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Assessing vulnerabilities and adapting to climate change in northwestern U.S. forests

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Abstract Multiple climate change vulnerability assessments in the Pacific Northwest region of the USA provide the scientific information needed to begin adaptation in forested landscapes. Adaptation options developed by resource managers in conjunction with these assessments, newly summarized in the Climate Change Adaptation Library of the Western United States, provide an extensive choice of peer-reviewed climate-smart management strategies and tactics. More adaptation options are available for vegetation than for any other resource category, allowing vegetation management to be applied across a range of spatial and temporal scales. Good progress has been made in strategic development and planning for climate change adaptation in the Northwest, although on-the-ground implementation is in the early stages. However, recent regulatory mandates plus the increasing occurrence of extreme events (drought, wildfires, insect outbreaks) provide motivation to accelerate the adaptation process in planning and management on federal lands and beyond. Timely implementation of adaptation and collaboration across boundaries will help ensure the functionality of Northwest forests at broad spatial scales in a warmer climate.

1 Introduction

Forests in the Pacific Northwest region of the USA (Washington, Oregon, Idaho, western Montana) provide many ecosystem services, including timber, water, food, bioenergy, plant

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and animal habitat, recreation opportunities, and cultural values. Climate change will likely affect the provisioning of these forest ecosystem services (Seidl et al. 2016), resulting in shifts in forest productivity (Latta et al. 2010; Littell et al. 2013), disturbance regimes (Stavros et al. 2014), and species composition (Littell et al. 2010). Increased temperatures over the last several decades in the Pacific Northwest (Abatzoglou et al. 2014) have already led to changes in hydrological processes, including reductions in snowpack (Mote 2006), mountain precipitation (Luce et al. 2013), and streamflow (Luce and Holden 2009). Across the western U.S., there have been increases in area affected by wildfire (Westerling et al. 2006) and insect outbreaks (Meddens et al. 2012). These trends are likely to continue as temperatures increase in the coming decades, with disturbance driving forest ecosystem change (Millar and Stephenson 2015).

To minimize the negative effects of climate change on forests and the services they provide, forest owners and natural resource managers need information to understand and address the potential effects of climate change. In recent years, governmental and nongovernmental organizations have been developing climate change vulnerability assessments and exploring adaptation options (Bierbaum et al. 2013), and public, private, and tribal land managers are all interested in these products. Federal land management agencies in the USA are required to evaluate the potential risks associated with climate change to minimize short- and long-term effects on their operations and mission. Many federal agencies have now developed general climate change vulnerability assessments, adaptation plans, and strategies for addressing climate change (Halofsky et al. 2015).

Despite the recent progress, development of local to regional-scale vulnerability assessments and adaptation plans has been slow and uneven across agencies and organizations (Bierbaum et al. 2013; Halofsky et al. 2015). Much of the progress to date has been accomplished through science-management partnerships, which have emerged as effective catalysts for developing vulnerability assessments and land management adaptation plans at both strategic (general) and tactical (on-the-ground) levels (Peterson et al. 2011; Littell et al. 2012; Swanston and Janowiak 2012; Cross et al. 2013; Halofsky et al. 2014). Science-management partnerships typically involve iterative exchange of information on regional climatology and climate change effects from scientists, and of information on local climate (and weather), ecology, and management from managers and/or private landowners (Peterson et al. 2011). This iterative information sharing aids identification of key vulnerabilities to climate change at the local scale, setting the stage for developing place-based adaptation strategies and tactics (Halofsky et al. 2014).

We initiated four science-management partnerships to support climate change vulnerability assessments and adaptation on U.S. Forest Service and National Park Service lands in the Pacific Northwest (Fig. 1). Goals of the partnerships were to (1) provide climate change education for resource managers; (2) synthesize published information and data to assess the vulnerability of key resources; (3) develop science-based adaptation strategies and tactics that will help to mitigate the negative effects of climate change and assist the transition of biological systems to a warmer climate; and (4) implement climate-informed practices in long-term planning and management. We describe here the process and outcomes of these adaptation partnerships, encompassing 21 national forests and 6 national parks. Specifically, we present the results of the climate change vulnerability assessments for forest vegetation and a library of adaptation strategies and tactics for forest resource management, representing the outcome of 8 years of adaptation partnership work. Themes and potential applications of the library in forest vegetation management are discussed.

2 Methods

Four climate change adaptation partnerships, including the Olympic, North Cascadia, Blue Mountains, and Northern Rockies Adaptation Partnerships, were initiated from 2008 to 2016 (Fig. 1, Table 1). Each adaptation partnership involved the following: (1) initial climate change education; (2) multi-disciplinary science-based vulnerability assessments; (3) development of adaptation strategies and tactics in hands-on science-management workshops; and (4) publication of peer-reviewed reports describing the vulnerability assessment and adaptation options. Scientists from the Forest Service, other federal agencies, and universities (see Table 1) developed state-of-science climate change vulnerability assessments for forest vegetation. Vulnerability assessments considered the sensitivity (susceptibility to harm) and adaptive capacity (capacity to cope and adapt) of species and ecosystems of interest (Noble et al. 2014). Potential exposure to climate change, a component of risk, was also assessed using recent regional climate science analyses (Mote and Salathe 2010; Dalton et al. 2013).

Vulnerability assessments synthesized the best available science, evaluating quality and relevance for each application, and identifying geographic locations with high vulnerability. All assessments evaluated vulnerability of vegetation types, and the Northern Rockies assessment included species vulnerabilities. In assessing vulnerabilities, scientists considered studies of long-term paleo-climate and species distribution, fire histories, and trends in vegetation with recent climate change. Vegetation impact model projections were also considered, as available, including new analyses using the MC1 (and the newer version, MC2) dynamic global vegetation model (Bachelet et al. 2001). Teams focused on effects and projections specific to the region of interest, and scientists worked with specialists to aid interpretation and apply information locally.

Based on initial vulnerability assessments, adaptation strategies and tactics were developed in a series of 2-day hands-on scientist-manager workshops. The first half to full day of the workshops was devoted to scientists' (or scientist-manager teams') presentations on future climate projections and vulnerability assessments for multiple resource areas (e.g., water, fish, vegetation, wildlife, recreation). Participants were then separated into work groups by resource area to (1) identify key climate change vulnerabilities; and for each key vulnerability (2)

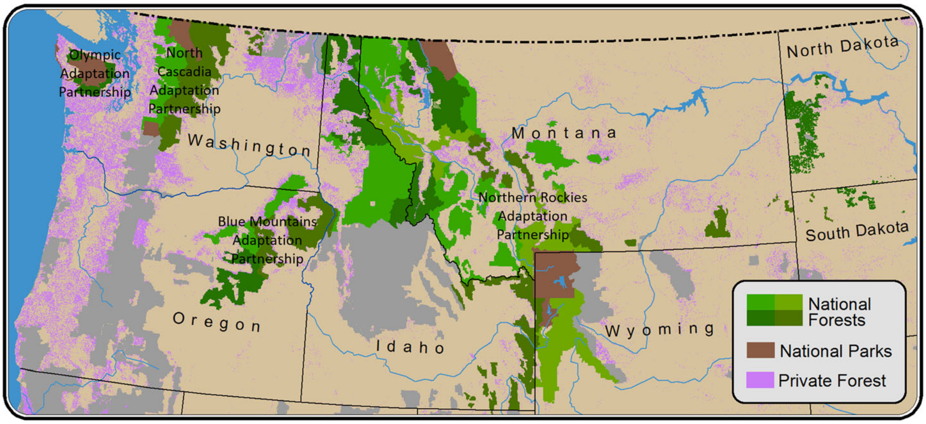

Fig. 1 Locations of the national forests and national parks involved in four climate change adaptation partnerships in the western United States. Private lands in the region are shown in *pink*, and other national forests (not involved in the assessments described here) are shown in *gray*. Map by R. Norheim

Table 1 Geographic region, participating units, scientists and resource managers, and products for four science-management partnerships developed in the Pacific northwestern United States

Partnership name	Geographic region and area	Primary partner units	Number of scientists	Number of resource managers	Products
Blue Mountains Adaptation Partnership	Northeastern Oregon, southeastern Washington; 2.1 million ha	Forest Service Pacific Northwest Research Station and Pacific Northwest Region; University of Washington; Oregon State University Climate Impacts Research Consortium; Malheur, Umatilla, and Wallowa-Whitman National Forests	10	50	Halofsky and Peterson (2016); Halofsky and Peterson (2017)
North Cascadia Adaptation Partnership	North-central Washington (North Cascade Range); 2.4 million ha	Forest Service Pacific Northwest Research Station; Mt. Baker-Snoqualmie National Forest; Okanogan-Wenatchee National Forest; North Cascades National Park Complex; Mount Rainier National Park	11	300	Raymond et al. (2013, 2014); Halofsky et al. (2014); Halofsky and Peterson (2016)
Northern Rockies Adaptation Partnership	Northern Idaho, Montana, northwest Wyoming, North Dakota, northern South Dakota; 6.9 million ha	Forest Service Northern Region and Pacific Northwest and Rocky Mountain Research Stations; Glacier, Yellowstone and Grand Teton National Parks; Great Northern and Plains and Prairie Potholes Landscape Conservation Cooperatives; North Central Climate Science Center; Greater Yellowstone Coordinating Committee; University of Washington; Oregon State University Climate Impacts Research Consortium; EcoAdapt	18	210	Buotte et al. (2016); Halofsky and Peterson (2016); Halofsky et al. (2017)
Olympic Adaptation Partnership	Northwestern Washington (Olympic Peninsula); 630,000 ha	Forest Service Pacific Northwest Research Station; Olympic National Forest; Olympic National Park; University of Washington Climate Impacts Group	31	110	Peterson et al. (2011); Halofsky et al. (2011b); Littell et al. (2012); Halofsky et al. (2014); Sample et al. (2014)

develop (feasible) general adaptation strategies or approaches; and (3) develop specific on-the-ground tactics or actions. Each work group had a facilitator and note taker, and key vulnerabilities, and adaptation strategies and tactics were recorded using worksheets adapted from Swanston and Janowiak (2012). While complete group consensus was not required, strategies and tactics recorded in the worksheets were generally agreed upon by group members. Scientists played only a consulting role in the work groups. Participating resource managers had 10–35 years of forest management experience, making them well-qualified to provide expert judgments about responses to climate change. Resource managers were also diverse in terms of area of expertise, age, and experience in natural resources, resulting in diverse perspectives and ideas for adaptation to climate change.

Results of vulnerability assessments and adaptation workshops were compiled and incorporated into chapters of technical reports for the Olympic (Halofsky et al. 2011a), North Cascadia (Littell et al. 2014), Blue Mountains (Kerns et al. 2016), and Northern Rockies (Keane et al. 2017). Draft chapters were first reviewed and edited by editorial teams of scientists. Then, each chapter, including the adaptation strategies and tactics, was peer-reviewed both internally (by Forest Service managers and other project participants) and externally by at least two scientists (and at least one external to the Forest Service). Thus, the adaptation strategies and tactics presented here were vetted and peer-reviewed at four points in the process: (1) in work group discussions at the workshops, (2) in the initial editorial process, (3) during the internal review, and (4) during the external review.

3 Results

3.1 Key climate change vulnerabilities for forest vegetation

In the Northwest climate, topography generates orographic effects that affect forest composition, producing an assemblage of plants locally adapted to climate. Mountain ranges of the Northwest interact with wet-marine air masses from the Pacific Ocean and dry-continental air masses to produce strong west-east moisture and temperature gradients. West of the Cascade Range, forests experience ample moisture and mild temperatures which are conducive for Douglas-fir (*Pseudotsuga menziesii*), red alder (*Alnus rubra*), western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), bigleaf maple (*Acer macrophyllum*), western redcedar (*Thuja plicata*), and lodgepole pine (*Pinus contorta var. latifolia*). Productivity in these moist forests is limited by temperature as well as light due to cloud cover and competition. In comparison, forests of the interior Northwest, west of the Rocky Mountain Range, experience moisture deficits and warmer temperatures that engender dry forests that are favorable for ponderosa pine (*Pinus ponderosa*), lodgepole pine, Douglas-fir, western juniper (*Juniperus occidentalis*), white fir (*Abies concolor*), grand fir (*Abies grandis*), and quaking aspen (*Populus tremuloides*).

Trees are locally adapted to climate in the Northwest and tolerate moderate changes in climate. However, large and rapid changes in climate may be beyond the capacity of some species to endure (Chmura et al. 2011). Across the Northwest, climate change projections for the end of the century (2070–2099) suggest an increase in average annual temperature of 2–6 °C (Abatzoglou and Brown 2012; Abatzoglou 2013). Precipitation projections are uncertain, but lower snowpack is expected with more precipitation falling as rain than snow and snowpacks melting earlier, resulting in longer dry seasons (Luce et al. 2016). Higher temperatures and longer dry periods between precipitation events are expected to lead to more frequent and severe droughts (Chmura et al. 2011).

Projected shifts in climate will affect tree reproduction, growth, phenology, and mortality (Chmura et al. 2011). Shifts in climate have already occurred, leading to significant droughts that have led to high mortality in some Western forests (Allen et al. 2010; Millar and Stephenson 2015; Clark et al. 2016). Although drought is common in Northwest forests, particularly east of the Cascade Mountain Crest, warmer droughts will amplify moisture limitations that will reduce tree growth and forest regeneration (Littell et al. 2008, 2010; Restaino et al. 2016). For moist forests, projected increases in temperature will likely ease energy limitations in the short term, allowing for greater productivity until reductions in soil water availability limit further growth (Chmura et al. 2011; Luce et al. 2016).

Changes in climate will also likely increase tree stress and mortality through shifts in ecological disturbances (van Mantgem et al. 2009; Chmura et al. 2011; Kolb et al. 2016), including wildfires and insect outbreaks. Drought, in concert with increased tree stress due to insects and disease, may increase wildfire intensity and extent in dry Northwest forests (Allen et al. 2010; Littell et al. 2010; Stavros et al. 2014). However, recent bark beetle outbreaks in the western U.S. have caused greater mortality than wildfires, particularly in lodgepole pine, Douglas-fir, and spruce/fir forest types (Hicke et al. 2016). With drought, the effects of pathogens on Northwest forests may become more frequent and severe, except for pathogens that require moist conditions such as Swiss needle cast and Phytophthora root rot (Kolb et al. 2016). Additional research is needed to understand how parasitic plants will affect Northwest forests; mistletoes increase tree stress during droughts, yet also suffer higher mortality during intense droughts (Kolb et al. 2016). Overall, projected shifts in climate will increase these ecological disturbances, which will affect forest vegetation and ecosystems (Littell et al. 2010). It is unclear to what extent Northwest forests can absorb these enhanced disturbances and remain resilient (return to a prior condition after disturbance). Once forest resilience thresholds are crossed, major ecological transformation may occur (Millar and Stephenson 2015; Clark et al. 2016).

3.2 Adaptation strategies and tactics for forest vegetation

Based on local vulnerability assessments, resource managers in the adaptation partnerships developed 41 adaptation strategies and 124 adaptation tactics for forest vegetation management. These strategies and tactics were compiled in the newly developed Climate Change Adaptation Library for the Western United States (http://adaptationpartners.org/library.php), a resource open for others interested in climate change adaptation in natural resources. Though the Library covers a diversity of resources, including water, infrastructure, fish, wildlife, and recreation, we focus here on themes and highlights from the forest vegetation portion of the Library (Table 2).

Adaptation strategies to increase ecosystem resilience to climate change were ubiquitous across regions. Managers were particularly concerned about wildfire, insects, and drought (Table 2), and thus many adaptation strategies and tactics were focused on decreasing forest density to increase drought resilience and decrease the severity of wildfire and insect attacks. For example, managers identified promoting disturbance-resilient forest structure and species as key strategies. Thinning and prescribed fire can both be used to reduce forest density, increase spatial heterogeneity in forest structure, and promote disturbance-resilient species (Joyce et al. 2009; Spies et al. 2010; Stephens et al. 2010; Churchill et al. 2013; Cross et al. 2013). Disturbance-resilient species can also be planted.

Table 2 Climate change sensitivities, adaptation strategies, and adaptation tactics associated with forest vegetation. Adaptation strategies and tactics were developed by resource managers in a series of hands-on workshops in the Pacific Northwestern U.S. Applicability of individual tactics will vary based on the type of landowner, management goals, ecosystem types, and other factors

Sensitivity to climate change	Adaptation strategy	Adaptation tactics
Large disturbances will create the potential for mortality events and regeneration failures	Mitigate consequences of large disturbances by planning ahead	• Maintain a tree seed inventory with high-quality seed for a range of species, particularly species that may do well in the future under hotter and drier conditions • Increase production of native plant materials for post-disturbance plantings
	Use judicious managed relocation of genotypes where appropriate	• Modify seed zone guidelines to include genotypes from warmer locations; use a variety of genotypes rather than just one
Increased drought stress will decrease forest productivity at lower elevations	Increase forest resilience and facilitate transitions	• Increase the amount of thinning and possibly alter thinning prescriptions • Use girdling, falling and leaving trees, prescribed burns, and wildland fire to reduce stand densities and drought stress • Maximize early-successional tree species diversity by retaining minor species during pre-commercial thinning activities to promote greater resilience to drier conditions • Consider including larger openings in thinning prescriptions and planting seedlings in the openings to create seed sources for native drought-tolerant species
Increased warming, drought and wildfire will reduce tree vigor and increase susceptibility to insects and pathogens, with increased potential for large and extensive insect and pathogen outbreaks, particularly of non-native insects and pathogens	Increase resilience of forest stands to disturbance by increasing tree vigor	• Thin to decrease stand density, increase tree vigor and accelerate development of late-successional forest conditions • Harvest to variable densities • Reduce density of post-disturbance artificial regeneration • Plant disease-resistant species or genotypes where species-specific insects or pathogens are a concern • Increase stand-scale biodiversity and minimize monocultures • Treat existing pathogen outbreaks more aggressively
Higher temperature and more drought will lead to more wildfire (larger aerial extent and more high-severity patches) and more area in recently burned or early-successional stages	Plan and prepare for greater area burned	• Incorporate climate change into fire-management plans • Anticipate more opportunities to use wildfire for resource benefit • Plan post-fire response for large fires • Consider using prescribed fire to facilitate transition to a new fire regime in drier forests • Manage forests for future range of variability
	Increase resilience of existing vegetation by reducing hazardous fuels and forest density	• Thin and prescribe burn to reduce hazardous fuels, especially in the wildland-urban interface • Increase intentional use of lightning-ignited fires

Table 2 (continued)

Sensitivity to climate change	Adaptation strategy	Adaptation tactics
		• Consider using more prescribed fire where scientific evidence supports change to a more frequent fire regime • Use prescribed fire to maintain structure and promote fire-tolerant conifer species • Increase interagency coordination • Use regeneration and planting to influence forest structure
	Increase resilience and facilitate forest transitions through post-fire management	• Consider climate change in post-fire rehabilitation • Determine where native seed may be needed for post-fire planting • Anticipate greater need for seed sources and propagated plants • Plant fire-tolerant tree species after fire • Increase post-fire monitoring
Increasing drought and disturbance will alter species composition, relative abundance, and species distribution patterns	Increase knowledge of patterns, characteristics, and rates of change in species distributions	• Expand long-term monitoring programs
Areas with limited species and genetic diversity will likely be more susceptible to climate change stressors	Promote species and genetic diversity	• Plant potential microsites with a mix of species • Maintain species diversity during thinning • Interplant to supplement natural regeneration and genetic diversity
Increased flooding and lower low flows will alter riparian habitats	Reduce riparian impacts by storing more water on the landscape	• Inventory current and potential habitat • Increase beaver populations with translocation and trapping to create more wetland habitat • Restore riparian habitat
Climate change stressors cross boundaries, forcing agencies to coordinate and work across boundaries	Work across jurisdictions at larger scales	• Align budgets and priorities for program of work with neighboring lands • Communicate about projects adjacent to other lands, and coordinate on the ground • Work across boundaries to preserve roads, trails, and access with increasing fire and flood events

Preparing for disturbance will also be important under a changing climate (Millar et al. 2007). Regeneration after severe fire may be more limited in the future with climate shifts (Littell et al. 2010; Chmura et al. 2011). Promoting legacy trees of disturbance-resilient species may help to increase post-fire regeneration. Managers may also want to increase seed collection and ensure that adequate nursery stock that is adapted to future climate conditions is available for post-disturbance planting (Halofsky et al. 2011a).

Promoting biological diversity, including species, genetic, and landscape diversity, was another theme in the adaptation strategies and tactics. Increasing diversity is a “hedge your bets” strategy that reduces risk of major forest loss. Areas with low species and genetic diversity will likely be more susceptible to stressors associated with climate change, so promoting species and genetic diversity (e.g., through plantings and thinning treatments) will increase forest resilience to changing climate (Joyce et al. 2009; Littell et al. 2010; Dymond et al. 2014). Promoting landscape heterogeneity, in terms of species and structure, will also increase resilience to wildfire and insects (Stephens et al. 2010) and potentially increase climate change refugia (Morelli et al. 2016).

Riparian forests provide critical wildlife habitats and increase water quality across the western U.S. (Naiman and Decamps 1997). The primary strategy for improving riparian habitat resilience on federal lands was maintaining healthy American beaver (*Castor canadensis*) populations (Table 2). Beavers can buffer riparian systems against both low and high stream flows (Pollock et al. 2003; Lawler 2009), providing habitat structure and foraging opportunities for multiple species (Pollock et al. 2003). In addition, accelerating riparian restoration is an effective and long-lasting way to improve hydrological function and water retention (Luce et al. 2012). Reducing damage by livestock grazing on riparian vegetation and stream banks can also help increase riparian vegetation resilience and reduce stream temperature increases, but may face opposition from those who access national forests for grazing.

Finally, managers recognized that stressors associated with climate change cross boundaries, making it increasingly important that agencies and private landowners coordinate and work across boundaries (Joyce et al. 2009; Spies et al. 2010; Stein et al. 2013). Agencies can coordinate by aligning budgets and priorities for programs of work, communicating about projects adjacent to other lands, and working across boundaries to maintain roads, trails, and access that will be affected by fire and flood events in a warmer climate.

4 Discussion

The Climate Change Adaptation Library provides a science-based foundation for resource managers who want to develop climate-smart management actions, or management responses that consider climate change and can help to minimize the negative effects. Many of the adaptation options in the Library are already established as tools and techniques used in sustainable resource management. Resource managers may also find comfort in the fact that the Library is based on information elicited from other managers like themselves, and is not developed by scientists without real-world input. Thus, although climate change adaptation is not a cookbook process, the vetted and peer-reviewed adaptation strategies and tactics in the library can be used “off the shelf” and grounded in the unique management context of a particular place.

In the process of incrementally building the Adaptation Library, we found considerable concurrence in adaptation strategies among different regions and management units (Halofsky and Peterson 2016). This suggests that there is a finite set of general responses to potential climate change effects in the Pacific Northwest, and that although the Library is intended as a dynamic resource, the rate of increase in adaptation strategies will diminish over time. This concurrence also exists between the Library and a large, independent effort conducted for forest systems in the eastern U.S. (Swanston and Janowiak 2012), thus providing confidence in the universality of at least a core of adaptation options. However, adaptation tactics will need to be customized for specific landowners, ecosystems, and management objectives, and implementation will likely vary with management context.

In the Adaptation Library, similar or complementary adaptation options were identified for more than one resource sector (e.g., water resources and fisheries), suggesting a need to integrate adaptation planning across multiple disciplines. For example, restoring floodplains can improve hydrologic function, with benefits to water quantity and quality, riparian vegetation, and fish habitat. Such adaptation options that yield benefits to more than one resource are likely to have the greatest benefit (Peterson et al. 2011; Halofsky and Peterson 2016). However, some adaptation options involve trade-offs and uncertainties that need further exploration. For example, while thinning may help to increase dry forest resilience to fire and drought, wildlife species have variable responses to thinning treatments, depending on species' needs and where and how treatments are applied (e.g., Carey and Harrington 2001). Dialog among managers from multiple resource areas allows for better consideration of trade-offs.

As it is a relatively new endeavor for private landowners and natural resource managers, climate change adaptation is typically filled with uncertainty (Millar et al. 2007), and science-based processes and guidelines are still evolving and being tested. Climate change vulnerability assessments are increasingly a component of risk assessment for resource planning and management, and adaptation is increasingly a component of risk management (Yohe and Leichenko 2010; Peterson et al. 2011). Including climate change as a component of resource planning and management, which was viewed in the recent past as merely desirable, is now required in the U.S. Forest Service (Federal Register 2012) and National Park Service (NPS 2010), and is becoming a more common element of agency operations.

Northwest forest owners vary in their capacity to address climate change. The biggest challenge for U.S. federal agencies has been building the organizational capacity to address a complex issue that affects multiple resources. Federal agencies have seen a steady decline in budgets and personnel over the past 20 years, making it difficult for most resource specialists who are fully committed to ongoing projects and regulatory requirements to take on additional projects. Family forest owners span a broad range of views and understanding about climate change and its effects on forest resources based on perceptions of climate science credibility, personal experiences, and worldviews (Grotta et al. 2013); outreach efforts must account for this span of views. Commercial forest owners are developing climate policies and managing their operations to reduce greenhouse gas emissions and increase carbon sequestration, but research is still needed for all forest owners to advise adaptation strategies, especially for short-rotation forestry. Although education and training on climate change have generally been available, they are only a precursor to aspects of decision making and management that require assessment of climate change effects and responses to them. Development of accessible decision-making tools that incorporate risk management with adaptation strategies (such as those in the Adaptation Library), along with effective outreach programs, will benefit all forest landowners.

After development of climate change adaptation strategies and tactics, implementation is the next step, but implementing adaptation options in local management units can be challenging, and progress to date has been slow (Halofsky et al. 2015). Implementation will likely occur over time as policies change, as plans and programs are revised, and especially when extreme weather events (e.g., multi-year droughts) and major disturbances (e.g., large wildfires) capture the attention of agencies, local communities, and stakeholders (Millar et al. 2014). Adaptation is more likely to be successful when multiple parties collaborate on implementation across large landscapes, rather than acting independently (Joyce et al. 2009; Spies et al. 2010; Stein et al. 2013). As adaptation options are implemented, it will be critical to monitor their effectiveness across different landscapes. Monitoring data provide feedback that can be used to validate existing options, inform their modification, or develop new options to be tested. Working across multiple jurisdictions and boundaries and collaborating with the research community will help ensure that diverse perspectives are represented and that effectiveness monitoring is robust.

5 Conclusions

Although uncertainties exist about the magnitude, likelihood, and timing of climate change effects on natural resources, sufficient scientific information is available to begin the adaptation process on forest lands. Climate change vulnerability assessments are nearly comprehensive across forested regions of the northwestern U.S. In addition, adaptation options have been developed through partnerships that included 70 scientists and nearly 700 resource managers from federal agencies and other organizations, resulting in the development of the Climate Change Adaptation Library for the Western United States. The spatial extent of the assessments, large number of contributors, and peer-reviewed documentation provide confidence that adaptation options in the Library are effective, feasible, and scientifically robust.

The coproduction of knowledge (Meadow et al. 2015) in our climate change vulnerability assessments provides a foundation for adaptation that is relevant for on-the-ground management and planning, and is therefore more likely to be embraced and implemented. Climate change vulnerability assessments that are produced over a relatively short time span facilitate a continuous dialog among participants, thus ensuring consistency and relevance that are often diluted in processes that drag on for many years. Facilitating communication from one climate change vulnerability assessment to the next, through purposeful mixing of personnel and shared learning, improves organizational capacity and ensures consistency across multiple geographic regions. Also, allowing resource specialists and scientists to “self-select” their roles in each assessment allows partnerships to create their own balance of skills and personalities, and reduces unrealistic expectations for commitments of time and energy from people who are already busy with other assignments.

The presence of new federal regulatory mandates is helping to motivate implementation of climate-smart planning and resource management, especially in national forests that are revising existing land management plans or writing new vegetation management plans. On-the-ground implementation is proceeding slowly, but good examples are emerging, often in conjunction with other management objectives (e.g., forest thinning to increase vigor, restoration of riparian areas, removal of non-native species). Many existing management practices are inherently consistent with climate-smart management, providing a foundation on which to build active programs of climate change adaptation. Although the Library described above was developed mostly with federal agencies, many of the adaptation options are also applicable on private and tribal lands in the Northwest. Applying adaptation strategies and tactics across ownerships, allowing flexibility to account for differences in objectives, will improve the likelihood of minimizing the negative effects of climate change.

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