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Understanding and Managing the Effects of Climate Change on Ecosystem Services in the Rocky Mountains

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Public lands in the US Rocky Mountains provide critical ecosystem services, especially to rural communities that rely on these lands for fuel, food, water, and recreation. Climate change will likely affect the ability of these lands to provide ecosystem services. We describe 2 efforts to assess climate change vulnerabilities and develop adaptation options on federal lands in the Rocky Mountains. We specifically focus on aspects that affect community economic security and livelihood security, including water quality and quantity, timber, livestock grazing, and recreation. Headwaters of the Rocky Mountains serve as the primary source of water for large populations, and these headwaters are located primarily on public land. Thus, federal agencies will play a key role in helping to protect water quantity and quality by promoting watershed function and water conservation. Although increased temperatures and atmospheric concentration of CO_2 have the potential to increase timber and forage production in the Rocky Mountains, those gains may be offset by wildfires, droughts, insect outbreaks, non-native species, and altered species composition. Our assessment identified ways in which federal land managers can help sustain forest and range productivity, primarily by increasing ecosystem resilience and minimizing current stressors, such as invasive species. Climate change will likely increase recreation participation. However, recreation managers will need more flexibility to adjust practices, provide recreation opportunities, and sustain economic benefits to communities. Federal agencies are now transitioning from the planning phase of climate change adaptation to implementation to ensure that ecosystem services will continue to be provided from federal lands in a changing climate.

Keywords: *Adaptation; ecosystem management; mountain ecosystems; vulnerability assessment; USA; Sustainable Development Goals; Agenda 2030.*

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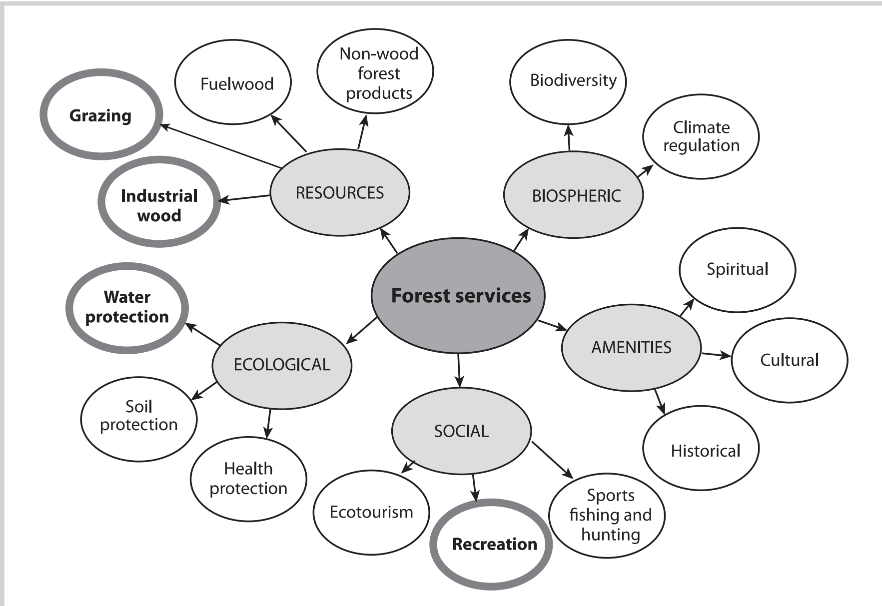
Introduction

Efforts to integrate ecosystem services, or the benefits people receive from nature, into US federal land management policy and practice have increased over the last 5 years. The US Forest Service is required to address ecosystem services in management plans for national forests (Federal Register 2012). The National Park Service incorporated ecosystem services into management planning and made ecosystem services a key part of their 2011 Call to Action (Jarvis 2011). In the strongest commitment to date, a Presidential Memorandum was issued in October 2015, instructing federal agencies to incorporate ecosystem services into decision making, and requiring each agency to formalize a plan for doing so (Office of the President of the United States 2015).

This emphasis on ecosystem services at the federal level is consistent with the role mountain ecosystems play in the United Nations 2030 Agenda for Sustainable Development (UN 2015) and with UN sustainable development goals (UN 2017). For example, the UN's Sustainable Development Goal (SDG) 15.4 is to "By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development." Protection of water-related ecosystems, including mountains, is also a goal (6.6).

Ecosystem services from public lands in the US Northern and Middle Rocky Mountains are critical for neighboring communities. Major uses of water in the region include domestic and municipal water supply, industrial use, oil and gas development, recreational uses, and hydroelectric power production. Both "Old West" livelihoods like timber and grazing and "New West" lifestyles tied to outdoor recreation are part of the cultural heritage of the region. Although their relative economic importance has declined in recent decades, timber and livestock grazing are important economic forces in the Rocky Mountains. Forest products make up about 23% of direct manufacturing employment in Montana (McIver et al 2013), and public lands are an important source of forage for ranchers, both as primary

FIGURE 1 Major classes of forest services, as adapted from the Millennium Ecosystem Assessment (2005). Ecosystem services included in climate change vulnerability assessments described here are outlined in bold. We added grazing as a service provided by federal lands in the Northern Rockies.



places to graze and as supplements to grazing on private lands (US GAO 2005). This region is also home to iconic landscapes such as Yellowstone National Park, Glacier National Park, and the Salmon River. More than 15 million people visit national forests and parks in the Greater Yellowstone Area and Glacier National Park area, and total annual expenditures by visitors in 2014 were more than US$ 800 million (according to National Visitor Use Monitoring Data; English et al 2001).

Climate change will likely result in increased occurrence of fire, insect outbreaks, and drought in the Rocky Mountains, driving ecosystem change and making the future provisioning of ecosystem services uncertain (Seidl et al 2016). Climate change will affect water availability and quality, human behavior and recreation, and provisioning of timber and forage (Mendelsohn and Markowski 2004; Mooney el al 2009; Montoya and Raffaelli 2010; Groffman et al 2014). Decreased quantity and quality of ecosystem services produced by public lands will affect human systems that rely on them, requiring communities to seek alternative means of providing these services or to change local economies and lifeways.

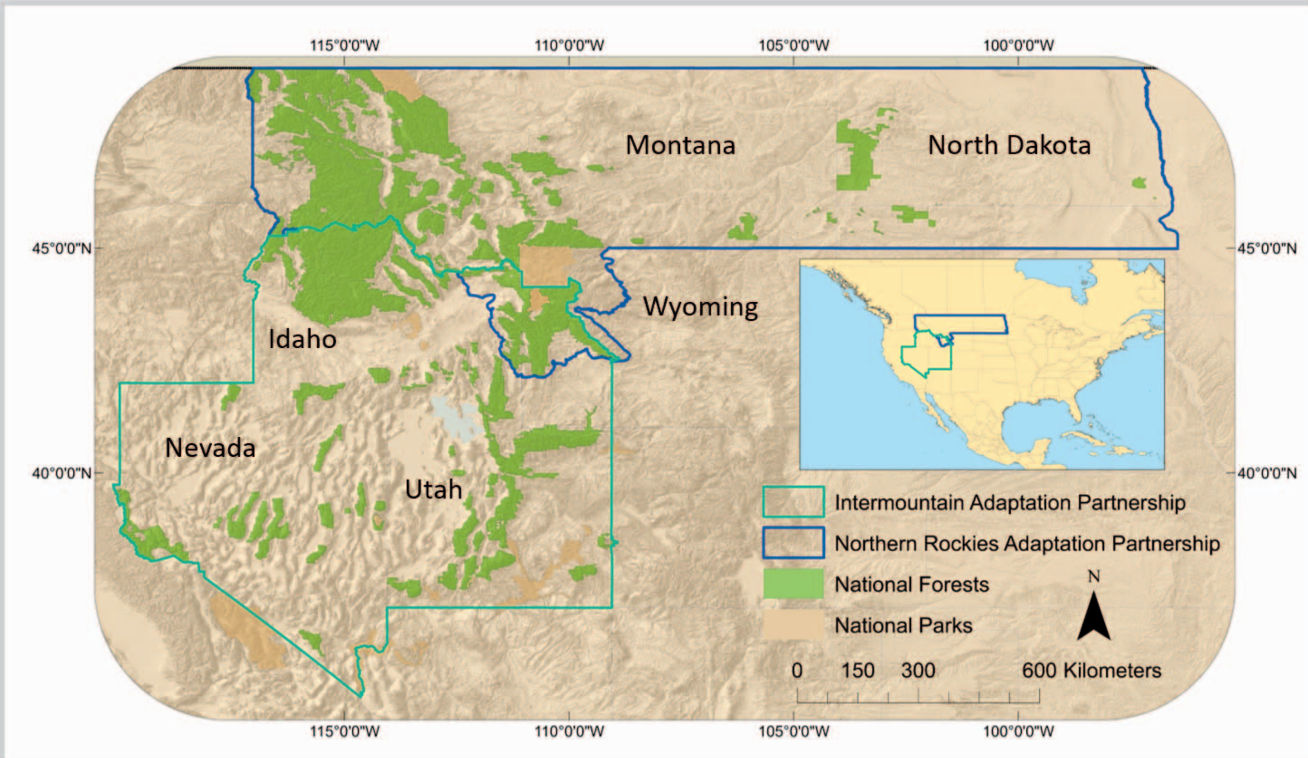
We describe here 2 recent science-based climate change vulnerability assessment and adaptation efforts for ecosystem services on federal lands in the US Northern and Middle Rocky Mountains. We specifically address the following questions: (1) How will climate change affect ecosystem services in the Northern and Middle Rocky Mountains? and (2) How can mountain ecosystems be managed to minimize negative impacts of climate change on ecosystem services and help meet UN SDGs 6 and 15? Although climate change affects every aspect of mountain ecosystems listed in the Millennium Ecosystem Assessment (2005), we focus here on aspects that affect community economic security and livelihoods, specifically water, timber, livestock grazing, and recreation (Figure 1).

Methods

Two science-management partnerships were developed to conduct climate change vulnerability assessments and determine adaptation options for US Forest Service and National Park Service lands in the Northern and Middle Rocky Mountains. Partnership locations included the Forest Service Northern and Intermountain Regions (Northern Rockies and Intermountain Adaptation Partnerships, respectively; http://adaptation partners.org) (Figure 2). Vulnerability assessments covered hydrology, fisheries, forest and rangeland vegetation, ecological disturbance, and ecosystem services. Generally, assessments for ecosystem services built on assessments for the associated natural resources.

Vulnerability assessments for ecosystem services were conducted in each of the study regions (Figure 2) by teams of scientists from the US Forest Service, other federal agencies, and universities. Assessments used the best available science and considered exposure, sensitivity, and adaptive capacity (sensu Parry et al 2007) for each ecosystem service (Halofsky et al 2017). To determine likely levels of exposure to climate change, or the degree of deviation in temperature and precipitation in the future compared to a historical period, downscaled general circulation model (GCM) climate projections, obtained from the Geo Data Portal at the US Geological Survey Center for Integrative Data Analytics, were summarized for the study areas (Joyce et al 2017). These data included projections from 34 GCMs under

FIGURE 2 Northern Rockies and Intermountain (Middle Rockies) adaptation partnership locations, with participating national forests and national parks. (Map by Jessica Halofsky)



Representative Concentration Pathways 4.5 and 8.5 (van Vuuren et al 2011) from the Coupled Model Intercomparison Project 5, used in the Intergovernmental Panel on Climate Change Fifth Assessment Report (Stocker et al 2013). Climate projections were downscaled using the bias-correction and spatial disaggregation method (Maurer et al 2007).

Methods to assess climate change sensitivity differed by ecosystem service. In all cases, scientists reviewed published literature and available climate change impact model projections to determine sensitivity. Quantitative data were used when possible, but qualitative descriptions or proxy measures were often used. For timber and grazing, assessments drew from forest and rangeland vegetation vulnerability assessments (Keane et al 2017; Reeves et al 2017). Vegetation model output, such as that from the MC2 dynamic global vegetation model (Bachelet et al 2001) was used, where available. For water availability, the assessments were based on projections from the Variable Infiltration Capacity model (Liang et al 1994) and other analyses (Luce 2017). The recreation assessments were primarily qualitative assessments using a newly developed framework (Hand and Lawson 2017). To evaluate adaptive capacity, defined here as the institutional capability to modify management, decision-making, and policy to ensure sustainable production of ecosystem services, we evaluated the potential for ecosystems, agencies, and society to adjust to changing climate.

The vulnerability assessments were used as the basis for developing adaptation strategies and tactics in 10 workshops (Table 1); 5 workshops were conducted throughout each study region to capture geographic variation in resource condition and management issues. In the first part of the workshops, scientists presented vulnerability assessments for the resource areas (eg hydrology, vegetation, etc). Resource managers then separated into small groups by resource area and engaged in facilitated discussion to complete worksheets (adapted from Swanston and Janowiak 2012). In consultation with scientists, managers identified key vulnerabilities to climate change for each resource area and developed:

1. Adaptation strategies, or overarching approaches for resource planning and management (eg building resilience, increasing diversity) and
2. Adaptation tactics, or on-the-ground management actions (eg accelerating hazardous fuels management).

Managers identified options considered feasible given current regulations, funding, and personnel. Most of the resource managers participating in the workshops had 10–25 years of experience in their fields (Table 1), making them well qualified to provide strong expert judgements about appropriate management response to climate change (Halofsky and Peterson 2016). Adaptation options were also reviewed by teams of scientists and managers

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TABLE 1 Number of resource managers, scientists, and agencies/organizations that participated in the 10 workshops as a part of the Northern Rockies Adaptation Partnership (Montana, North Dakota, and northern Idaho) and Intermountain Adaptation Partnership (Utah, Nevada, and southern Idaho). Participants had diverse backgrounds, with expertise in hydrology, soils, vegetation (botany, silviculture, forests, and rangelands), fire, entomology, wildlife, recreation, engineering, ecosystem services, and archaeology.

Workshop location	Number of scientists	Number of resource managers	Number of agencies and organizations represented
Bozeman, Montana	17	50	12
Bismarck, North Dakota	6	17	6
Missoula, Montana	18	57	18
Coeur d'Alene, Idaho	6	43	12
Helena, Montana	9	43	13
Ogden, Utah	9	39	7
Boise, Idaho	10	41	13
Salt Lake City, Utah	9	44	13
Reno, Nevada	6	35	12
Idaho Falls, Idaho	10	40	11

after the workshops to ensure scientific validity (Halofsky et al 2017).

Below, we summarize the results of the vulnerability assessments, as well as adaptation options developed in the science-management workshops, focusing on timber production, livestock grazing, water availability and quality, and recreation.

Results

Water availability and quality

Water yield, timing, and quality affect water supply for municipal and agricultural use, and all 3 will be affected by climate change in the Rocky Mountains. Water yield and timing are closely tied to snowpack in mountain landscapes, and warmer temperatures will likely result in reduced snowpack in the Rocky Mountains (Luce et al 2014). Earlier snowmelt will cause earlier stream runoff, and reduced snowpack will cause lower summer streamflows (Luce and Holden 2009). By the 2080s, the median flow date is expected to be over 20 days earlier in most locations in the Rocky Mountains, and summer flows are projected to decline by 20–40% in most locations (compared to 1977–2006 with moderate warming) (Luce 2017). Altered timing and quantity of summer flow are expected to cause shortages of surface water in locations where demand is high in the summer months (Figure 3). Municipal systems may experience increased treatment costs and greater dependence on groundwater intakes to meet demand.

Water quality may also be affected by changing climate in the Rocky Mountains. Stream temperatures are expected to increase in response to increased air temperature and lower summer flows (Isaak et al 2016). Extreme weather and a higher rain:snow ratio may increase runoff from agricultural fields and add pesticides and fertilizers to streams. In addition, increased number and severity of wildfires can accelerate sediment deposition in streams, lakes, and reservoirs (Benda et al 2003; Coombs and Melack 2013).

Public lands are a critical source of municipal water supplies. Increasing implementation of current practices that improve watershed function, such as restoring and protecting riparian systems and wetlands, reducing hazardous fuels in dry forests, and reducing erosion potential, will help ensure that public lands continue to provide high quality water to communities (Luce 2017). These tactics will be more effective if prioritized in high-value locations (near communities and reservoirs). Water storage can be increased by increasing American beaver populations, constructing wetlands, and decommissioning roads (Table 2). Reducing water use and increasing efficiency will also be increasingly important for maintaining adequate supplies. Federal agencies can demonstrate leadership in water conservation, conveying a positive image to local communities.

Timber

With increased temperatures and atmospheric CO_2, the potential exists for increasing forest productivity (Aston 2010) and biomass accumulation (Lin et al 2010), which may lead to increases in timber production at higher elevations (Garcia-Gonzolo et al 2007; Keane et al 2017). Moisture limitations, ecological disturbances, and their interactions may reduce forest growth at low elevations (Littell et al 2013). Over decades, higher temperature and soil moisture deficits may cause the location of some desirable timber species to shift and in some cases to be more susceptible to root disease (Keane et al 2017).

Climate change may also increase wildfire area burned (Westerling et al 2006; Rocca et al 2014; Barbero et al 2015), drought severity (Littell et al 2016; Vose et al 2016), and insect outbreaks (Bentz et al 2010; Loehman et al 2017). These disturbances are often associated with

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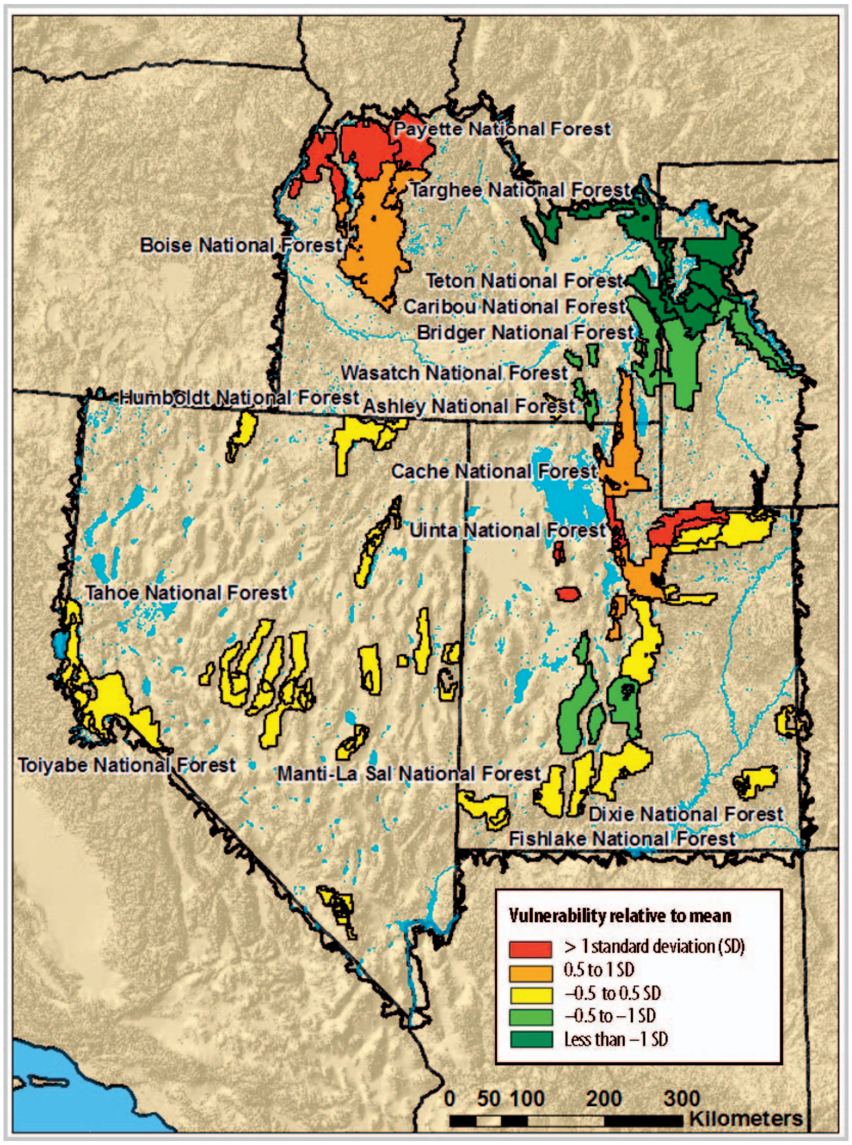
FIGURE 3 Drinking water vulnerability in national forests in the Intermountain Region under changing climate. The analysis utilized municipal drinking water intake locations and nearby spatial characteristics to identify drinking water vulnerability for the various users who depend on National Forest System lands within the region. Vulnerability is measured based on indicators of exposure, sensitivity, and adaptive capacity. The final components for each system were standardized for comparison to other water systems within the region. Exposure was measured according to projected changes in annual stream flow, summer stream flow, stream temperature, and runoff timing from downscaled climate models. Sensitivity and adaptive capacity were measured according to current sub-watershed land cover, use, conditions, and threats. (Analysis and map by Matt Elmer, Colorado State University)



significant tree mortality. Though harvests can increase in the short term through salvage of dead and dying trees, long-term timber availability is expected to decrease (Warziniack et al 2017). Warmer winters and associated freezing and thawing may increase forest road erosion and landslides, making winter harvest more difficult and expensive, and potentially reducing timber supply (Karl et al 2009). However, adaptation in US timber and wood product markets may offset potentially negative effects of climate change (Irland et al 2001).

Adaptation strategies for timber (Table 3) mainly focused on increasing resilience to changing conditions (Keane et al 2017). For example, many strategies and associated tactics focused on promoting productivity and vigor of existing forests to reduce susceptibility to stress from drought, insects, and wildfire. Current practices, including forest thinning and prescribed fire, were suggested as tools that could be increasingly used to reduce stress from multiple sources (Littell et al 2013). More novel approaches, such as promoting disturbance-resilient species and increasing species and genetic diversity through plantings, could also help increase resilience to changing climate (Dymond et al 2014) (Table 3). In the future, modifying tree-species seed zones and assisted migration could be used to help transition ecosystems to new climates (Halofsky and Peterson 2016).

TABLE 2 Summary of climate change vulnerabilities, adaptation strategies, and adaptation tactics for water quantity and quality in the Rocky Mountains.

Vulnerability to climate change	Adaptation strategy	Adaptation tactic
Reduced base flows will shrink riparian habitats and alter morphology, affecting groundwater storage and shallow alluvial aquifers.	Increase natural storage and built storage.	Increase natural water storage with constructed wetlands, beavers, and road obliteration.
		Promote distributed small-scale water storage, using small dams, retention ponds, and swales in stream channels and uplands.
		Use groundwater injection wells and sills to retain water upstream in alluvial deposits (and retain higher water table).
	Increase knowledge about the groundwater resource.	Map aquifers and alluvial deposits.
		Determine legal availability and develop a better understanding of physical availability of water for aquifer recharge.
		Improve monitoring of streamflow and groundwater to improve understanding of surface water-groundwater interactions; obtain real-time data.
Discharge from natural springs and seeps may be reduced, affecting water quantity and quality and water for livestock.	Protect natural springs and seeps from potential degradation and development.	Develop map of springs and seep locations.
		Instrument (piezometer) prioritized representative springs to get detailed flow information.
		Implement local protection strategies such as fencing; develop alternative water sources.
Increased occurrence of disturbances such as drought and flooding will reduce water quality.	Build an information base for a timely response to disturbance, thus ensuring that data are available to inform decision-making.	Prioritize data collection based on projections of future drought.
		Collect pre-disturbance data on stream and riparian conditions, including high-quality values and habitat in need of protection.
Decreased snowpack and increased disturbance will alter water quantity and quality of lakes and reservoirs (including dam operations).	Determine how climate change will alter lakes and reservoirs.	Develop a clearinghouse of information on the effects of climate change from all available sources.
		Increase coordination between all partners (federal, state, tribal, private).
		Improve understanding about connectivity and interaction of streams and lakes (eg temperature, nutrient sinks, sources).
Higher temperatures and decreased snowpack will reduce water availability.	Reduce water use and increase efficiency, demonstrate leadership in water efficiency, and create outreach opportunities.	Research successful water saving tactics, and apply tactics where appropriate.
		Install low-flow appliances at administrative sites.
		Replace landscaping with drought tolerant plants.
		Communicate water saving tactics and benefits.
Higher temperatures, higher evapotranspiration rates, and earlier runoff may reduce recharge to shallow aquifers, reducing downstream domestic water yields.	Identify and protect shallow aquifer recharge zones by communicating and partnering with stakeholders.	Map/inventory recharge zones, especially in areas where water is heavily utilized (municipal watersheds).
		Form watershed user groups to identify concerns and solutions.
		Improve diversion efficiencies (eg install headgates, convert ditches to pipelines, and install weirs as needed).

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TABLE 3 Summary of climate change vulnerabilities and adaptation options for timber in the Rocky Mountains. (Table continued on next page.)

Vulnerability to climate change	Adaptation strategy	Adaptation tactic
Increased frequency and scale of disturbances, such as fire and drought.	Promote disturbance-resilient species, such as ponderosa pine, western larch, western white pine, Douglas-fir, and lodgepole pine.	Thin to favor disturbance-resilient species.
		Plant disturbance-resilient species.
		Promote resilient species with prescribed fire and/or wildland fire use.
Sites with limited species and genetic diversity are more likely to be impacted by climate change and climate-related stressors.	Work across jurisdictions at larger spatial scales.	Plant potential microsites with a mix of species to hedge bets.
		Maintain species diversity during thinning.
		Interplant to supplement natural regeneration and genetic diversity.
Potential shifts in lodgepole pine ecosystems with changing climate.	Promote resilience by maintaining age–size class composition at the stand and landscape levels.	Identify areas appropriate for wildfire use and increase flexibility in fire management; emphasize modified suppression and resource benefit fire.
		Proactively treat stands with prescribed fire to reduce fire and insect mortality, and increase individual tree vigor.
Homogenization of the ponderosa forest type across the landscape results in increased density and risk of stand-replacing fires, increased risk of drought mortality, and loss of large ponderosa pine and large ponderosa snag recruitment.	Decrease the density within ponderosa pine–Douglas-fir stands, and increase structural diversity.	Reduce stand density with thinning, prescribed fire, and wildland fire use, with density and structural goals based on predicted future conditions.
		Promote age class and structural diversity across the landscape, through regeneration harvest, thinning, prescribed fire, and wildland fire use.
		Monitor establishment, survival, and development of ponderosa pine by age class and in different conditions (eg aspect, heat load, and soil moisture).
Accelerated root disease mortality due to climate stressors.	Reduce dominance of root disease sensitive species (eg Douglas-fir and grand fir) on root-disease-prone sites.	Regenerate and plant with species less susceptible to root disease.
		Thin out root-disease–susceptible species where less root-disease–susceptible species are abundant.
		Conduct a hot prescribed burn, followed by a reburn.
Changing moisture regimes with changing climate.	Replace plant association group/habitat typing with an index based on biophysical variables.	Identify a set of biophysical predictors related to habitat types, site productivity, vegetation composition, and structure. Possible predictors include landform, soil depth, texture, type, actual and potential evapotranspiration, and water balance deficit.
		Predict site productivity based on biophysical predictors; make concept operationally implementable so it can be used to support planting decisions, and aid understanding of long-term effects of management and long-term goals for a site.
		Project into the future based on climate change models.
Increasing moisture demands and drought stress in moisture demanding species (western hemlock and western redcedar) on upland sites.	Minimize the effects to the stand from the affected species (western hemlock and western redcedar).	Implement precommercial thinning to limit dominance of these species on drought-prone sites.
		Encourage regeneration harvest and planting with a more diverse species mix.

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TABLE 3 Continued. (First part of Table 3 on previous page.)

Vulnerability to climate change	Adaptation strategy	Adaptation tactic
Homogenization of the larch forest type across the landscape results in increased density and risk of stand-replacing fires, increased risk of mortality from drought, loss of western larch on stressful sites, loss of large larch, and reduced water yield.	Decrease density within stands, and increase structural diversity across the landscape.	Promote age class and structural diversity across the landscape, through regeneration harvest, thinning, prescribed fire, and wildland fire use.
		Monitor establishment and survival of western larch by age class across different aspects/heat load/soil moisture.
		Prioritize management for larch on landscape facets where monitoring indicates it is going to persist (eg on north aspects, but not southern aspects, or by habitat types).
		Maintain and promote large diameter western larch across the landscape, so that large diameter snags, larch seed sources, and wildlife habitats are also maintained.

Livestock grazing

In the Northern Rocky Mountains, increased temperatures and growing season length are expected to increase net primary productivity in rangelands, particularly at higher elevations (Reeves et al 2014; Reeves et al 2017). Increased atmospheric CO_2 concentrations may also increase rangeland productivity by increasing water use efficiency (Izaurralde et al 2011; Polley et al 2013; Reeves et al 2014). However, in low-elevation, moisture-limited areas of the Northern and Middle Rockies, without significant increases in precipitation, increased temperatures will increase evaporative demand, reducing soil moisture and productivity (Polley et al 2013). Increased wildfire area burned and establishment of non-native species may also decrease rangeland productivity. For example, dominance of non-native annual grasses can create a positive feedback in which frequent fire leads to increased dominance of annual grasses, which create fuel conditions that facilitate more frequent fire (Chambers et al 2007). These conditions are exacerbated by wetter and warmer winters (Joyce et al 2017).

Adaptation strategies for grazing focused on increasing resilience of rangeland vegetation, primarily through current approaches to non-native species control and prevention. Demand for grazing on high-elevation national forest land may increase with warming. Federal land managers identified increasing flexibility in timing, duration, and intensity of authorized grazing as a tactic to prevent ecosystem degradation and allow ecosystems to transition to new conditions (Table 4). They also stressed the importance of developing a holistic approach to grazing management, taking ranchers' needs into consideration, and developing a collaborative relationship with range permittees that focuses on problem solving rather than rule enforcement.

Recreation

Warming temperatures in the Rocky Mountains will likely increase participation in outdoor recreation (Bowker et al 2013), with increases in warm-weather activities outweighing losses in winter activities (Loomis and Crespi 2004; Mendelsohn and Markowski 2004). Warming is expected to reduce season length and the likelihood of reliable winter recreation seasons. Lower elevations may become unsuitable for snow-based recreation because of warmer temperatures. High-elevation sites will likely experience more variability in season length (Hand and Lawson 2017).

In contrast, climate change is expected to lengthen the season for warm-weather activities as snow- and ice-free sites become accessible earlier, and temperatures are higher during the autumn and spring "shoulder" seasons (Hand and Lawson 2017). However, extreme summer temperatures can dampen participation during the hottest weeks of the year (Bowker et al 2012), shifting demand to cooler weeks or to alternative sites less exposed to extreme temperatures (eg lakes, reservoirs, and streams). Wildfire activity may reduce demand in some years because of degraded site desirability, impaired air quality from smoke, and limited site access. Recreation visits to sites with highly valued natural characteristics (eg glaciers and charismatic wildlife species) may also decrease in the future if the quality of those sites is threatened (Scott et al 2007). For example, fishing for cold-water species (eg salmon) is expected to decline with increased stream temperatures that threaten habitat (Jones et al 2013).

Adaptive capacity among recreationists is high because they can switch to alternative sites, alter the timing of visits, and alter capital investments (eg gear). The ability of federal managers to adjust recreation management to climate change is generally more limited. To provide sustainable recreation opportunities, it will be necessary to consider how infrastructure investments and maintenance of facilities align with changing ecological conditions and demands for recreation settings (Table 5). For winter recreation, recreation management can transition to shorter seasons and changing use patterns.

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TABLE 4 Summary of climate change vulnerabilities and adaptation options for grazing in the Rocky Mountains.

Vulnerability to climate change	Adaptation strategy	Adaptation tactic
Higher temperatures and increased fire activity will alter vegetation composition, productivity of forage, water sources, and modify grazing regimes.	Increase resilience of habitats used by ungulates.	Integrate grazing strategies and vegetation treatments (for both wild and domestic ungulates).
		Emphasize collaborative problem solving with permittees and other interested parties rather than enforcement.
Shift in climate change will likely lead to shift in grazing patterns.	Develop a holistic approach to grazing management; understand ranchers' business approaches, lands used, water management, and competing demands from other resources and multiple uses.	Modify flexibility in timing, duration, and intensity of authorized grazing.
		Incorporate grazing as a method of vegetation management.
		Minimize impacts and design more efficient livestock water developments (eg shutoff valves for tanks, protect spring sources).
Increased temperature and drought will cause more and larger wildfires, leading to mortality of sagebrush and grasslands and increased dominance of fire-adapted herbaceous and non-native species.	Maintain intact ecosystems and increase resilience and resistance of native sagebrush-grass ecosystems.	Manage fire for resource benefits.
		Manage livestock grazing through planning efforts that serve as livestock movement guides (within-season triggers) and allow for the maintenance and/or enhancement of plant health (end-point indicators).
		Use targeted grazing to address contemporary vegetation management challenges (eg control invasive exotic and noxious weeds and undesirable species, reduce fire risk).
		Identify and manage (eg close, obliterate, re-route) non-system/user created routes (roads and trails).
		Maintain or restore adequate native plant cover, vigor, and species richness.

Specifically, opportunities may exist to expand facilities where concentrated use increases, and options for snow-based recreation can be diversified to include more snow-making, additional ski lifts, and higher elevation runs. For warm-season recreation, a first step will be to conduct assessments to understand changing use patterns. Then, adjustments can be made to increase the capacity of recreation sites that are showing increased use (eg campgrounds).

Discussion

Communities in the rural American West rely on ecosystem services for necessities like water, recreation, and resource-based jobs. As climate change alters natural systems, more effort will be needed to protect the services provided by ecosystems. Adaptation will be critical in protecting ecosystem services and in meeting UN SDGs (UN 2015). The science–management partnership approach described here helped to facilitate the adaptation process in the Rocky Mountains. The process and outcomes will help to ensure that climate change is considered in future management of natural resources on federal lands in the Rocky Mountain region, thus helping to ensure sustainable development in the region (Table 6). Our approach can be applied in any location where there is sufficient engagement of scientists and local resource managers.

Our efforts are particularly relevant for water resources (SDGs 6.6, 15.1), which are expected to experience near-term changes in a warmer climate, but for which good options are available to reduce potentially negative outcomes (Table 2). Climate change will likely increase stress on limited water resources in the Rocky Mountains, which are already stressed by increasing populations. The headwaters, which are the primary source of water in the region, are mostly on public lands. Thus, watershed health and resilience in these headwaters is critical in protecting water quantity and quality for large populations, and federal agencies will play a key role in helping to protect water in a changing climate. Restoring and sustaining hydrological processes is a primary strategy for protecting water resources under a changing climate.

TABLE 5 Summary of climate change vulnerabilities and adaptation options for recreation in the Rocky Mountains. (Table continued on next page.)

Vulnerability to climate change	Adaptation strategy	Adaptation tactic
Recreation access needs may change with climate change, including change of location, season of use, type of use, and duration of use.	Ensure that access is adequate for projected recreation use and demand and compatible with resource and climate change conditions.	Evaluate and prioritize existing access by season (eg trailheads and trails) to ensure consistency with changing recreation opportunity spectrum settings.
		Identify new access needs and potential changes to existing access by season.
		Strategically invest in new and potential changes to existing access by season.
Recreation settings (recreation opportunity spectrum and scenery), both motorized and non-motorized, during all seasons will be affected by the expected changes in climate.	Align our recreation settings with changing landscape conditions and demand.	Assess existing recreation opportunity spectrum settings and scenic character to determine which are most vulnerable to climate change effects.
		Develop management strategies to shift or maintain existing recreation opportunity spectrum settings and scenic character in response to climatic change.
Recreation user demand and the shift in recreation activity, amount of use, and patterns of use will be driven by climate change, technology, demographics, and culture.	Align our recreation opportunities with future demand to commercial (permitted) and non-commercial recreation users.	Understand the changes in demand, demographics, and economic trends, both regionally and nationally.
		Conduct research to clearly identify localized impacts of climate change.
		Conduct research to understand the latest and upcoming technology that impacts recreation.
Changes in demand for warm weather recreation.	Transition to address extended seasons or changing use patterns.	Assess use patterns to understand demand shifts and address recreation niches identified for the area.
		Identify natural resource impacts and increase coordination with partners and concessionaires.
		Adjust capacity issues and potentially expand campgrounds and fee opportunities.
Seasonality of whitewater rafting will likely shift with changing climate and timing of peak flows.	Increase management (primarily permitting) flexibility.	Vary permit season to adapt to changes in peak flow and duration.
		Educate the public about changes in peak flows and permitting.
Winter recreation (eg ice fishing, cross-country skiing, snowmobiling) will be at risk with increased temperatures.	Transition to address shorter average season and changing use patterns, and increase management (primarily permitting) flexibility.	Maintain current infrastructure and expand facilities in areas where concentrated use increases (anticipate additional use as lower elevation areas have reduced snowpacks).
		Shift winter use, address safety concerns, and engage partners to implement changes needed in use.
		Relocate sites as necessary and add signs to guide the public.
Shorter winters with less snow and wetter or icier snow.	Consider diversifying permitted activities, assess infrastructure and recreation sites, and develop prioritization process and criteria.	Develop options for diversifying snow-based recreation.
		Examine viability of agency snow-based recreation sites, permitted downhill resorts and all permitted winter operations.

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TABLE 5 Continued. (First part of Table 5 on previous page.)

Vulnerability to climate change	Adaptation strategy	Adaptation tactic
Risk to infrastructure with changes in the frequency and severity of natural hazards and disturbances.	Manage recreation sites to mitigate natural hazards.	Maintain safety by assessing risk factors.
		Identify flood plains and risks to campgrounds (developed sites) and dispersed recreation sites.
		Identify effects after disturbance to recreation sites and prioritize treatments or conversions (eg relocation, arming, and/or mitigation measures).
The future viability of recreation facilities will be affected by changes in climate.	Provide recreation facilities that accommodate future demand and reduce user and natural resource conflicts.	Prioritize existing recreation facilities, by season, for viability, investment, and change in services.
		Invest strategically in developed recreation facilities.
		Design facilities for flexibility in use.

Although increased temperatures and atmospheric concentration of CO_2 have the potential to increase timber and forage production in the Rocky Mountains, those gains may be offset by wildfires, droughts, insect outbreaks, non-native species, and altered species composition (Littell et al 2013). Efforts to reduce negative outcomes of increased disturbance are relevant to SDG 15.4. Typical rates of return on livestock in the West are already as low as 2% (Holechek et al 1994), and private rangelands have become increasingly fragmented with land use change (Holechek 2001; Resnik et al 2006). Thus, climate change may render livestock operations unprofitable in the future. Rangeland managers often have limited financial resources and limited options to diversify livelihoods beyond livestock grazing, making the accelerated implementation of adaptation options critical (Briske et al 2015). Our assessment has identified ways in which federal land managers can help sustain forage productivity. For example, reducing introduction and spread of invasive species will be critical in sustaining productivity of rangelands in the future (relevant to SDG 15.8). Increasing communication between federal land managers and rangeland permittees will also help to ensure that sustainable grazing plans are developed.

Societal, economic, and policy changes have also affected timber on federal forests. Between 1998 and 2013, employment in the timber industry fell by a third in both the study area and throughout the United States

TABLE 6 Contributions of the Northern Rockies and Intermountain Adaptation Partnerships to meeting the UN Sustainable Development Goals 6 and 15 in the Rocky Mountain region.

SDG	SDG description (UN 2017)	Contribution of adaptation partnerships
6.6	By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes	Produced scientific information on potential climate change effects on water availability and aquatic habitats in the region; developed strategies and tactics to restore and sustain hydrological processes and aquatic habitats (see Table 2).
15.1	By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements	Developed strategies and tactics to restore and sustain hydrological processes and aquatic habitats based on expected impacts of climate change on water resources (eg reduce erosion, protect natural springs, increase resilience of riparian areas and wetlands, and restore floodplains [see Table 2]).
15.4	By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development	Developed strategies and tactics to increase ecosystem resilience to changing climate, particularly to disturbances that are likely to increase with climate change, such as drought, wildfire, and insect outbreaks (eg see Table 3).
15.5	Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species	Identified vulnerable plant and animal species and habitats under changing climate; developed adaptation strategies and tactics to restore and maintain viable habitats and minimize loss of biodiversity with climate change (see Tables 2–4).
15.8	By 2020, introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species	Identified aquatic and terrestrial habitats vulnerable to invasive species; developed strategies and tactics to reduce abundance and spread of invasive species (see Table 4).

(Warziniack et al 2017). These changes were driven by higher imports of wood products, declines in housing starts, changes in preferences for electronic media over paper, and growing emphasis on habitat preservation and amenity values of forests (Skog et al 2012; Weber and Chen 2012). Off-forest changes are likely to continue affecting on-forest harvest. However, to minimize negative effects of climate change, land managers can work to increase forest resilience in the near term, primarily by reducing dry forest density and increasing abundance of drought and disturbance resilient species (relevant to SDG 15.5). In the long term, species composition can be adjusted to promote diversity and sustain timber production.

While the "Old West" struggles, the "New West" is thriving in many Rocky Mountain communities, especially those with strong ties to recreation. Recreation spending in and near national forests and parks now exceeds revenue from timber in most parts of the western United States. This growth has led to a change in priorities for managers, from extractive commodities to leisure uses of the land. With changing climate, many of the demands for recreation may not match up with current management approaches for recreation in national forests and parks. Participants in the adaptation workshops repeatedly mentioned the need for recreation management systems that were more flexible, both for forest infrastructure like roads and trails and for concessionaire contracts that may not always align weather with peak demand from residents and tourists.

The effort described here highlighted the importance of federal lands in the Rocky Mountains in providing ecosystem services to society, and the ways in which federal land managers can adapt to the effects of changing climate. Federal agencies are now transitioning from the planning phase of climate change adaptation to implementation (Halofsky et al 2015), which will ensure that ecosystem services will continue to be provided from federal lands in a changing climate.

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