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Climate Change Vulnerabilities and Adaptation Options for Forest Vegetation Management in the Northwestern USA

Jessica E. Halofsky [1,*,†] and David L. Peterson [2,†]

1 School of Environmental and Forest Sciences, University of Washington, PO Box 352100, Seattle, WA 98195, USA
2 U.S. Forest Service, Pacific Northwest Research Station, 400 N. 34th Street, Seattle, WA 98103, USA; peterson@fs.fed.us
* Correspondence: jhalo@uw.edu; Tel.: +1-206-543-9138
† The authors contributed equally to this work.

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Abstract: Recent vulnerability assessments, conducted in diverse regions in the northwestern United States, indicate that many commonalities exist with respect to projected vulnerabilities to climate change. Dry forests are projected to have significant changes in distribution and abundance of species, partially in response to higher temperature and lower soil moisture, but mostly in response to projected increases in extreme events and disturbances—drought, wildfire, and insect outbreaks. Wildfire and mountain pine beetles have caused extensive mortality across millions of hectares in this region during the past decade, and wildfire area burned is projected to increase 200%–300% by mid-21st century. Science–management partnerships associated with recent assessments have identified an extensive list of adaptation options, including both strategies (general planning) and tactics (on-the-ground projects). Most of the options focus on increasing resilience to disturbances and on reducing current stressors to resource conditions. Adaptation options are generally similar across the biogeographically diverse region covered by assessments, suggesting that there may be a limit on the number of feasible responses to climate change. Federal agencies in the northwestern United States are now using these assessments and adaptation approaches to inform sustainable resource management and planning, mostly through fine tuning of existing practices and policies.

Keywords: adaptation; climate change; resource management; vegetation; vulnerability assessment

1. Introduction

Climate change will have both direct and indirect effects on forest vegetation in western North America. Direct effects of higher temperatures on forests include altered tree growth, mortality, and regeneration, in addition to the indirect effects of changing disturbance regimes on forest vegetation [1,2]. Understanding potential shifts in local vegetation is critical for land managers to develop adaptive strategies and minimize the negative effects of climate change on ecosystems and the services they provide [3].

Some natural resource agencies and organizations have developed climate change vulnerability assessments and adaptation strategies for addressing climate change [4]. However, development of local to regional-scale vulnerability assessments and adaptation plans in western North America has been slow and uneven [4,5]. Progress in development of finer-scale assessments has largely been made through science–management partnerships [6–11]. Through iterative exchange of information, these partnerships help to identify key climate change vulnerabilities and develop adaptation strategies and tactics based on those vulnerabilities [11].

We initiated four science–management partnerships to support climate change vulnerability assessments and development of adaptation options in western U.S. Forest Service and National Park Service lands. Goals of the partnerships were to: (1) conduct analyses and synthesize published information and data to assess the vulnerability of key resources; and (2) develop science-based adaptation strategies and on-the-ground tactics that will help reduce negative effects of climate change and assist the transition of biological systems to a warmer climate. Partnership locations included the Olympic Peninsula of Washington State (Olympic Adaptation Partnership); North Cascade Range of north-central Washington (North Cascadia Adaptation Partnership); Blue Mountains region of northeastern Oregon (Blue Mountains Adaptation Partnership); and Northern Rocky Mountains (Northern Rockies Adaptation Partnership) (Figure 1). Although vulnerability assessments encompassed a diverse set of resources, including water, fisheries, wildlife, recreation, infrastructure, and ecosystem services (e.g., carbon storage, timber production, and cultural heritage), we focus here on assessments of forest vegetation and disturbance and related adaptation options. Our objective is to synthesize vulnerabilities of vegetation to climate change across the four assessment regions and identify key adaptation strategies and tactics to address those vulnerabilities.

Figure 1. Locations of the four science–management adaptation partnerships.

2. Assessment and Adaptation Process

Teams of scientists from the Forest Service, other federal agencies, and universities conducted state-of-science climate change vulnerability assessments for vegetation in each of the four study regions (Figure 1). Assessments considered exposure, sensitivity, and adaptive capacity (*sensu* [12]) of the species and ecosystems of interest. Far more than literature reviews, teams conducted vegetation modeling analyses at a subregional level, synthesized other available science, evaluated the quality and relevance of the science for each application, and identified geographic locations where vulnerability is highest.

The first step in the vulnerability assessment process involved a review of available general circulation model projections to determine likely levels of exposure to climate change (degree of deviation in temperature and precipitation at mid and late-21st century compared to a historical period) in the assessment area. For the Olympic and North Cascadia Adaptation Partnerships, regional-scale climate projection summaries were provided by the University of Washington Climate Impacts Group, based on a Washington State assessment [13]. These summaries were provided in chapters of peer-reviewed Forest Service general technical reports for the Olympic Peninsula [14] and the North Cascades [15]. The Blue Mountains Adaptation Partnership utilized information from a regional assessment [16], conducted as a part of the U.S. National Climate Assessment. Climate projections for the Blue Mountains were summarized in a chapter of a peer-reviewed general technical report describing the Blue Mountains vulnerability assessment [17]. Finally, for the Northern Rockies Adaptation Partnership, downscaled climate projections, obtained from the Geo Data Portal at the U.S. Geological Survey (USGS) Center for Integrative Data Analytics, were summarized for the study area by analysts at the USGS North Central Climate Science Center [18]. In all cases, the latest global climate model runs were used in analyses. For example, Coupled Model Intercomparison Project 5 projections, which were used in the Intergovernmental Panel on Climate Change Fifth Assessment Report [19], were used for the recent Blue Mountains and Northern Rockies assessments.

In the next step, relevant literature and available model projections of climate change effects were reviewed to evaluate vegetation sensitivity, or the degree to which a species or system is affected by climate variability or change. The Northern Rockies assessment included both vegetation type and species level vulnerabilities, whereas the other three projects focused on vegetation types as the unit of assessment. Scientists considered long-term paleoecological studies of climate and species distribution, fire histories, tree growth and establishment, and studies reporting trends in tree growth and species composition with recent climate change. Available vegetation model projections, including those for gap models, climate envelope models, and process-based models, were also considered as available, and new analyses using the MC1 (and the newer version, MC2) dynamic global vegetation model [20] were conducted for all four study areas (Figure 2). Scientists worked with local specialists to interpret available information and apply it more directly to vegetation types and species of interest. Trends that were consistent across models and/or climate scenarios (Figure 2) were emphasized.

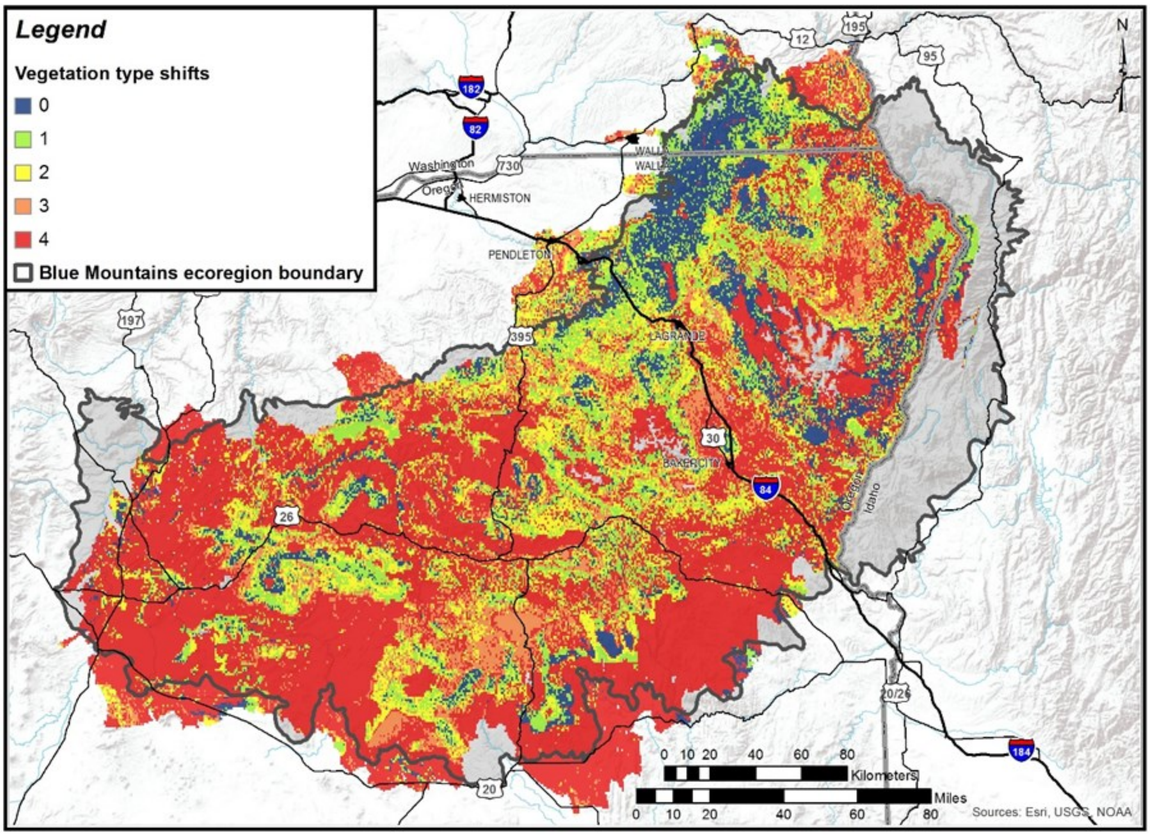

Figure 2. Number of scenarios (inputs from four different general circulation models) for the Blue Mountains region in northeastern Oregon, USA with projections resulting in a vegetation type shift by the MC2 model from the historical period (1979–2008) to the late 21st century (2071–2100).

Finally, adaptive capacity, or the ability of a plant, species, or system to adjust to climate change, was evaluated based on published literature and expert knowledge. Adaptive capacity was addressed most explicitly for the Northern Rockies assessment, from a genecological perspective, and on a species-by-species basis. Current management activities in national forests and national parks were also reviewed to identify management constraints and evaluate some aspects of institutional capacity to implement adaptive actions.

The vegetation vulnerability assessments were used as the basis for developing adaptation strategies and tactics in hands-on science–management workshops. During the first portion of workshops, scientists presented the vegetation vulnerability assessment and invited feedback from workshop participants. In the second portion of the workshops, resource managers engaged in facilitated discussion and completed worksheets, adapted from [9]. The worksheets required that managers identify key vegetation vulnerabilities to climate change and develop adaptation options associated with those vulnerabilities. Adaptation options were developed under the constraint that they be realistic and feasible with respect to regulations, funding, and available personnel. Nearly all of the resource managers had 10–35 years of experience in working in forest landscapes throughout the western United States, providing a strong foundation for making expert judgments about appropriate responses to future landscape conditions. Options were stated through a two-tiered approach focused on: (1) adaptation strategies, or overarching approaches for resource planning and management (e.g., building resilience, increasing diversity); and (2) adaptation tactics, or on-the ground management actions (e.g., accelerating hazardous fuels management, modifying genetic diversity in tree planting). Managers were encouraged to develop adaptation strategies and tactics that both increase ecosystem resilience to climate change (*i.e.*, the ability of a system to return toward a prior condition after disturbance [21]) and facilitate transition of systems in a changing climate ("response" *sensu* 21).

Results of both the vegetation vulnerability assessments and adaptation workshops were incorporated into chapters of peer-reviewed technical reports for Olympic National Forest and Park [22], the North Cascades region [23], the national forests of the Blue Mountains [24], and the national forests and national parks of the Northern Rockies [25].

3. Results and Discussion

Key vulnerabilities of vegetation to climate change are generally stratified by elevation. Trees in high elevation, energy-limited systems will likely see increased growth and establishment with increasing temperatures [1,26], although these systems will likely also by affected by increased drought and disturbance [27,28]. However, habitat for species adapted to the coldest environments may shrink. In contrast, trees in water-limited systems at lower elevations will likely experience increased drought stress and decreased growth and establishment [1,26]. Increased disturbances, including fire and insect outbreaks, will affect vegetation types at most elevations [1]. Changing patterns of tree growth and establishment, in concert with changing disturbance regimes, will result in shifting species distribution and patterns of biodiversity. These vegetation sensitivities are described in further detail in Sections 3.1 and 3.2 below, and corresponding adaptation options are described in Section 3.3.

3.1. Effects on Vegetation

In high-elevation systems of the study region, tree growth and establishment are limited by snowpack amount and duration and associated growing season length; greater snowpack amount and duration lead to a shorter growing season and decreased growth in high elevation trees. For example, mountain hemlock (*Tsuga mertensiana*) growth in the Pacific Northwest is limited by spring snowpack depth and low summer temperatures [29]. Increasing temperatures with climate change will lead to more precipitation falling as rain rather than snow, earlier snowmelt, and thus lower snowpacks and longer growing seasons [30]. Longer growing seasons will likely alleviate growth-limiting factors and likely result in increased growth and productivity and greater tree establishment at higher elevations [1], although these effects may be at least partially counteracted by increased drought and disturbance [27,28]. In addition, MC2 model simulations show contraction of climatically-suitable habitat for alpine and subalpine vegetation in all four study regions [22–25]. Thus, the area in current high-elevation vegetation types may shrink considerably. This could put some high-elevation tree species, such as whitebark pine (*Pinus albicaulis*), at higher risk [24,25].

In dry forests throughout the study regions, tree growth and establishment are limited by low summer soil moisture [1,31]. Ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*), although more drought tolerant than other conifer species with which they are associated, are limited by water supply throughout most of their range [1,31]. Increasing temperatures, lower winter snowpack, and early snowmelt with climate change will result in decreased soil moisture during the growing season [30]. These decreases in summer soil moisture will likely lead to increased stress in most tree species at low elevations, even in some of the wetter portions of the study regions (e.g., west side of the Olympic and Cascade Mountains) [1,32]. Decreased summer soil moisture may also limit tree regeneration, especially following large, high-severity disturbances [32].

3.2. Effects on Ecological Disturbances

As climate continues to warm during the 21st century, the most rapidly visible and significant short-term effects on vegetation will be caused by altered disturbance, often occurring with increased frequency and severity. Increased disturbance will be facilitated by more frequent extreme droughts, amplifying conditions that favor wildfire, insect outbreaks, and invasive species [32–43]. Interacting disturbances and other stressors have the biggest effects on ecosystem responses, simultaneously altering species composition, structure, and function [28,43].

A warmer climate will cause an increase in the frequency and extent of wildfire in most dry forest and shrubland ecosystems [35,36]. By around 2050, annual area burned in most of the western United States is projected to be at least 2–3 times higher than it is today [32,37]. In addition, the intensity and severity of fires may increase in some areas if higher temperatures exacerbate low moisture content in fine fuels [20].

There is potential for more frequent and severe disturbances from insects, including mountain pine beetle (*Dendroctonus ponderosae*), with changing climate [32]. Many bark beetle life history traits that influence population success are temperature-dependent [38], and warming temperatures associated with recent warming have directly influenced bark beetle-caused tree mortality in some areas of western North America [39]. Future interactions among insects, host trees, and other disturbances such as fire may be complex, and in some cases, hard to predict (e.g., see [28]).

New exotic species will likely establish with changing climatic conditions [40–42]. Some exotic species will likely expand with climate change, because ecosystem disturbance and shifts in native species ranges will provide opportunities for exotic establishment. Some exotic species are invasive, with characteristics that facilitate their expansion and dominance in a warmer climate, such as broad temperature tolerances and high dispersal ability [40]. The effectiveness of management actions to control invasive plants is decreasing in some areas as a result of reduced herbicide efficacy [44], and biocontrol methods may not be as effective in a warmer climate [40].

3.3. Adaptation Options

Resource managers identified *19 specific vulnerabilities* that were considered to be critical for forest ecosystems in at least two of the four study regions; in response to these vulnerabilities, they developed *41 adaptation strategies*, and *123 adaptation tactics* associated with the strategies. The vulnerabilities and adaptation options most commonly identified for the study regions are summarized in Table 1. Although climate change is generally considered to be a complex issue with high uncertainty, especially for effects on vegetation, federal forest and vegetation managers were able to develop extensive lists of adaptation options in just a few hours at workshops, often including novel approaches. With each additional workshop, we observed increasing redundancy with adaptation options from previous workshops, suggesting that there may be a limit to the number of realistic and feasible potential adaptation options.

Table 1. Summary of climate change vulnerabilities, adaptation strategies, and adaptation tactics for forest ecosystems (derived from the Climate Change Adaptation Library for the Western United States).

Vulnerability to Climate Change	Adaptation Strategy	Adaptation Tactic
The distribution of subalpine forests is likely to shift as a result of increasing temperatures with climate change	Monitor and detect change in seedling survival, species composition, and mortality of mature trees in subalpine forests	• Install and analyze additional plots to gather trend information over time, targeting areas where changes are expected • Use Forest Inventory and Analysis plot information to determine trends in subalpine forests
Increased forest drought stress and decreased forest productivity at lower elevations	Increase resilience in forests	• 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 thinning activities to promote greater resilience to drier conditions • Include larger openings in thinning prescriptions and planting seedlings in the openings to create seed sources for native drought-tolerant species
	Protect genotypic and phenotypic diversity	• Protect trees that exhibit adaptation to water stress; collect seed for future regeneration • Maintain variability in species and in tree architecture in some locations
	Maintain and enhance forest productivity regardless of tree species; focus on functional ecosystems and processes	• Manage species densities to maintain tree vigor and growth potential • Prepare for species migration by managing for multiple species across large landscapes • Maintain soil productivity through appropriate silvicultural practices
	Use tree improvement programs to ensure availability of drought tolerant tree species and genotypes	• Develop seed orchards that contain a broader range of tree species and genotypes than in the past

Table 1. *Cont.*

Vulnerability to Climate Change	Adaptation Strategy	Adaptation Tactic
More fire (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 • Use prescribed fire to facilitate transition to a new fire regime in dry forests • Manage forest restoration for future range of variability
	Increase resilience of existing vegetation by reducing hazardous fuels and forest density and maintain low densities	• Thin and prescribe burn to reduce hazardous fuels in the wildland-urban interface • Use more prescribed fire where scientific evidence supports change to more frequent fire regime • Conduct thinning treatments (pre-commercial and commercial) • Use regeneration and planting to influence forest structure
	Manage forest landscapes to encourage fire to play a natural role	• Implement fuel breaks at strategic locations • Create incentives to encourage wildland fire use • Implement strategic density management through forest thinning
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 accelerate development of late-successional forest conditions • Harvest to variable densities • Thin to decrease stand density and increase tree vigor • Reduce density of post-disturbance regeneration • Consider using genetically improved seedling stock • Plant resistant species or genotypes where species-specific insects or pathogens are a concern • Increase stand-scale biodiversity and minimize monocultures
	Increase forest landscape resilience to large and extensive insect or pathogen outbreaks	• Design forest gaps that create establishment opportunities • Increase diversity of patch sizes • Consider planting desired species (assisted migration) rather than relying on natural regeneration and migration
	Promote diversity of forest age and size classes	• Diversify large contiguous areas of single age and size classes by "punching holes" in them
	Revegetate with native plant species	• Use seeding of native plant species in areas with non-native species • Reduce grazing practices that encourage spread of non-native species

Table 1. *Cont.*

Vulnerability to Climate Change	Adaptation Strategy	Adaptation Tactic
Increased opportunity for exotic species establishment with dry forest habitats potentially more susceptible	Increase exotic species control efforts	• Implement early detection/rapid response for exotic species treatment • Coordinate exotic species management, funding, and support between agencies
	Prevent exotic plants from establishing after disturbances	• Include exotic species prevention strategies in all projects • Inventory regularly to detect new populations and species • Coordinate exotic species management, funding and support between agencies
	Prevent widespread outbreaks of exotic species or pathogens	• Plan for extreme events and events with low probability • Maintain permits for aggressive treatment of exotic species (e.g., burning and herbicide)
	Increase resilience by promoting native genotypes and adapted genotypes of native species	• Consider assisted migration • Emphasize use of plant species that will be robust to climate change in restoration projects • Plant genetically adapted species from appropriate seed zones
	Maintain integrity of native plant populations and prevent exotic species invasions	• Assertively implement early detection/rapid response • Promote weed-free seed • Prevent exotic plant introductions during projects • Ensure weed-free policies are included in planning documents

Most of the adaptation strategies for vegetation focus on building resilience to altered conditions that are considered inevitable, rather than on attempting to resist future change [22–25]. Many strategies and associated tactics promote productivity and vigor of existing forests to reduce susceptibility to stress from drought, insects, wildfire, and exotic species, with an emphasis on lower severity rather than elimination of a stressor. Forest thinning (stand density management) and prescribed burning were often cited as tactics that reduce stress from multiple stressors, demonstrating that resilience cuts across different categories of vulnerability in a warmer climate. Regeneration following severe fire may be more limited in the future with increased drought [32], and 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 is available for post-disturbance planting [22].

Promoting biological diversity is another prominent adaptation strategy, including species diversity, genetic diversity, and landscape diversity. Increasing diversity is a "hedge your bets" strategy that reduces risk of major forest loss when disturbances and stressors occur, ensuring that some portion of the landscape will retain older forests with a high degree of functionality. Areas with low species and genetic diversity will likely be more susceptible to the stressors associated with climate change; promoting species and genetic diversity through plantings and in thinning treatments will likely increase forest resilience to a changing climate [32,45]. Promoting landscape heterogeneity, in terms of species and structure, will also increase resilience to wildfire, insects, and disease [46].

Managers also considered options to help transition systems to new climatic conditions ("response" *sensu* [21]). For example, managers thought that focusing on ecosystem function and processes, regardless of species, would be more prudent with a changing climate and shifting species composition. They suggested that assisted migration and seed zones modifications be considered to help transition systems to new climates.

Resource managers recognized that stressors associated with climate change cross boundaries, making it increasingly important that agencies coordinate and work across different landownerships [47,48]. 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 likely be more frequently affected by fire and flood events under changing climate. Organizational tactics that support on-the-ground activities include improved knowledge (e.g., better understanding of effects of climate change), and data (e.g., geospatial information on vegetation).

4. Conclusions

The climate change adaptation partnerships for which results are presented here include 21 national forests and six national parks, a significant sample across diverse biogeographic landscapes. Whether study regions were small (e.g., Olympic Peninsula) or large (e.g., Northern Rockies), similar climate vulnerabilities were identified in the assessments, and many similar adaptation options were articulated by resource managers, albeit with some specifications relevant for local landscapes. These commonalities suggest that there may be a an upper limit to the number of issues and solutions for climate change effects in forest ecosystems in the western United States, and that it is reasonable to use the knowledge base discussed here as a point of departure. However, workshop participants were asked to develop adaptation options under the constraint that they be realistic and feasible with respect to regulations, funding, and available personnel, and this may have precluded the inclusion of additional adaptation strategies and tactics that could be achieved with more resources and/or changing policies and regulations. Thus, managers and policy-makers may want to revisit adaptation strategies and tactics every few years and revise to address new scientific information and changing funding and policy environments.

A framework for climate change vulnerability assessments in federal lands is well documented in concept and practice [6,9], and has been implemented in several recent assessments [24,25]. To complement the assessment documentation, we recently compiled the Climate Change Adaptation Library for the Western United States as a foundation for future climate change adaptation efforts [49]. The library contains 145 adaptation strategies and 468 adaptation tactics for climate change effects on forest vegetation (Table 1 is derived from this section), non-forest vegetation, wetland/riparian systems, wildlife, water resources, fisheries, and recreation. This peer-reviewed information contains "menus" of options that can be selected or revised for inclusion in planning and project documents, helping to jump-start adaptation projects and providing consistency within and between projects. Because the library is intended as a dynamic resource, we anticipate that it will grow over time, but at a relatively slow rate because of the limitations mentioned earlier.

Although the science–management partnerships described here helped to build organizational capacity to address the potential effects of climate change, vulnerability assessments and adaptation options need to be fully incorporated in the following aspects of federal agency operations (Figure 3):

- National forest/national park planning: Overarching resource plans required for all national forests and national parks are the highest level of implementation of climate change information. These plans tier down to all other planning and management functions in the federal agencies.
- Landscape management assessments: Vulnerability assessments provide information on departure from desired conditions and best science on effects of climate change on resources for inclusion in long-term assessments. Adaptation strategies and tactics provide desired conditions, objectives, standards, and guidelines for federal planning.
- Resource management strategies: Vulnerability assessments and adaptation options are used to incorporate best science in conservation strategies, fire management plans, infrastructure planning, and State Wildlife Action Plans.
- National Environmental Policy Act analysis: Vulnerability assessments provide best available science for documentation of resource conditions, effects analysis, and alternatives development. Adaptation strategies and tactics provide mitigation and design tactics at specific locations.
- Project design: Vulnerability assessments and adaptation options guide the development and implementation of vegetation management and restoration projects, helping to modify "standard" practice with "climate smart" actions.
- Monitoring plans: Vulnerability assessments help identify knowledge gaps that can be addressed by monitoring in broad-scale strategies, plan-level programs, and project-level data collection.

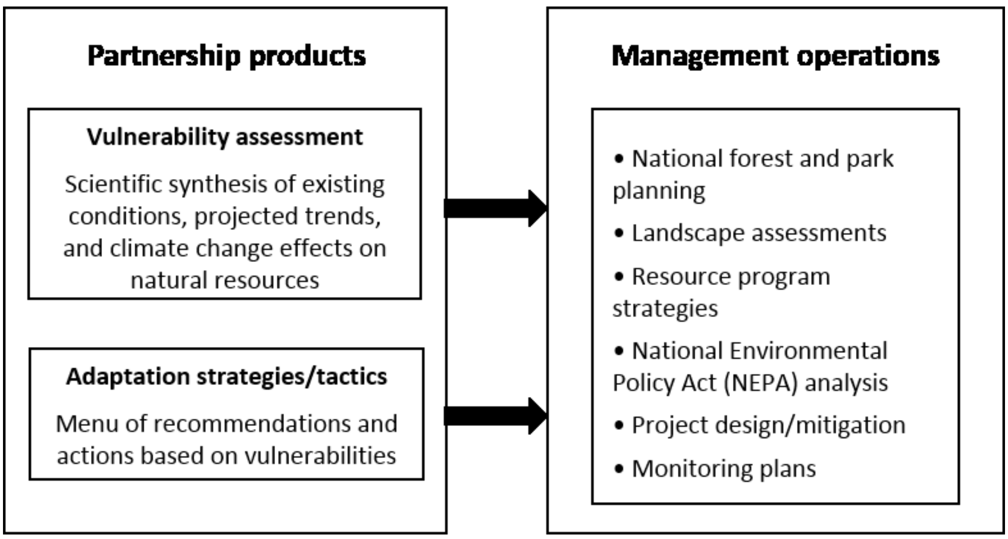

Figure 3. Example applications of adaptation partnership products in the operations of land management agencies.

Full implementation of climate-informed operations in federal agencies will require time, as resource specialists adjust to including climate change as a new element in risk assessment and risk management. Federal agencies are currently transitioning from implementation being not just advisable, but required by U.S. federal regulations (e.g., the U.S. Forest Service 2012 Planning Rule), providing greater urgency to use assessments. In an era of declining budgets, federal agencies can use previous assessments and the Climate Change Adaptation Library to streamline their own assessments and management practices, thus saving considerable time and money while maintaining consistency across disparate federal lands. National forests and national parks in the western United States are already modifying plans and projects to accommodate projected climate change effects, providing examples of successful efforts that can be emulated by others. We anticipate that this process of shared knowledge and experience will rapidly build the organizational capacity needed to address climate change over the next decade.

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