managing the transition of forests to new norms can help prevent a total collapse of an ecosystem. Ultimately, managers will need to consider whether to accommodate or accept changes, and when, where, and how they might actively direct transitions to a new desired state—strategies often referred to in Forest Service adaptation literature as *response* or *realignment* (Joyce et al. 2008; Perring et al. 2013;

Millar and Stephenson 2015; Radeloff et al. 2015; Truitt et al. 2015; Colloff et al. 2017a, 2017b; Schuurman et al. 2020; Thompson et al. 2021).

Many of the response and realignment strategies implemented by the Forest Service and its partners to date have focused on enabling forests to respond to change by seeking to work with natural adaptive processes, such as increasing redundancy and diversity of habitats and managed stands, enhancing habitat connectivity to facilitate species migration, and expanding genetic guidelines for replanting (Joyce et al. 2008, 2009; DeRose and Long 2014; Janowiak et al. 2014; Oliver et al. 2015; Spathelf et al. 2018; Isabel et al. 2020). Adaptation strategies at this level can be described as "incremental" and "anticipatory" adaptation, where incremental strategies provide benefits under current climate conditions, and anticipatory strategies apply similar techniques but are more future oriented (Stanturf 2015). Reflecting this approach, Butterfield et al. (2017) introduce the concept of "prestoration"—using alternative species in restoration for which a site represents suitable habitat both now and in the future. Such a strategy may reduce planting failures in the near term while at the same time improve the likelihood that at least some species will thrive over time. Similarly, studies across North America suggest that expanding seed sources (e.g., from zones farther south or at lower elevations) for forest restoration efforts, rather than relying on fixed zones or narrowly constrained ecotypes, may be important to facilitate adaptation over time (e.g., Aitken and Bemmels 2016, Etterson et al. 2020, Pike et al. 2020). Of note, however, sourcing seeds from a broader range of environmental conditions and ecotypes, rather than using locally adapted seeds, is contrary to what currently is considered best practices for ecological restoration (Breed et al. 2018).

In other cases, a more explicit effort to direct ecological change may be warranted—an approach that has been referred to by some as *transformational adaptation* (Kates et al. 2012, Stanturf et al. 2018). At the Chippewa National Forest in north-central Minnesota, for example, researchers are experimenting with planting ponderosa pine from the Black Hills of South Dakota, a species not native to the region but which is more drought-tolerant than the local red pine. (Nagel et al. 2017).

To prepare for expected declines of red pine (shown) under warming and drying conditions, transition-oriented experimental plantings include ponderosa pine, a more drought-tolerant species similar to red pine, but not native to the region (Chippewa National Forest, Minnesota). Photo: Brett Whaley/Flickr.

As mentioned previously, however, change is a relative term, and perspectives on what constitutes change may depend on one's values or desired outcomes. Expanding a ski area to accommodate shifting snow conditions, for instance, may be considered an undesirable change by some if it adversely affects habitat of a rare species, yet it may allow for persistence of associated recreational opportunities. This is where the concept of functional restoration is useful, in that it focuses on the "societal values and services a forest provides, rather than on the specific species compositions and structures that formerly were present" (Dumroese et al. 2015). This necessitates understanding the societal values of forest function, not just a particular ecological condition, to determine what constitutes successful restoration (Crow 2014, Stanturf et al. 2014, Dumroese et al. 2015). Dumroese et al. (2015) acknowledge that functional restoration may well entail approaches that may not have been considered appropriate under traditional ecological restoration, such as *assisted migration* (see sidebar) and bioengineering.

Facilitating Change Through Assisted Migration

Assisted migration, which perhaps more appropriately should be termed *managed relocation,* refers to human-assisted movement of a species in response to climate change. Assisted migration may be considered when a species is unable to disperse at a pace necessary to keep up with changing climatic conditions, when dispersal is limited by natural or anthropogenic barriers, or when the species may be subject to local extirpation or extinction without proactive management. Done thoughtfully, it also may be implemented for the benefit of the recipient system, to increase biodiversity or improve desired ecological functions (Swanston et al. 2016, Wallingford et al. 2020, Karasov-Olson et al. 2021). The Forest Service recognizes the following types of assisted migration of trees (Williams and Dumroese 2013, Handler et al. 2018):

- ***Assisted population migration,*** including assisted gene flow, involves moving seed sources or populations to new locations within the species' historical range;
- ***Assisted range expansion*** involves moving seed sources or populations from within the current range to suitable areas just beyond their historical range, facilitating natural migration;
- ***Assisted species migration*** involves moving seed sources or populations far outside of their historical range, beyond locations accessible by natural dispersal.

Although there are instances of assisted migration of tree species already underway, use of the strategy within the Forest Service has generally been limited to experimental research or use of "no regrets" strategies, based on relatively near-term (e.g., 20-year) climate projections (Handler et al. 2018).

To some scientists, the distinction between transformational adaptation and incremental or anticipatory adaptation lies in the degree of tolerance for novel conditions, where novelty represents "the degree of dissimilarity of a system, measured in one or more dimensions relative to a reference baseline" (Radeloff et al. 2015, Stanturf et al. 2018). For instance, Stanturf et al. (2018) suggest that incremental adaptation does not support novelty—rather, efforts are aimed at *preventing* nonnative species or emergence of native species in new combinations (i.e., "neo-native" ecosystems). The concept of anticipatory adaptation supports management of *neo-native* systems and might allow for establishment of nonnative species into a system, but only if desired ecological functions are maintained. Transformational adaptation, by contrast, is often understood to embrace and actively manage for truly novel assemblages (which may include novel combinations of native species as well as native/nonnative mixes) or different ecological systems that are considered more likely to persist under changing climatic conditions (Stanturf et al. 2018; Colloff et al. 2016, 2017a; Löf et al. 2019; Dudley et al. 2020). Here, the use of the term "transformation" can be multifold, with ecological transformation (e.g., a shift to novel assemblages or from one system type to another) leading to transformation from a societal perspective (e.g., changes in associated ecosystem services) (Colloff et al. 2017b).

5.2.2.1. Challenges and Opportunities in Managing for Transformation in Practice

To some forest managers, the idea of accepting or managing toward ecological transformations that differ from historical conditions may run counter to what are considered best practices for forest restoration—primary among them the focus on use of locally adapted native species (e.g., Murcia et al. 2014, Backstrom et al. 2018, Breed et al. 2018). Given the pervasive ecological and economic impacts of nonnative, invasive plant species in national forests across the country, for instance, invasive species control has understandably and importantly been a high priority for the Forest Service (D'Amato et al. 2017, Poland et al. 2021). Similarly, forest restoration has traditionally adhered to the mantra of "local is best" when considering sources for seeds or seedlings, based on the assumption that local populations are likely to be better adapted to local conditions (Prober et al. 2015, Aitken and Bemmels 2016).

Certainly, many conventional forest restoration and management strategies will continue to be relevant and useful in an era of climate change. As some scientists suggest, it is important that we not "throw the baby out with the bathwater" (Prober and Dunlop 2011) or abandon fundamental principles of ecological restoration, such as focusing on ecosystem processes and functions (Hanberry et al. 2015). Yet, there is growing recognition that, in some areas, the rate and degree of climatic changes are going beyond the adaptive capacity of species and ecosystems to cope or adjust, which may necessitate more rigorous interventions to forestall change, or, alternatively, decisions to either accept or actively manage for change (Millar and Stephenson 2015; Dey et al. 2019; Kemp et al. 2019; North et al. 2019; Parks et al. 2019a, 2019b; Prober et al. 2019; Stevens-Rumann and Morgan 2019).

The consideration of ecological transformations as an outcome of restoration may be particularly appropriate in instances where landscapes are so altered that a return to a previously desirable set of conditions, such as those represented by HRV/NRV, is deemed unlikely or infeasible, with or without management intervention (Miller and Bestelmeyer 2016). For instance, low-elevation ponderosa pine and Douglas-fir forests in parts of the West may already have passed a threshold where regeneration is unlikely due to the combined effects of climate change and high-severity fire (Davis et al. 2019). Proponents of transformational adaptation argue that, given the pace of climate change combined with a host of additional, often synergistic stressors, novel conditions are likely to occur in many forest ecosystems, even within a single tree generation (Stanturf et al. 2018). Golladay et al. (2016) note that, in light of inevitable and possibly irreversible change, the ability of forest systems to provide valued ecosystem services will depend, in part, on the development of novel ecosystems. Perring et al. (2013) argue that the already existing pervasiveness of novelty and novel ecosystems underscores the need for a broader perspective for conservation and restoration. They suggest several goals for managing novel ecosystems. For example, it may be useful to focus on restoring ecosystem services through experimental and innovative approaches (i.e., “test beds”) to determine the most ecologically and ethically sound approaches. The Forest Service’s Experimental Forests and Ranges, for instance, are likely to be especially relevant for this approach. Another option entails conservation of desired species through the use of novel components, or the creation of new ecosystems to achieve desired goals, such as afforestation in highly degraded areas (e.g., on abandoned mine sites) (Evans et al. 2013).

For forest systems that are either nearing or have surpassed ecological thresholds and are unlikely to recover, proactive measures may enable managers to achieve certain desired outcomes compared to strategies (e.g., no action) that leave the system to shift spontaneously. This necessitates a better understanding and anticipation of potential ecological thresholds in terrestrial and aquatic forest systems, which can be challenging (Keenan 2015, Cantarello et al. 2017). Several studies also underscore the importance of identifying indicators to help managers anticipate potential ecological tipping points—thresholds that, if reached or exceeded, lead to fundamental system change (e.g., Reyer et al. 2015, Scheffer et al. 2015, Johnstone et al. 2016, Miller et al. 2019, Sánchez-Pinillos et al. 2019, Turner et al. 2020). Often, tipping points are only identified once they have been crossed (Stein et al. 2014). As noted by Millar and Stephenson (2015), however, being able to anticipate an approaching forest transition can help managers identify possible management strategies to ensure that delivery of desired ecosystem services is maintained. Recent research on the response of forests to disturbances such as extreme droughts, massive wildfires, and severe insect outbreaks has offered important insights into the role of thresholds and ecological conversions (e.g., Koch et al. 2009, Adams 2013, Allen et al. 2015, Reyer et al. 2015, Scheffer et al. 2015, Teskey et al. 2015, Johnstone et al. 2016, Sánchez-Pinillos et al. 2019, Batllori et al. 2020, Turner et al. 2020). On the Kenai Peninsula, Alaska, for instance, researchers have been assessing the potential trajectories of ecological systems to identify where prospective management, including active facilitation of ecological conditions, may be possible (Magness and Morton 2018).

High severity fire and changing climatic conditions can compromise seedling establishment and natural regeneration, leading in places to conversion from forests to non-forested systems. (Santa Fe National Forest, New Mexico) Photo: Los Alamos National Laboratory.

Managing forest ecosystems for climate resilience, such as in the carbon-dense temperate rainforests of the Pacific Northwest, is essential to ensure that forest-related climate mitigation strategies will offer long-term benefits (Olympic National Park, Washington). Photo: Jarr1520/Flickr.

6. MANAGING NATIONAL FORESTS TO ACHIEVE NATURAL CLIMATE SOLUTIONS

Strategies that support or enhance the ability of natural systems to store and sequester carbon—often referred to as *natural climate solutions*—are considered essential to help stabilize the climate and mitigate climate change at a scale necessary to prevent the most catastrophic impacts (Griscom et al. 2017, IPCC 2018, NASEM 2019). Forests play a critical role in the global carbon cycle, with carbon flowing from the atmosphere to forests and back through processes such as photosynthesis, respiration, decomposition, and combustion (Ryan et al. 2010). In general, about 60% of carbon in mature forests is stored in live and dead tree matter, with the other 40% in soil and forest litter (Ryan et al. 2010). Carbon gains and losses in forest systems fluctuate, with gains in carbon (i.e., sequestration) occurring largely through vegetative growth, and losses occurring through respiration, disturbances (e.g., fires and insect outbreaks), and harvest. Whether a forest is a net carbon "sink" (i.e., it gains more carbon than it loses) or "source" (i.e., it loses more than it gains) depends on the balance among each of these factors

Strategies that support or enhance the ability of natural systems to store and sequester carbon—often referred to as natural climate solutions—are considered essential to help stabilize the climate.

Forest ecosystem carbon stocks on Forest Service lands alone account for more than 26% of the nation's total forest carbon stocks—more than for any other federal land agency.

(Ryan et al. 2010). In turn, how much net CO_2 enters the atmosphere over time depends on factors such as rate and extent of forest regrowth, how quickly forest matter combusts or decomposes, and how much harvested timber is stored in durable wood products.

Studies suggest that managing the nation's forests to enhance carbon sequestration has the potential to contribute significantly to achieving national and international goals for reducing atmospheric CO_2 (USFS 2012c, Fargione et al. 2018, Baker et al. 2019). In 2019, the forestry sector represented an estimated net uptake of 774.6 million metric tons of CO_2 equivalent (MMT CO_2 eq.), offsetting approximately 11% of total U.S. greenhouse gas emissions (U.S. EPA 2021). Based on estimates developed from current FIA database evaluations, total forest ecosystem carbon stocks on Forest Service lands alone account for more than 26% of the nation's total forest carbon stocks—more than for any other federal land agency (Smith et al. 2019).

Accordingly, maintaining forest carbon stocks and enhancing carbon sequestration have gained prominence as a goal for Forest Service management. In 2014, the USDA formally acknowledged carbon sequestration on national forests as a land-use objective (USDA 2014, McNulty et al. 2018). This policy was further clarified in the USDA's *Building Blocks for Climate Smart Agriculture and Forestry* (USDA 2016). These policies provide general guidance on management of forests for carbon; however, considerable variability in carbon sequestration potential across the country, including significant differences among ecosystems, makes it challenging to translate this broader goal to on-the-ground management actions (McNulty et al. 2018, Ontl et al. 2020).

In particular, projecting future forest carbon fluxes in the United States is uncertain and varies greatly with assumptions for future economic and political contexts, as well as physical conditions, such as forest growth trends and the influence of fire and other disturbances (Nepal et al. 2012, Coulston et al. 2015, Wear and Coulston 2015, Janowiak et al. 2017, Keeton 2018, Tian et al. 2018, Birdsey et al. 2019). For example, the amount of carbon stored in forests depends on both the area and condition of forest land and specific forest management practices, and the degree and rates of carbon sequestration and storage over time will vary considerably by region and forest type. The ability of terrestrial systems to provide for sustainable carbon sequestration also depends on the potential for significant releases of forest carbon due to more severe disturbances, land-use changes, and other factors (Seddon et al. 2019). Disturbances, for instance, can have long-lasting impacts on forest carbon stocks, as stock recovery through vegetation regrowth is far more gradual, often requiring a decades-long time horizon, when compared to the disturbance-induced carbon loss (Williams et al. 2016). In addition, there are considerable uncertainties regarding the potential for *climate change—carbon cycle feedbacks* to affect future climate change (Friedlingstein 2015, Sellers et al. 2018).[4] Reflecting these complexities, some studies suggest that the carbon storage capacity of U.S. forests will decline in the future (e.g., Boisvenue and Running 2010, Wear and Coulston 2015, Dugan et al. 2018), while others are more optimistic (e.g., Nepal et al. 2012, Tian et al. 2018). Thus, it will be important for forest planners and managers to consider the underlying assumptions and context of scientific assessments for carbon sequestration when developing forest climate mitigation strategies (Dugan et al. 2017, Janowiak et al. 2017).

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[4] Climate change—carbon cycle feedbacks may be positive or negative. Positive feedbacks occur when climate-related impacts, such as larger wildfires or thawing permafrost, lead to greater atmospheric CO_2. Negative feedbacks occur when changes in climatic variables increase carbon sequestration, such as through enhanced plant growth.

6.1. OPTIMIZING, RATHER THAN MAXIMIZING, CARBON SEQUESTRATION OPPORTUNITIES

Enhancing the carbon sequestration potential of forests across the United States will require a concerted effort that includes scientific research, collaborative management, and supportive state and federal policies (Anderson et al. 2019). As discussed in greater detail in chapter 7, significant trade-offs may exist between carbon sequestration and other forest management goals. Accordingly, the Forest Service should strive to optimize, rather than maximize, forest carbon, as focusing on the latter could limit the agency's ability—and mandate—to meet other important management objectives (Jackson et al. 2005, Seidl et al. 2007, Janowiak et al. 2017, Dybala et al. 2019). In particular, recent studies highlight the need for managers to consider near- and longer-term consequences of management actions in the context of both climate adaptation and mitigation (Duveneck and Scheller 2016, Hof et al. 2017, Janowiak et al. 2017, Morecroft et al. 2019, Ontl et al. 2020, St-Laurent et al. 2021a). In some forest systems, for instance, implementing strategies to restore natural patterns of fire may emit carbon in the near term, but will enhance forest health and help maintain long-term carbon pools by reducing the risk of carbon losses due to severe wildfires (Funk et al. 2019, Hurteau et al. 2019, Krofcheck et al. 2019). Thus, the cost of such short-term emissions should be balanced against the role of disturbances in maintaining or restoring longer-term system resilience and, in return, carbon sequestration and storage (Janowiak et al. 2017, James et al. 2018, St-Laurent et al. 2021a).

Optimize, rather than maximize, carbon sequestration opportunities. National forests will play an increasingly important role in achieving the nation's climate mitigation goals. Managers should seek to optimize sequestration opportunities by balancing carbon goals with other important forest restoration, management, and resilience outcomes.

Furthermore, although the carbon sequestration potential on Forest Service lands is considerable, climate mitigation strategies must be undertaken within the broader national and international policy context. For example, Fahey et al. (2010) stress that potential carbon benefits of management actions should be measurable, verifiable, and sustainable. The Forest Service has engaged in rigorous assessments of baseline carbon stocks and changes due to disturbance and management, which is essential for understanding how potential management strategies will affect forest carbon stores (e.g., Dugan et al. 2017, 2018). Yet, some scientists argue that further advances may be warranted to improve the accuracy of forest carbon accounting, such as through more effective measurement and reporting on what happens with postharvest wood (Hudiburg et al. 2019), improved understanding of post-disturbance carbon dynamics (Bartowitz et al. 2019), and a better understanding of how to measure belowground carbon (Case et al. 2021b).

6.1.1. Strategies to Maintain Carbon Sequestration and Storage

Maintaining and enhancing carbon sequestration and storage on forest lands can be achieved through a variety of management approaches, although the appropriateness and effectiveness of specific strategies will vary given differences in forest types, management goals, and other social and ecological contexts (Janowiak et al. 2017, McNulty et al. 2018, Domke et al. 2020). Strategies may include: avoiding conversion of forests to other land uses; increasing forest cover through reforestation and afforestation; managing forests to enhance productivity; lengthening timber harvest rotation cycles; and increasing markets for long-term wood products (Ontl et al. 2020).

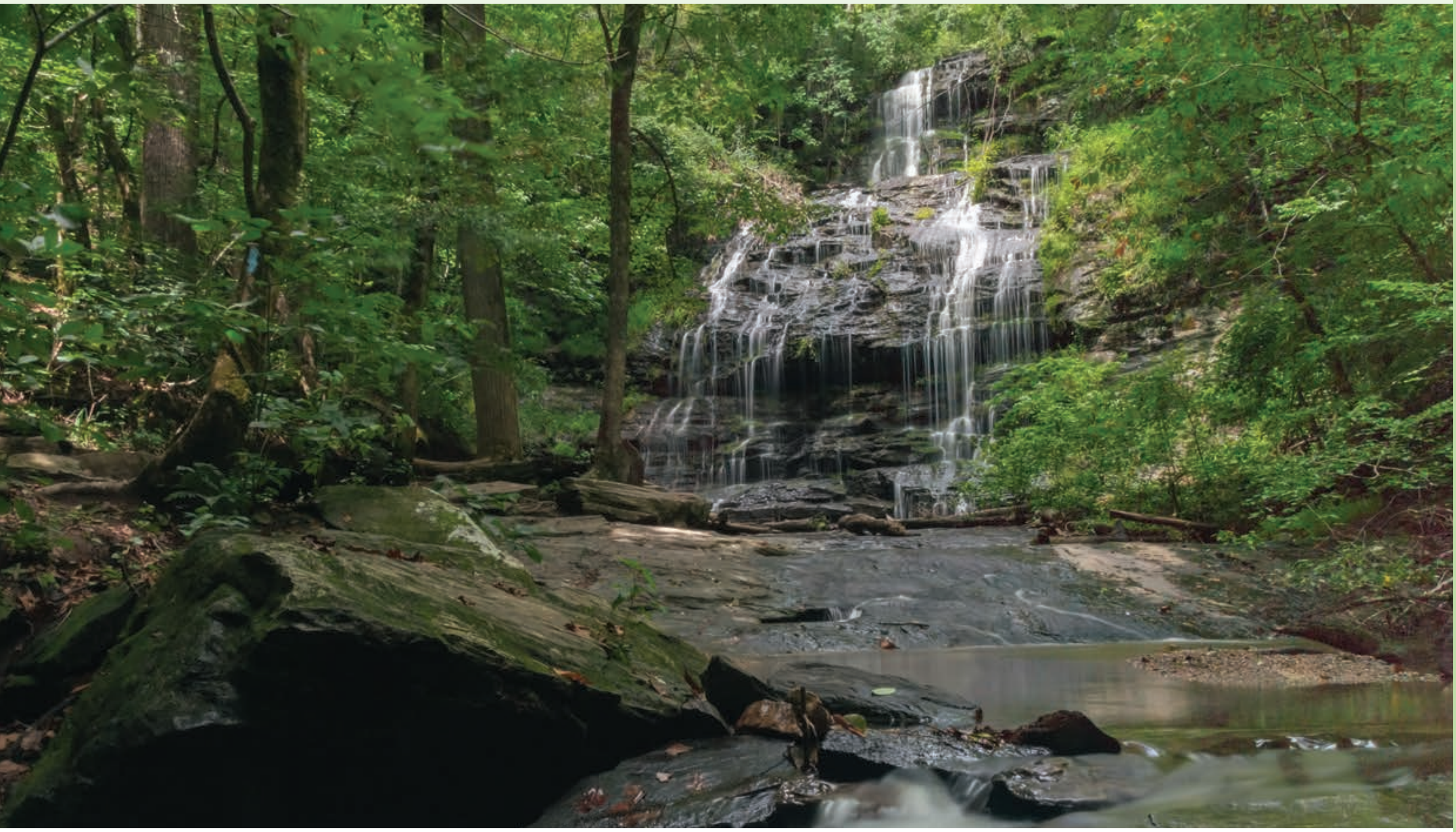
Between 1990 and 2019, "forest land remaining forest land" was the nation's largest net carbon sink, and conversion of forest land to other uses was the largest source of land-based emissions .

In general, both protecting existing, intact forests and restoring forest health at a large scale will be essential components of an effective, ecologically sound carbon management and climate mitigation strategy (Watson et al. 2018; Funk et al. 2019; Krofcheck et al. 2019, McCauley et al. 2019, Moomaw et al. 2019). Between 1990 and 2019, "forest land remaining forest land" was the nation's largest net carbon sink, and conversion of forest land to other uses was the largest source of land-based emissions (U.S. EPA 2021). Nevertheless, it is important to recognize that even intact, historically unmanaged forests are at risk from changing climatic conditions. In fact, some scientists suggest that wilderness and other protected areas may be especially vulnerable to climate-enhanced wildfire and other disturbances, particularly where they are small and isolated, are sensitive to stressors from outside their boundaries, and are limited in terms of treatment options compared to more managed systems (McKenzie and Littell 2011).

As noted previously, effectively managing the nation's national forests to provide a range of ecosystem services, including natural climate solutions, will require a concerted effort to reduce climate vulnerabilities and enhance the capacity of forest systems to adapt to changing conditions (Janowiak et al. 2017, Ontl et al. 2020, St-Laurent et al. 2021b). The importance of restoration efforts aimed at reducing risks of catastrophic forest loss to disturbances, for example, has gained prominence in both the science and policy arenas, owing to both recent extreme events and the considerable restoration backlog within the National Forest System. Reforestation on national forests, in particular, is likely to play a significant role in efforts to enhance long-term carbon sequestration (Dumroese et al. 2019). Areas affected by wildfires, droughts, and other disturbances provide an important near-term opportunity to significantly scale up reforestation, provided conditions are sufficient for long-term growth and productivity (Sample et al. 2015, Halofsky et al. 2018, Dumroese et al. 2019, Nave et al. 2019, Meyer et al. 2021). For instance, Sample (2017) estimates that reforesting productive sites on non-stocked Forest Service–managed lands across the contiguous United States has the potential to sequester more than 16 MMT CO2 eq. each year, enough to offset emissions from nearly 3.5 million cars (U.S. EPA, n.d.).

Future climatic conditions should be a consideration in the selection of plant materials used in reforestation efforts following major disturbance events (Kaibab National Forest, Arizona). Photo: USFS.

Where reforestation is practicable, however, scientists argue that such efforts should take broader ecological values into consideration, rather than focusing primarily on carbon. In particular, climate mitigation activities on the nation's forest lands should be designed synergistically with adaptation outcomes. For example, North et al. (2019) suggest that efforts to enhance carbon sequestration and storage in dry forests with a history of frequent fires should promote lower and variable tree densities to lessen the risk for more high-severity fire. This multi-values perspective is consistent with the Forest Service's emphasis on managing forests for a suite of ecosystem services. As Janowiak et al. (2017) note, a balanced, comprehensive, and science-based approach to considering carbon in forest management will help ensure that multiple ecosystem services, including carbon sequestration, are achievable.



National forests provide a wide range of ecosystem services, including clean water for downstream communities, and restoration efforts will need to account for different social values and possible trade-offs (Sumpter National Forest, South Carolina). Photo: Eric Harrison/Flickr.

7. BALANCING TRADE-OFFS AMONG ECOSYSTEM SERVICES

As highlighted in the 2012 Planning Rule, forest management plans are required to emphasize management of National Forest System lands so they are "ecologically sustainable and contribute to social and economic sustainability; consist of ecosystems and watersheds with ecological integrity and diverse plant and animal communities; and have the capacity to provide people and communities with ecosystem services and multiple uses that provide a range of social, economic, and ecological benefits for the present into the future" (USFS 2012b).

Framing national forest conservation from an ecosystem service perspective stems from a desire to help forest managers better articulate the broad range of national forest benefits to the public and, in turn, build support for management actions (Ruhl and Salzman 2020). Ultimately, the agency has an interest in engaging entities who benefit from particular services, such as water resources and recreational opportunities, to assist in carrying out projects, which will enhance collaboration and help ensure more effective management outcomes at broader landscape scales given limited resources (Smith et al. 2011, Kline and Mazzotta 2012, Kline et al. 2016, Halofsky et al. 2017).

While forest planners will need to develop associated goals that can be measured and evaluated at the project level, the 2015 *Land Management Planning Handbook* specifies that forest plan revisions must focus on "key" ecosystem services—those that are important in the broader landscape outside of the plan area and are likely to be influenced by the land management plan (USFS 2015a, Deal et al. 2017b). The *Handbook* offers flexibility for individual national forests, which is important given that "desired" conditions and ecosystem services will vary by region, forest type, and the values of stakeholders. However, given the likelihood that there will be trade-offs when managing forests for multiple ecosystem services, conflicts could ensue even among those who believe they share the same goals (Botkin 2014).

Certainly, the Forest Service has had to navigate trade-offs in land uses throughout its history. Yet, the challenges and uncertainties associated with changing climatic conditions, along with the need to achieve both climate adaptation and mitigation goals, could render managing for multiple, sustained ecosystem services difficult over the long term (Luce et al. 2012, Spies et al. 2018).

7.1. EXAMPLES OF TRADE-OFFS IN NATIONAL FOREST MANAGEMENT

The following examples illustrate just a few of the trade-offs that national forest managers and collaborators may face in the context of climate-smart restoration and management.

7.1.1. Carbon Sequestration and Other Ecosystem Services

As highlighted in chapter 6, national forests have a critical role to play in mitigating climate change through carbon sequestration and storage. Yet, some management efforts focused on enhancing carbon uptake of forests may result in outcomes that interfere with other ecosystem services, and vice versa (Strassburg et al. 2010, Creutzburg et al. 2017, James et al. 2018, Buotte et al. 2019a, Ontl et al. 2020). For example, studies suggest that strategies to maximize carbon sequestration by planting young, rapid-growing trees may lead to a reduction in water yield due to high losses from evapotranspiration (Bennett et al. 2009, McNulty et al. 2010, Cademus et al. 2014, Duan et al. 2016). Without consideration of that potential outcome, efforts to increase carbon sequestration in some areas could lead to water shortages for human communities and make forests more susceptible to disturbances such as wildfire, particularly where higher temperatures and enhanced evaporation due to climate change are expected (Duan et al. 2016). On the other hand, there are a number of potential synergies between forest adaptation and mitigation strategies. For instance, research by Dybala et al. (2019) suggests that restoration of deforested or degraded riparian areas has the potential for rapid carbon sequestration while also enhancing floodplain connectivity and biodiversity.

Ontl et al. (2020) suggest that evaluation of potential trade-offs between carbon management and adaptation-oriented goals should account for anticipated long-term changes in carbon fluxes. To facilitate this, the authors have developed a menu to help managers align adaptation strategies and actions specifically with carbon sequestration goals (Ontl et al. 2020). The Forest Service has also developed a framework to help identify potential trade-offs among services that can be applied at national, forest unit, and project-based levels (Deal et al. 2017a, 2017b; Deal 2020). Continued engagement and investment in these and related efforts will facilitate national forest stewardship to achieve a range of ecosystem services in this era of climate change.

7.1.2. Wildfire Management and Carbon Sequestration

The effects of wildfire management practices such as thinning and prescribed fire on carbon stocks is likely to depend on the initial state of a forest, the types of fuel reduction treatments conducted, and the time period over which the carbon balance is assessed (Ellenwood et al. 2012). As noted previously, however, near-term carbon emissions (as well as the potential for smoke-related health impacts) associated with treatments such as prescribed burns may ultimately lead to greater forest carbon resilience (and a reduced risk of prolonged smoky conditions associated with extreme wildfires) despite climate change and associated shifts in fire regimes. For example, a model-based assessment of a dry western forest system in the Lake Tahoe Basin of California and Nevada found that, although there was some carbon lost during simulated fuel treatments, those losses were ultimately compensated over the longer term by increased growth of residual stock due to greater available soil water and shift in species composition to more drought- and fire-tolerant Jeffrey pine at the expense of shade-tolerant, fire-susceptible white fir (Loudermilk et al. 2017). Research on the Sierra National Forest, California, suggests that, despite emitting carbon in the short term, a combination of thinning and maintenance burning would significantly stabilize forest carbon under the extreme fire conditions expected over the coming decades by reducing the risk of high-severity wildfires (Krofcheck et al. 2017).

In the Southeast, prescribed fire and thinning to enhance dominance of longleaf pine and reduce forest density to support the red-cockaded woodpecker was found to reduce total ecosystem carbon compared to untreated areas (Martin et al. 2015). Although this represents a trade-off between restoring fire-adapted forests and increasing carbon sequestration and storage in the near term, given the long lifespan and tolerance of longleaf pine to disturbances, continued management of restored forests is expected to provide resilient, long-term carbon benefits despite changing climatic conditions (Brantley et al. 2018).

7.1.3. Wildfire Management and Other Ecological Goals

Achieving both ecological and risk reduction objectives on increasingly fire-prone public lands can be especially challenging, as management approaches may necessitate accepting compromises across differing goals (Barros et al. 2018, Donovan et al. 2019). For example, salvage logging (i.e., the removal of standing and down fuels following a disturbance) has often been touted as a way to lessen the risk of subsequent wildfires, despite a lack of scientific consensus on its risk reduction benefit. However, the practice can have significant adverse ecological impacts, such as through mechanical disturbance, soil compaction, and the removal of organisms, organic material, and other elements of a post-disturbance forest system that are

Protecting surrounding communities from wildfires has always been an overarching concern for state and federal forest managers. As climate change contributes to an increase in fast moving and destructive "megafires," wildfire risk reduction measures will continue to drive many forest restoration efforts (2020 Almeda Fire, Phoenix, Oregon). Photo: Oregon Department of Transportation/Flickr.

The habitat requirements for sensitive wildlife species, such as this northern spotted owl fledgling, are important to consider in setting restoration goals and designing adaptation and mitigation approaches. Photo: Zia Fukuda/BLM.

important for forest regeneration (Lindenmayer and Noss 2006; Lindenmayer et al. 2012; Leverkus and Castro 2017; Leverkus et al. 2018, 2021; Thorn et al. 2018; Müller et al. 2019). Actions to reduce wildfire risks to communities also may run counter to achieving habitat and water quality goals (Sun et al. 2019). In parts of the Pacific Northwest, for example, maintaining roads can provide access for fuel reduction treatments and fire response, but they also fragment habitat and can lead to erosion and siltation into streams (DellaSala et al. 2011, Luce et al. 2012). Conversely, several studies suggest that limiting the use of treatments such as thinning and prescribed fire in parts of the region in an effort to protect closed-canopy habitats for species such as the northern spotted owl have led to increased risks from insect outbreaks and severe wildfire (Hessburg et al. 2016, Spies et al. 2018). This suggests the need to carefully consider trade-offs between maintaining existing habitat conditions and promoting landscape characteristics that are more resilient to large-scale disturbances (Hessburg et al. 2016).

Schultz et al. (2019a) note that part of the reason trade-offs between wildfire risk reduction and ecological goals exist is due to ambiguous and sometimes conflicting terminology and management directives. For instance, while some documents focus on fire as an ecological process and highlight "restoration" of natural fire regimes as important for long-term forest health, others emphasize fire as a hazard that needs to be "controlled." The authors argue that the current system of fire management leads to prioritization of

Ecological forestry, which seeks to use knowledge of disturbance ecology and retention-based management to achieve ecological and commodity goals, has emerged as an important concept for addressing wildfire risks as well as enhancing the health of forest ecosystems.

management for near-term risks at the expense on longer-term ecological goals. They suggest a more integrative approach that encompasses multiple problem definitions. Toward this, *ecological forestry,* which seeks to use knowledge of disturbance ecology and retention-based management to achieve ecological and commodity goals, has emerged as an important concept for addressing wildfire risks as well as enhancing the health of forest ecosystems (D'Amato et al. 2011, 2018; Palik and D'Amato 2017; Franklin et al. 2018; Spies et al. 2018; Kelsey 2019). Here, ecological forestry practices can include a combination of strategic thinning, prescribed fire, and managed wildfire (i.e., allowing some naturally ignited wildfires to burn, with selective suppression to protect property and infrastructure) to reduce the risk of high-severity wildfire and promote healthier, more resilient forests (Stephens et al. 2016, 2018; Kelsey 2019). Done thoughtfully, the approach can help balance trade-offs between short-term impacts of treatment with long-term benefits of reduced risks of large, high-severity fires (Kelsey 2019, Krofcheck et al. 2019, Stephens et al. 2021). For example, Hessburg et al. (2016) recommend a combination of managed wildfire, prescribed fire, and variable thinning in parts of the Pacific Northwest to support heterogeneous landscapes that confer resistance to severe wildfires as well as enhance habitat for old-growth-dependent species.

7.1.4. Wildfire Management and Timber Production

Although the volume of timber harvested on Forest Service lands has declined considerably from its peak in the mid- to late-20th century, commercial timber production remains an important activity for the agency (USFS, n.d.). Ager et al. (2017) note that, although efforts to optimize revenue to help finance restoration can lead to a sharp reduction in the attainment of other socioeconomic objectives, such trade-offs vary considerably among different planning areas and forest units. For example, Vogler et al. (2015) assessed potential trade-offs among restoration projects on the Wallowa-Whitman National Forest in eastern Oregon, which is considered a national priority for restoration to increase fire resilience and sustain a range of ecosystem services. One of the sharpest trade-offs they found was between net revenue from forest management activities and implementing projects that treat areas likely to contribute to fire in the surrounding wildland–urban interface. This creates a management challenge, as the costs of forest restoration projects are often offset through production of timber revenues.

Indeed, across the western United States, conflicting management objectives may occur between ecological, risk reduction, and wood production goals, which has implications for revenues to support Forest Service restoration activities as well as rural economies. As described by Ager et al. (2019), the generalization that "logging necessarily reduces wildfire risk has merit only if one considers that removing value from land (i.e., logs) reduces expected loss more than it affects fire spread and severity." To address these challenges, scientists in northern California have been working with traditionally natural resource–dependent communities to become more engaged in a variety of

The generalization that "logging necessarily reduces wildfire risk has merit only if one considers that removing value from land (i.e., logs) reduces expected loss more than it affects fire spread and severity." (Ager et al. 2019).

Although the volume of timber harvested on Forest Service lands has declined considerably from its peak in the mid- to late-20th century, commercial timber production remains an important activity for the agency (Chattahoochee National Forest, Georgia). Photo: Cecilio Ricardo/USFS.

post-fire restoration activities as a way to enhance local economies (Long et al. 2014). Although salvage logging for timber is among the strategies considered, there has been a concerted effort to identify approaches that are appropriate to, and less harmful of, forest ecology. As noted by Ryan and Hamin (2009), research on post-fire restoration suggests that salvage logging is likely to be more socially acceptable if done in ways that do not harm the local ecology and, in turn, provide revenues for forest restoration.

7.2. ENHANCING COLLABORATION TO IDENTIFY SHARED VALUES, NAVIGATE TRADE-OFFS, AND MAXIMIZE SYNERGIES

The challenge of navigating these and other trade-offs and achieving multiple benefits from climate adaptation and mitigation efforts underscores the importance of engaging a diversity of stakeholders throughout the national forest planning process (Thom and Seidl 2016, Janowiak et al. 2017, Seidl et al. 2017, Armatas et al. 2018, McNulty et al. 2018). The *Land Management Planning Handbook* requires forest planners to build a "collaborative process" to ensure that diverse needs are addressed throughout a plan's development and implementation, including engaging the public in efforts to "explore resolutions to one or more issues" (USFS 2015a). In addition, the development and use of a range of decision-support tools and approaches will be essential to help forest planners and managers achieve desired climate adaptation and mitigation outcomes across a range of values (e.g., Janowiak et al. 2014, Swanston et al. 2016, Ontl et al. 2020, Soto-Navarro et al. 2020).

Enhance collaboration to identify shared values, navigate trade-offs, and maximize synergies in the context of changing conditions. Engaging local communities and diverse constituencies as early as possible in the forest planning process helps gain buy-in and identify opportunities to minimize trade-offs and maximize synergies, including acknowledgment and discussion of the potential for fundamental changes in national forest conditions.

As noted previously, decisions on whether, where, and how to manage national forests for change are ultimately values based (Backstrom et al. 2018, Dudney et al. 2018). While climate-driven changes are both ongoing and inevitable, the collaborative decision-making processes that have become a foundation for Forest Service adaptation efforts, such as Adaptation Partners and the Climate Change Response Framework, will be essential to ensure that strategies reflect evolving societal goals for forest management (Swanston et al. 2016, Halofsky et al. 2018). Indeed, the agency's Research and Development arm offers an array of resources and services to facilitate consideration of managing for change among both national forest managers and their collaborators across the country. Initiatives like the Collaborative Forest Landscape Restoration Program (CFLRP) have helped leverage resources and build capacity to promote a range of ecological, economic, and social sustainability goals (Schultz et al. 2012). Through the CFLRP, collaborative groups are tasked with defining what "ecological restoration" means to them, create landscape-level goals, develop individual projects, monitor for effectiveness, and adaptively manage (Antuma et al. 2014).

Given the added complexities and uncertainties associated with climate change, however, bridging the research and management divide remains a challenge for public lands management (Brice et al. 2020, Carter et al. 2020). For example, several recent assessments of CFLRP efforts to date found that participants have found it difficult to define ecological objectives and develop management proposals when dealing with

Engaging stakeholders in developing a vision for forest restoration and management is key to understanding differing social values and successfully navigating trade-offs (Nez Perce-Clearwater National Forests, Idaho). Photo: NatPar Collection/Alamy Stock Photo.

complex ecological systems, variable conditions, and uncertainty (Antuma et al. 2014, Urgenson et al. 2017, Walpole et al. 2017). As noted by Walpole et al. (2017), restoration poses a unique challenge for collaboration given the need for participants to collectively determine which historical conditions are best to use as a reference, the degree of departure from those conditions necessary to warrant a management response, and how to balance historical conditions with expected future conditions. This is particularly challenging for systems that are not currently considered significantly degraded from historical conditions (Walpole et al. 2017).

Differing socioeconomic backgrounds and motivations for participation between agency and non-agency members have also limited the ability of some collaborative groups to develop and achieve mutually desired goals (Davis et al. 2017). In addition, it has been hard to maintain collaborative partnerships over the longer time frame necessary to effectively monitor and assess effectiveness of many adaptation strategies due to participant turnover, including Forest Service staff (Coleman et al. 2021). To be sure, establishing easily agreed-upon goals in collaborative forest management efforts has helped build relationships, trust, and momentum for tackling more contentious issues (Walpole et al. 2017). Given that many management decisions made today will have significant implications for national forests for decades to come, further work is necessary to better operationalize collaborative planning approaches and techniques for building consensus around climate-smart restoration (McKelvey et al. 2021). Recent experience suggests that collaborative restoration efforts can navigate the challenges posed by disagreement over use of historical references by: 1) integrating information about past, present, and anticipated future conditions; 2) identifying reference periods that are analogs to current or projected future climate; and 3) balancing science-based targets with other social values in restoration planning (Urgenson et al. 2018).

Forest restoration principles and practices will need to continue evolving to meet the challenges of accelerating climatic changes. Photo: David R./Alamy Stock Photo.

8. A PATH FORWARD

As discussed throughout this report, a rapidly changing climate has significant implications for the effectiveness of restoration efforts on America's national forests. There has been considerable progress in scientific assessment of climate change and its impact on forests, and parts of the Forest Service have strongly embraced the need to advance both climate adaptation and mitigation outcomes. The 2012 Forest Planning Rule and subsequent management directives have established an important foundation for national forest managers and their partners to adopt the collaborative, flexible management approaches necessary to effectively address climate change given inherent complexities and uncertainties. Nonetheless, varying perspectives on what climate change means for ecological restoration in practice continue to pose challenges in national forest planning and management.

There is a growing recognition that conventional restoration practices—including use of natural range of variability as a benchmark for management—must evolve to meet the emerging challenges of a changing climate. A science-based and shared understanding of what constitutes climate-smart restoration will be important to the Forest Service's ability to achieve its mission of sustaining the wide range of ecosystem services provided to society by the nation's national forests. Toward this end, we suggest the need for continued dialogue and collaboration between national forest managers and their partners in the state, tribal, nonprofit, and private sectors to adopt climate-smart and ecologically appropriate forest restoration and management, supported by the proposed, science-based principles highlighted in this paper. Such partnerships can build on existing collaborative initiatives and planning tools in working toward a sustainable and resilient future for America's national forests.

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