

Climate Change Vulnerability Assessment for Guiding Ecosystem Restoration in Fire-Prone Landscapes of the Western U.S.

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ABSTRACT

Climate-driven alterations to fire regimes challenges forest management and restoration in the western United States, where increased wildfire severity threatens ecosystem integrity and resilience. In this study, we demonstrate the application of the FireCLIME (Fire-Climate-Landscape Interactions in Montane Ecosystems) Vulnerability Assessment (VA) as a decision-support tool for evaluating management actions, including restoration strategies, under climate uncertainty. Through collaborative workshops with USDA Forest Service managers, we assessed three project areas in two national forests: Lincoln National Forest (LNF, New Mexico) and Bighorn National Forest (BNF, Wyoming). These two locations represent distinct climate zones, forest ecosystems, and fire regimes. We examined how changing climate and fire regimes affect ecosystem vulnerability with the FireCLIME VA, which integrates exposure to climate and fire regime changes, ecosystem response factors, and adaptive capacity via management intervention to compare vulnerability outcomes relative to desired future conditions (DFC). Results revealed that forests that departed more from historical conditions (LNF) exhibited greater vulnerability. Soil burn severity and associated erosion emerged as common vulnerability drivers across all sites. For both forests, treatments were able to reduce departure from DFC. Treatment effectiveness varied by ecosystem type; some interventions demonstrated broad capacity to lower vulnerability and achieve DFC for a wide range of components, while others had more targeted effects for specific components. This assessment framework reveals substantial synergy between climate adaptation planning and restoration ecology principles, suggesting that vulnerability assessments can effectively guide restoration planning under climate uncertainty by balancing risk reduction with ecosystem resilience enhancement.

Keywords: climate adaptation, climate-fire interaction, co-production, desired future conditions, fuel treatment, national forests

This article was prepared by a U.S. government employee as part of the employee's official duties and is in the public domain in the United States.

Across the western United States (hereafter, the West), changing climate and fire regimes pose growing threats to the integrity and resilience of social and ecological systems (Williams et al. 2010, Macias-Fauria et al. 2011, Berner et al. 2017, Holden et al. 2018, Loehman

et al. 2018, Singleton et al. 2019). Development of strategies for responding and adapting to widespread and rapid environmental change is a central challenge for land managers (Lawler 2009, Schultz et al. 2019, Parks et al. 2025). Predicting future conditions and management outcomes is difficult because ecological systems exhibit complex, emergent behavior and non-linear feedbacks that produce novel and unanticipated landscape responses when exposed to disturbance (Temperli et al. 2013, Buma 2015, Coop et al. 2016). The rapid pace of change and uncertainty in future conditions may require new management approaches and decision-making processes to account for unknown future trajectories and outcomes (Figure 1; Lawler 2009, Keenan 2015).

Successful management of natural resources requires intentional climate adaptation planning to meet near-term needs for ecosystem services and at the same time incorporate strategies to restore ecosystems impacted by anthropogenic disturbance (Shannon et al. 2019). For federal land management agencies like the United States

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 Supplementary materials are available online at: <https://er.uwpress.org>.

doi:10.3368/er.44.3.163

Ecological Restoration Vol. 44, No. 3, 2026

ISSN 1543-4060 E-ISSN 1543-4079

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🌿 Restoration Recap 🌿

- Vulnerability assessments can integrate restoration ecology and climate adaptation.
- Under changing climate, future strategies may need to combine resilience-building and risk mitigation. In particular, managers noted a desire to reduce immediate catastrophic fire risk while also facilitating long-term reintegration of fire into fire-adapted systems.
- Soil stabilization activities emerged as a universal priority in both near- and longer timeframes.
- For some fire-suppressed landscapes, climate change may move different ecosystem components closer to desired future conditions due to increased fire frequency and area burned.

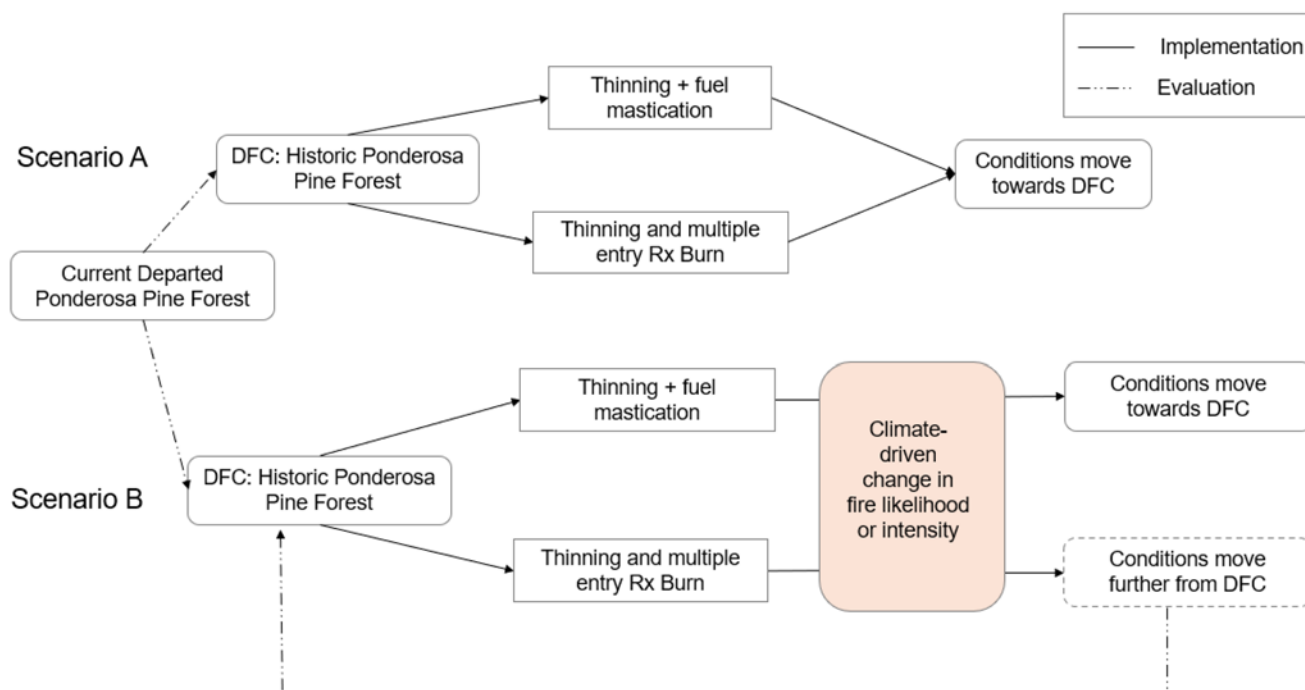


Figure 1. Restoration and conservation strategies designed to deal with current departures may not lead to the same outcome under additive effects of changing disturbance regimes. Scenario A shows a typical decision process that evaluates (dashed arrows) current conditions relative to Desired Future Conditions (DFC) for a hypothetical forest system and identifies strategies that, once implemented (solid arrows), move the system closer to DFC. In Scenario B, climate-driven changes in fire regimes (orange box) cause further or unexpected shifts in conditions leading to more variable outcomes. In this context, managers may have fewer or different strategies available. Where actions fail to achieve goals, reevaluation (dashed line) of DFC may be warranted. In this paper, we demonstrate how the vulnerability assessment process can inform management strategies to reduce risk for ecosystems to climate-fire synergies. Note: Desired future conditions may or may not be based on historical conditions.

Forest Service (USFS), navigating these tradeoffs is critically important. As a primary wildland fire organization in the United States, the USFS's response to climate change and wildfire is shaped by both statutory mandates including the Forest Restoration Act of 2003 and a management legacy that has left forests primed for extreme wildfire (USDA Forest Service 2015, Schultz et al. 2019). Forests altered by decades of fire suppression require expansive restoration efforts before wildfire can be returned to its natural, critical role within ecosystems (Parks et al. 2025). Climate change adds to management challenges, as increasingly warm and arid conditions influence not only risk of wildfire, but outcomes from restoration work itself

(Figure 1). Management planning exists within this complex environment, underscoring the need for frameworks that identify management actions most likely to achieve near- and longer-term goals of restoring ecosystems and supporting more resilient and fire-adapted landscapes (Sample et al. 2022).

Vulnerability assessments (VAs) are widely used in ecosystem management to support decision-making in the context of the uncertainty created by changing climate regimes (IPCC 2001, Friggens et al. 2013, Weaver et al. 2012, Hyman et al. 2025). Vulnerability assessments have been used to identify and support management actions across multiple sectors at local, state, and federal levels

both within and outside of the U.S. (Downing et al. 2002; AFW 2021; USDA Forest Service 2022, 2025; NMDW 2025; Dekens et al. 2026). Vulnerability measures the extent to which a target ecosystem, resource, or species is susceptible to impacts by disturbance (Friggens et al. 2013). The inherent flexibility of VAs, which can be applied to a range of targets and use a variety of data inputs, has led to their use in a wide range of studies focused on species, ecosystems, and resources (e.g., Friggens et al. 2013, Furniss et al. 2013, Foden et al. 2019). Designed to incorporate complex interactions, system-wide feedbacks, and uncertainties, VAs can be applied to compare outcomes under a range of environmental conditions to facilitate development of actionable adaptation plans at scales relevant to the administrative domains of land and resource managers (McNeeley et al. 2017). However, to date, VAs have not been used to evaluate the interactive effects of climate and fire regime changes on landscape components (although Thorne et al. 2018 do include wildfire as a stress factor in their assessment of forest vulnerability to climate change).

In this study, we apply a VA tool explicitly designed for ecosystems threatened by both changing climate and altered wildfire regimes to (1) assess the potential consequences of climate-related fire regime shifts for two distinct forest types, and (2) consider the results of the assessment process and indicated management strategies through the lens of restoration ecology. Through this process, we explore the synergy between ecological restoration practices that move a damaged system to an ecological state that is within some acceptable limits relative to a less disturbed system (Palmer et al. 2006), and climate adaptation actions that help reduce vulnerability to the current or expected impacts of climate change (IPCC 2014). For landscapes and ecosystems vulnerable to the interacting perturbations of changing climate and altered wildfire regimes, restoration treatments may limit the area burned in future, high-severity fire events, reduce potential for conversion from forested to non-forested conditions, increase resistance to insect and pathogen outbreaks and climatic variability, and enhance ecological resilience (Allen et al. 2002, O'Donnell et al. 2018, Stoddard et al. 2021). Building resilience to natural disturbances is a key management objective in climate adaptation planning, achieved via manipulation of stand and landscape structure (Halofsky et al. 2018). Importantly, promoting more integrated restoration and adaptation approaches may help overcome institutional tendencies to prioritize actions that address short-term risk over longer-term adaptation—a challenge common to large land management organizations (Wilson et al. 2011, Schultz et al. 2019).

The Fire-Climate-Landscape Interactions in Montane Ecosystems Vulnerability Assessment (FireCLIME VA [<https://mfriggens.github.io/FireClimateVA/index.html>], Friggens et al. 2019) builds upon tools developed

specifically to help managers prioritize management strategies to reduce vulnerabilities that arise as a result of exposure to disturbance (e.g., Bagne et al. 2011, Glick et al. 2011, Foden et al. 2019). The FireCLIME VA generates a score based on the cumulative impacts of fire regime change and ecosystem response, which can be used to compare relative potential impacts among different project sites, ecosystems, or under different climate scenarios (Friggens et al. 2019). Developed as part of a science-management partnership (www.fireclimate.org), the FireCLIME VA is unique for incorporating user-defined desired future conditions and management treatment options as components in its evaluation process.

Here, we demonstrate use of the FireCLIME VA to evaluate the feasibility and effectiveness of ecological restoration approaches for obtaining desired future conditions (DFC) that may include emergent or novel ecosystem properties to foster the maintenance of critical ecosystem services (Figure 1; Golladay et al. 2016). With two case studies from the West, we illustrate and define a co-production approach for deriving the necessary inputs for the FireCLIME VA. We use project outcomes to identify common themes related to restoration actions across ecosystems and demonstrate how climate adaptation concepts integrate with restoration principles to promote climate-resilient landscapes. We conclude that commonalities between the fields of restoration ecology and climate adaptation support the use of vulnerability assessment tools for restoration planning.

Methods

FireCLIME Vulnerability Assessment (VA)

The FireCLIME VA is a framework for comparing responses of management areas or ecosystems to the interactive effects of altered climate and fire regime components in the context of hypothetical management actions. The FireCLIME VA provides a structured process to gather, evaluate, and input data representing climate exposure, fire response, and internal and external adaptive capacity (Table 1). This framework was developed in response to needs identified by fire ecologists and managers in the southwestern US who envisioned a tool that could incorporate climate and fire interactions and identify management targets and outcomes (Friggens et al. 2019). With this overall objective in mind, the FireCLIME VA was designed to: (1) be flexible to a variety of inputs (e.g., empirical data, information from previous studies, expert knowledge), (2) operate across user-defined scales (e.g., stands or project areas to ecosystem), (3) allow users to compare outcomes under alternative management scenarios, and (4) integrate with common decision support frameworks (Table 1). Outputs generated from the tool provide rank scores to evaluate study site or project area vulnerability and determine the

Table 1. Components evaluated in the FireCLIME Vulnerability Assessment (VA) tool. VA considers the type, magnitude, and rate of disturbance to which a target is exposed (its exposure); the degree to which it is adversely affected (its sensitivity); and its capability to adjust to disturbance, either by moderating potential adverse impacts, taking advantage of opportunities, or responding to consequences (adaptive capacity) (IPCC 2001, Glick et al. 2011). In this system, Exposure (E) describes the magnitude and type of change in climate and fire regime components experienced by the study ecosystem. Climate variables include those that were identified through literature review as the most important for affecting fire regimes (Mueller et al. 2024, <https://swfireclime.org/science-synthesis/>). Similarly, fire regime change represents components with well-established links to ecosystem outcomes. Intrinsic Sensitivity (S_i) factors describe current conditions within the ecosystem that are likely to increase the negative outcomes resulting from changes in climate or fire regime. As part of S_i , users consider the current departure of each of the four fire regime components. Responses (positive/negative) of five ecosystem and three fuel components generate inputs for Sensitivity and Adaptive Capacity (S/AC). Extrinsic adaptive capacity (AC_E) considers the response of those same ecosystem and fuel components in context of a hypothetical management action. Table adapted from Friggens et al. 2019.

Exposure (E)	Sensitivity and Adaptive Capacity (S/AC)
Climate Change	Intrinsic Sensitivity Factors (S_i)
Fire Season Length	Current Departure Fire Regime (4)
Exposure	Historic Management Regime
Drought Frequency/Duration	Drought Sensitivity
Average Summer Temperature	Ecotone present
Relative Humidity	Invasive Plant present
Snowpack or Snow Water Equivalent (SWE)	Dispersal Limitations
Fire Regime Change	Fuel- or Weather-limited Regime
High-severity Patch Size	Projected Declines in Climate Suitability
Fire Frequency	Other Disturbances
Soil Burn Severity	Component Response (S/AC/AC_E)
Annual Area Burned	Ecosystem
	Species Survivorship
	Species Recruitment
	Erosion and Debris Flows
	Species composition
	Stand Structure
	Fuel
	Fuel Loading
	Fuel Horizontal Continuity
	Fuel Vertical Arrangement

components (ecosystem, fuel, or fire regime) that drive vulnerability. These components or the underlying drivers of change can then be targeted for management action (Shannon et al. 2019).

Within the FireCLIME VA, vulnerability is identified as the potential for the target system to experience undesirable outcomes that depart from user defined desired future conditions. Desired future conditions (DFC) are descriptions of ecosystem conditions preferred by stakeholders and managers (Landres et al. 1999), foundational to the development of National Forest Plans (USDA Forest Service 1982 Planning Rule) to identify the endpoints of management actions that include an array of restoration, mitigation, and transformation activities. Exposure is based on the expected change to six climate components, and the consequences of that change for four fire regime components (Table 1). Sensitivity is measured by considering the current condition of the study site (“Intrinsic Sensitivity Factors” or S_i), and the response of five ecosystem and three fuel components (Table 1). Responses

reflect the user-defined DFC, where impacts that lead to departure from DFC contribute to increased vulnerability, and impacts that reduce departure from DFC result in less vulnerability (Figure 2). The tool also considers the ability for management actions (“Extrinsic Adaptive Capacity” or AC_E) to impact fire regime, ecosystem, and fuel components in the context of DFC (Figure 2). Where management actions bring a component closer to DFC, extrinsic adaptive capacity is increased, and vulnerability is decreased (Figure 2c). The FireCLIME VA requires three types of input: 1) descriptive information about a study area or project, including: planning time frame, desired future conditions, climate scenario, ecosystem characteristics, and potential management actions or treatments (i.e., “Scenario Inputs”); 2) determination of fire regime response (positive or negative) to climate change and cascading ecosystem and fuel component responses; and, optionally, 3) determination of fire regime, ecosystem, and fuel component responses to management actions. Responses (positive or negative) are evaluated (through

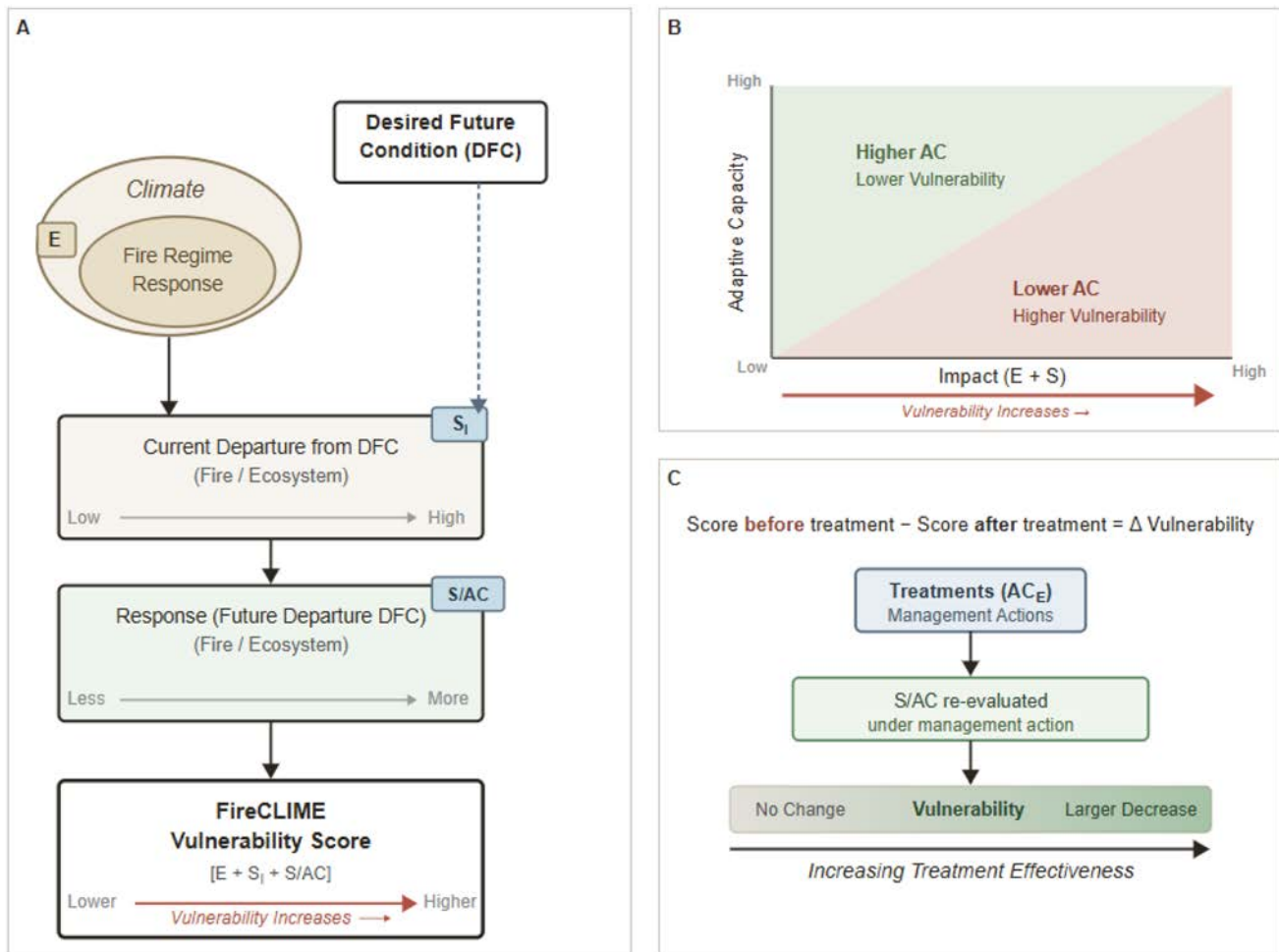


Figure 2. Schematic showing how vulnerability is calculated using the FireCLIME VA. **A)** Vulnerability to synergistic climate-fire impacts is estimated by considering change to Desired Future Conditions (DFC) as a result of Exposure (E) to climate and fire regime change and response of ecosystem and fuel components (S_i/AC) to that change. Vulnerability scores increase with increasing departure from DFC due to the collective impact of climate-driven fire regime change (E) and expected fire and ecosystem component response (S_i/AC). Greater Sensitivity (S_i) is inferred when components are likely to experience more departure from DFC because of exposure to fire regime change. Greater Adaptive Capacity (AC) occurs when an ecosystem or fuel component is expected to move toward DFC. Assessment process also includes evaluation of current departure from DFC, which represents Intrinsic Sensitivity (S_i). **B)** Vulnerability increases with increasing Impact (represented by Exposure + Sensitivity) and decreases with increasing Adaptive Capacity. **C)** Treatment (AC_E) effectiveness is assessed by reevaluating potential ecosystem and fuel component response under alternate treatments. Greater decrease in scores after treatment indicates greater effectiveness.

literature review, expert elicitation or both) relative to DFC and considered separately for fire regime, ecosystem, and fuels components, and then combined to give vulnerability scores for the target ecosystem. There are several important sources of uncertainty in any futuring exercise, including climate projections (IPCC 2022) and impacts of climate on a target (Sheppard et al 2002, Morrow et al. 2025). The FireCLIME VA incorporates a metric to evaluate the uncertainty associated with user response selection, which is considered in terms of user confidence (Friggens et al. 2019, IPCC 2022). For each potential input, researchers indicate their confidence on a scale of 1 to 3 for their chosen response based on the amount of information available to

supply the response and the robustness of that information. Additional information about suggested implementation of FireCLIME VA, definitions of climate, fire regime and ecosystem components and example outputs can be found in Friggens et al. (2019) and online (<https://mfriggens.github.io/FireClimVA/index.html>).

Study regions

We generated vulnerability assessments for three US national forest (USFS)-managed project areas: Perk-Grindstone and 16 Springs in the Lincoln National Forest in New Mexico, and the Buffalo Municipal Watershed in the Bighorn National Forest in Wyoming (Figure 3). The two

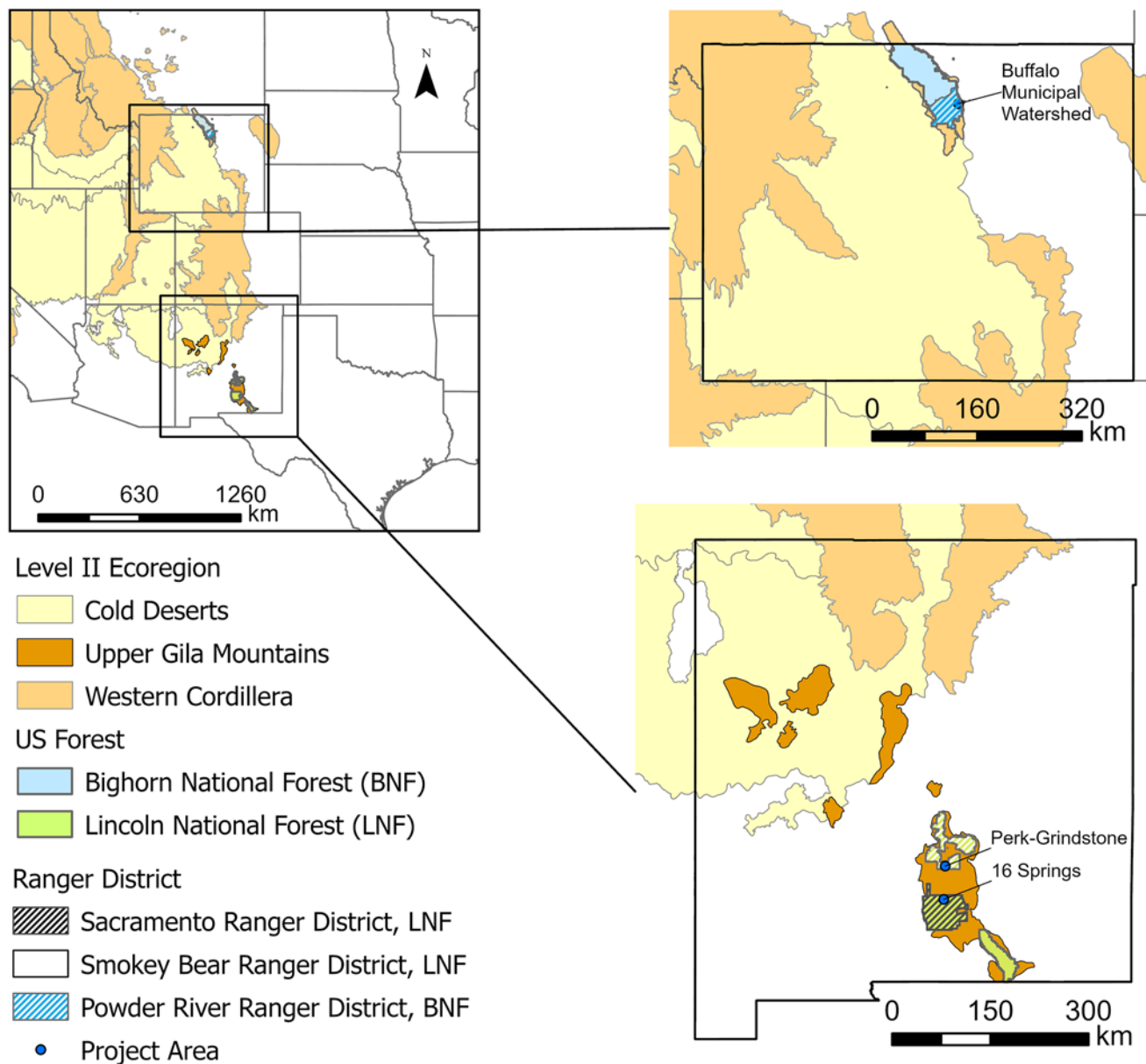


Figure 3. Case study sites in New Mexico and Wyoming. Each case study focused on fuels treatment projects (blue dot) within National Forests.

National Forests (NF) were chosen because they represent distinct climate zones, forest ecosystems, and fire regimes. The project areas within the NFs were identified by managers as priorities because they were in some stage of active management for fuel treatment. The USFS response to climate change and wildfire is shaped by both statutory mandates and decades of management legacy that has left forests primed for extreme wildfire. The Healthy Forest Restoration Act of 2003 (H.R. 1904, <https://www.congress.gov/bill/108th-congress/house-bill/1904>) and multiple use land directives focus agency efforts on landscape-scale fuel treatment and ecological restoration that aim to reduce fire risk and at the same time maintain values inherent in federal land stewardship. It is within this context that we

utilized the FireCLIME VA to identify vulnerabilities and evaluate management options.

Lincoln National Forest (Perk-Grindstone and 16 Springs project areas)

The Lincoln National Forest (LNF) covers 445,000 ha (1.1 million acres), encompassing four major mountain ranges in southern New Mexico. Within the LNF, we considered two project areas, both within the Sacramento Mountains. The 2,107-ha (5,207-acre) Perk-Grindstone project (LNF-PK) is within the Smokey Bear Ranger District and lies entirely within the wildland-urban interface adjacent to the city of Ruidoso, including the Grindstone Reservoir watershed. The 34,000-ha (85,000-acre) 16 Springs (LNF-16S)

project area is a non-urbanized area within the Sacramento Ranger District. Both contain *Pinus ponderosa* (ponderosa pine) and mixed conifer forests (e.g. *Abies concolor* [white fir], *Populus tremuloides* [aspen], *Picea engelmannii* [Engelmann spruce], *P. pungens* [blue spruce]) growing at elevations ranging from 1,980–2,400 m (6,500–8,000 feet) (Kaufmann et al. 1998). This assessment focused on the ponderosa pine forests present within each project area.

In New Mexico prior to Euro-America settlement, lower elevation ponderosa and mixed conifer forests were historically maintained and dependent on frequent, low-severity surface fires that kept forest conditions open and surface fuel accumulations low (Covington and Moore 1994, Fulé et al. 1997, Grissino-Mayer and Swetnam 2000). Fires were ignited by both lightning and peoples and were an important process that shaped forest composition, structure, and fuels (Covington and Moore 1994). As the result of overgrazing and active fire suppression during the 20th century, many forest stands in the southwestern U.S. have greatly increased tree densities and an accumulation of ladder fuels, increasing stress on old-growth trees and the risk of high severity fire (Singleton et al. 2019, Mueller et al. 2020). Management goals for these forests currently focus on hazardous fuels reduction and ecosystem sustainability, with desired conditions based on historical ranges of variation and consideration of multiple-use mandates and socio-economic factors (USDA Forest Service 2018a). Recently, several large, severe fires (for example, the 2012 Little Bear Fire, which burned 18,000 ha [44,330 acres] and destroyed 250 structures and the 2024 South Fork Fire which burned over 6,900 ha [17,000 acres], killed two people, and created extensive flooding post-fire), have impacted the forest landscapes and communities of the region (The South-Central Mountain Resource Conservation and Development Council, Inc. 2014). These and other large fire events across the area have elevated awareness of the need for an effective hazardous fuels reduction strategy. The goal of the LNF is to implement fuel treatments, emphasizing the use of prescribed fire, to re-establish fire adapted forest characteristics that promote desired fire behavior, and promote ecosystem sustainability (USDA Forest Service 2018a). The goal for the LNF assessment was to evaluate potential additive risks from climate change for current fire management challenges.

Bighorn National Forest (Buffalo Municipal Watershed Project Area)

The Bighorn National Forest (BNF) is in north central Wyoming's Bighorn Mountains. The total area within the Forest boundary is 451,290 ha (1,115,161 acres), which includes 3,031 ha (7,491 acres) of state and private land. Dominant forest types in the BNF are higher elevation *Pinus contorta* (lodgepole pine) and *Picea engelmannii*-*Abies lasiocarpa* (Engelmann spruce-subalpine fir) forests, and lower elevation ponderosa pine, *Populus tremuloides* (aspen), *Pinus*

flexilis (limber pine), and *Pseudotsuga menziesii* var *glauca* (Douglas-fir) woodlands (Despain 1973). Our assessment focused on lodgepole pine forests found within the BNF Buffalo Municipal Watershed (BNF-BMW).

Fire regimes in northern Wyoming forests range from longer-interval, high-severity fire in higher elevation forests to more frequent, low-severity fire in lower elevation forests. Historically, the fire regime in lodgepole pine forests included large-scale, stand-replacing crown fires recurring at intervals of 70 to 100+ years and often burning large proportions of the landscape, resulting in relatively even-aged stands that primarily regenerate following fires (Meyer et al. 2005). Post-European settlement, fire cessation, intensive timber extraction, and selective harvesting for large trees beginning in the second half of the 19th century reduced old-growth forests in the BNF (Meyer et al. 2005, Brown and Cook 2006). Still, compared to forests in NM, forests in WY are less departed from historical conditions. Currently, the mean fire return interval of stand-replacing fires in the last 100 years likely remains within the historical range of variation (HRV), despite fire suppression efforts (Bornong, USFS, pers. comm.). Fires in these forests are still dominated by high-severity, stand-replacing fires and post-fire regeneration also remains abundant due to the serotinous cones of lodgepole pine. About 10–20% of the current forest within the BNF-BMW is thought to have become established following a fire in the 1700s, and another 30% established after fires in the 1880s (Bornong pers. comm.). Since that time, two fires have been noted within the watershed: a 5,261-ha (13,000-acre) fire that burned in 1943, and a ~4,047-ha (10,000-acre) fire that burned in 1988. Timber harvest within the Bighorn NF began in the 1920s, relatively later than in surrounding forests because settlement activities did not start within this area until after the Little Bighorn Battle of 1876 resulting in less loss of old-growth forest (Bornong pers. comm.). Finally, unlike other areas in the Rocky Mountains (Sheppard et al. 2002), the Bighorn NF has only experienced endemic levels of mountain pine beetles. The goal of the BNF Assessment was to anticipate whether climate change would produce any unexpected outcomes in the ecosystems in BNF-BMW.

Implementation

Desired future conditions and treatments were defined as those of immediate importance for NF personnel who participated in workshops for this study (hereafter “working group” or “participants”). As a result, the outcomes of these case studies consider real world management decisions largely structured by existing management alternatives outlined in planning documents. The authors of this paper consider study outcomes under a theoretical framework to demonstrate a process to link real world applications such as these with climate adaptation and restoration sciences. We facilitated a manager-led implementation

Table 2. Desired future conditions (DFC) for each of four fire regime, five ecosystem, and three fuel components as outlined by managers at workshops for the Lincoln National Forest, Perk-Grindstone (LNF-PK) and 16 Springs (LNF-16S) project areas, and the Bighorn National Forest, Buffalo Municipal Watershed (BNF-BMW) project area. LNF DFC were developed for ponderosa pine ecosystems, whereas BNF DFC apply to lodgepole pine forests. During workshops, each group was presented with the component definition and asked to develop a management goal or DFC for that component.

Component	Project Area	Desired Future Condition
FIRE		
High-severity patch size —Average size of a contiguous area of tree mortality.		
	LNF-PK	Individual patches with less than 2–8 ha (5–20 ac) of high-severity patches
	LNF-16S	Prefer surface fires. Individual patches less than 8 ha (20 ac) of high-severity
	BNF-BMW	Decrease from typical large-scale and/or extreme fire needed due to human values (Wildland Urban Interface [WUI], etc.)
Fire Frequency —The recurrence of fire in a given area over time, in units of number of fires per unit area.		
	LNF-PK	2–20 years
	LNF-16S	Historic Range of Variation (HRV) pre-settlement = 3–10 years
	BNF-BMW	Decrease from typical large-scale and/or extreme fire needed due to human values (Wildland Urban Interface [WUI], etc.). More frequent fire and mechanical treatment (but smaller scale than Natural Range of Variation) to meet large-scale resiliency. Create forests resilient to an epidemic. HRV pre-settlement: Fire Return Interval = 40 to 400 years. DFC would include more frequent but smaller fires. BMW Environmental Assessment identifies goal for a Fire Return Interval (FRI) > 150 years
Soil Burn Severity —Fire-induced changes in the physical, chemical, and biological soil properties that impact hydrological and biological soil functions. The degree of soil burn severity is dependent on the peak temperatures and duration of those temperatures within the soil.		
	LNF-PK	< 10% of entire area with high soil burn severity
	LNF-16S	< 10% of entire area with high soil burn severity
	BNF-BMW	Historically stand replacing. However, DFC is to decrease high-severity patch size within the watershed
Annual Area Burned —The annual (typically calendar or water year) total mapped extent of wildfire within a specified area.		
	LNF-PK	~5–20% of entire area/year
	LNF-16S	~10–25% of the project area/year
	BNF-BMW	Maintain current levels*
ECOSYSTEM		
Survivorship —The ability of the local vegetation to survive several months post-fire.		
	LNF-PK	75%+ survival of young (13–30 cm; 5–12 in) and mature trees; 10% survival of seedlings and saplings
	LNF-16S	75%+ survival of young (13–30 cm; 5–12 in), mid-age trees (30–46 cm; 12–18 in) and mature trees (46–61 cm; 18–24 in); 10% survival of seedlings and saplings
	BNF-BMW	Typically stand-replacing with almost 100% mortality: No desired change to current conditions, but DFC would include smaller patches of mortality
Recruitment —The process by which new individuals (plants) establish a population or are added to an existing population. May refer to clonal offspring, but more commonly means seedlings. Potential modified definition suggested during BNF workshop: Trees/acre within specific time period. e.g., from seedling to sapling.		
	LNF-PK	50 trees/acre <i>Pinus ponderosa</i> (PIPO) over 5-year period
	LNF-16S	50 trees/acre PIPO over 5-year period
	BNF-BMW	No change to current conditions as regeneration is typically very abundant post disturbance. BMW EA notes a treatment target to create 0.1 to 0.4 ha gaps to provide for regeneration.
Erosion and Debris Flows —The movement and transport of soil by various agents, particularly water, wind, and mass movement. Consumption of trees, shrubs, forbs, grasses and forest litter by fire changes the susceptibility of soil to erosion.		
	LNF-PK	Reduce erosion scores. General increase in runoff with a decrease in soil loss
	LNF-16S	Reduce erosion scores. General annual increase in runoff with a decrease in soil loss
	BNF-BMW	Minimize soil erosion and sedimentation of water supply; maintain at least 2.5–5 cm (1–2 in) of litter plus duff to minimize soil erosion**
Species Composition —Forest composition, specifically, refers to all plant species found in a stand or landscape, including trees, shrubs, forbs, and grasses.		

Table 2, continued.

Component	Project Area	Desired Future Condition
	LNF-PK	Ponderosa dominant overstory. Reduction in piñon-juniper (PJ) and Douglas-fir (DF) understory. Open conditions that provide for a restored understory, including Gambel's oak, and a diversity of shrubs, forbs, and grasses
	LNF-16S	Ponderosa dominant overstory. Reduction in PJ understory. Open conditions that provide for a restored understory, including <i>Quercus gambelii</i> (Gambel oak), and a diversity of shrubs, forbs, and grasses
	BNF-BMW	Keep invasive species out. Lodgepole pine ecosystems are not highly diverse, but native plant diversity is still important. Target density of trees is 760 trees/ha (304 trees/acre)
Stand structure —The horizontal and vertical distribution of components of a stand, classified by the age distribution, height, diameter, crown layers and stems of trees, shrubs, herbaceous understory, snags, and down woody debris, etc.		
	LNF-PK	Move toward stands of uneven-aged trees with large interspaces between trees or small groups of trees. Create densities of 50–190 trees/ha (20–75 trees/acre) of PIPO
	LNF-16S	Move toward stands of clumped, uneven-aged trees with large interspaces between trees or small groups of trees. Create densities of 50–125 trees/ha (20–50 trees/acre) of PIPO. General increase in average tree size for clumps of old/mature trees = 46–6+ cm (18–24+ in) diameter. Old growth beginning to reappear (61+ cm; 24+ in)
	BNF-BMW	Generally, even-aged stands in lodgepole pine, and uneven-aged in Engelmann spruce/Subalpine Fir. Successional stages would include: ~20% early, 45% mid, 35% late; increase early successional stages over current amounts. Approximately 760 trees/ha (304 trees/ac) in lodgepole forests to enhance rate of tree growth and future individual tree size
FUELS		
Fuel Loading —The oven dry weight of available flammable material in an area, reported as the amount of available fuel per unit area, usually in tons of fuel per acre.		
	LNF-PK	Coarse woody debris (CWD) and fuels would be scattered throughout w/ total fuel loading of 7.5–25 tons/ha (3–10 tons/ac)
	LNF-16S	Coarse woody debris and fuels would be scattered throughout w/ total fuel loading of 12.5–17.5 tons/ha (5–7 tons/ac)
	BNF-BMW	Amount of coarse woody debris includes at minimum 17.5–40 tons/ha (7–16 tons/acre); retain largest snags > 20 cm (8 in). Remove excess slash to reduce fuel loading around WUI and reservoir areas
Horizontal Continuity —The arrangement of fuels in the horizontal plane or the degree or extent of continuous or uninterrupted distribution of fuel particles (live or dead) in a fuel bed.		
	LNF-PK	More continuity of surface fuels and less continuity of aerial fuels
	LNF-16S	Forests stocked to about 30% maximum density. Understory of dense grasses with some shrub cover
	BNF-BMW	Create natural barriers or fuel breaks to minimize risk to safety and property and provide options for fire management
Vertical Arrangement —Fuel vertical continuity, which influences fire reaching various levels or vegetation strata. The progression of vertical fuel arrangement can be described in three categories: ground fuels, surface fuels, and canopy fuels.		
	LNF-PK	Will vary due to uneven age management. Vertical arrangement is less critical as long as canopy gaps exist
	LNF-16S	Will vary due to uneven age management. Vertical arrangement is less critical as long as canopy gaps exist
	BNF-BMW	No change to current conditions. Even-aged stands of lodgepole pine lack vertical arrangement

*Discussion noted three > 4,050 ha (10,000 ac) fires since 2007 (i.e., Little Goose, Bone Creek and Gilead) that had little to no soil burn severity and corresponding levels of Burned Area Emergency Response (BAER) work post-fire; though sediment increases were noted, they did not reach levels to require management. Therefore, though counterintuitive, group decided that there was no need to “reduce” or change current outcomes for this component.

**Modified during final review at advice of Bornong. Original had 12.5 cm (5 in), which is an unusual depth for this site.

of the FireCLIME VA through a series of webinars and remote workshops (Supplementary Materials S1a). Prior to the formal start, we conducted consultations (Wilcox, LNF; Bornong, BNF) and sent surveys (SurveyMonkey) to each NF working group to identify potential project areas. This preliminary work provided us with a starting point to identify relevant background information including climate scenarios and management documents (e.g., Forest Revision documents and project reports cited in specific NF sections below). Based on these identified sites, our team gathered information on projected climate changes, historical and desired fire regimes, and potential DFC criteria for ecosystems in each NF project area (Supplementary Materials S1b). This information-gathering step followed the process outlined for a literature-based implementation of FireCLIME VA (Friggens et al. 2019). To elicit expert local knowledge, we held additional scenario planning calls to present summary information to managers, who then had the opportunity to ask questions, adjust proposed scenarios, verify or change DFC (if they differed from management goals), and select specific management alternatives. We then summarized information for each NF study site into pre-work sections of the FireCLIME VA. These were shared during a final series of remote, facilitated workshops during which managers determined expected fire and ecosystem responses in a live exercise. Participants considered responses under “no treatment” and three other previously identified treatment alternatives (Supplementary Materials S2). After each workshop, we generated vulnerability scores for each project area for each management scenario. Workshop and final reports were shared with each NF for review and comment.

Results

Desired Future Conditions

Prior to the LNF-PK and LNF-16S workshops, we generated information on current management DFC and HRV from the Lincoln National Forest Plan Draft Assessment Report, the Lincoln National Forest Perk-Grindstone Fuel Reduction Project Environmental Impact Statement (EIS) (USDA Forest Service 2007), the 16 Springs Forest Landscape Project Environmental Assessment (EA) (USDA Forest Service 2005), the USDA Silviculture and Fire/Fuels Report for the 16 Springs Analysis Area (USDA Forest Service n.d.), and published research on the pre-settlement historical range of variation in these ecosystems (Kaufmann et al. 1998). This information was considered and modified by managers during each workshop. Resulting DFCs for the two project areas were similar since they both pertained to southwestern ponderosa pine ecosystems and included both qualitative and semi-quantitative metrics (Table 2). In general, DFC described fewer high-severity fires than have occurred in recent decades, lower soil burn severity, and greater ecosystem and fuel structural diversity.

Desired future conditions for the BNF-BMW were based on the historical range of variation as described in the Buffalo Municipal Watershed EA (USDA Forest Service 2018b) and the Bighorn National Forest Revised Land and Resource Management Plan (USDA Forest Service 2005), and were modified by managers during workshops (Table 2). In general, DFC for the BNF-BMW outlined goals that would prevent further departure from current conditions (Table 2).

Expected Climate and Fire Regime Change

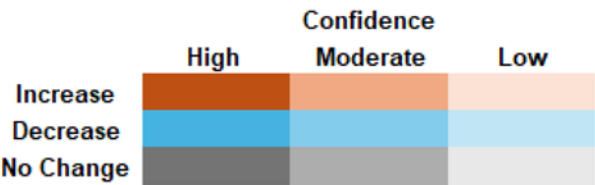
Expected changes to climate and fire regime components constitute exposure factors (Figure 2, Table 1). Prior to each initial workshop, we identified a warm-dry future climate trajectory based on the CCSM4 CMIP5 climate model for the moderate emissions scenario RCP 4.5, which assumes an average global increase in temperature of 1.8°C by the year 2100 and increased aridity and periods of drought in the southwestern U.S. (Collins et al. 2013; Supplementary Materials S1b). We also referenced conditions specific to the state of Wyoming (EPA 2016, Wyoming Water Resources Data System 2019). We used this climate scenario to assign an expected increase, decrease or no change to six climate variables (Figure 4; Supplementary Materials S1b). These climate trajectories were used to estimate whether the four fire regime components included in the FireCLIME VA (i.e., fire frequency, annual area burned, soil burn severity, and fire size) would move closer to or further from DFC (Figure 5).

Current Ecosystem Characteristics and Future Departure

Ecosystem conditions that are likely to increase the negative outcomes resulting from changes in climate or fire regime components constitute intrinsic sensitivity factors (S_i ; Table 1, Figure 2). For the LNF-PK and LNF-16S, all fire regime components were considered departed, but climate impacts were considered likely to bring two fire regime components (i.e., fire frequency and annual area burned) nearer to DFC (Figure 5). For BNF-BMW, fire regime components were considered within range currently but likely to shift away from DFC under a future, warmer-drier climate. Annual area burned was considered an issue for BNF-BMW (i.e., will not improve under future conditions) but not for the two LNF project areas (Figure 5). Nine other characteristics are also considered within intrinsic sensitive factors (S_i ; Table 1). For the LNF-PK, intrinsic sensitivity factors included: lack of previous fuel treatments, drought-sensitive plants, dispersal-limited plants, projected declines of desired dominant vegetation, and likelihood of other disturbance impacts (e.g., insect outbreaks). Responses for the LNF-16S project area were the same, with the addition of an invasive species sensitivity factor. For BNF-BMW, intrinsic sensitivity factors were presence of drought sensitive plants, presence of an ecotone within study area, and presence of invasive plant species.

	Lincoln NF	Bighorn NF
Fire Season Length	↑ increase	↑ increase
Energy Release Component	↑ increase	↑ increase
Drought Frequency and Duration	↑ increase	↑ increase
Average Summer Temperature	↑ increase	↑ increase
Relative Humidity	↓ decrease	↓ decrease
Snowpack or SWE	↓ decrease	↓ decrease

Figure 4. Climate-fire scenario generated for case study application in two National Forests (NF). Projected change in six climate characteristics important for fire regime changes were first derived from literature and climate models for landscapes in the SW (Mueller et al. 2024; <https://swfireclimate.org/science-synthesis/>). Climate scenarios and reasoning for determinations by each NF working group can be found in **Supplementary Materials 1b**. Confidence (depicted by shade) refers to the potential certainty of the users that this effect would manifest under future climate conditions. SWE = snow water equivalent.



	Type	LNF-PK	LNF-16S	BNF-BMW
	Change	Future DFC	Future DFC	Future DFC
High Severity Patch Size	↑ increase	➡ further	➡ further	➡ further
Fire Frequency	↑ increase	⬅ closer	⬅ closer	⬅ closer
Soil Burn Severity	↑ increase	➡ further	➡ further	➡ further
Annual Area Burned	↑ increase	⬅ closer	⬅ closer	● no change

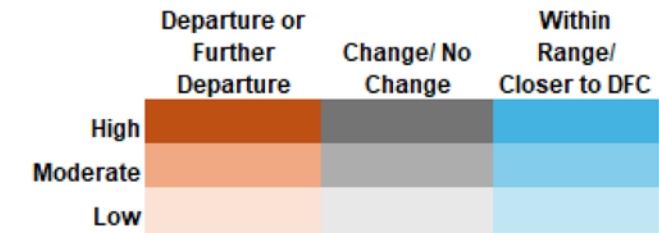


Figure 5. Expected impact of climate change on four fire regime components and resulting outcome for future conditions in terms of departure from Desired Future Conditions (DFC) for three project areas (Perk-Grindstone, 16 Springs, Buffalo Municipal Watershed or PK, 16S, BMW, respectively) in two National Forests, Lincoln and Bighorn (LNF and BNF, respectively). “Further” indicates expected shift away from DFC as a result of climate related impacts to fire regime. “Closer” indicates an expected shift toward DFC. Predictions are based on group discussion. Confidence is indicated by shade.

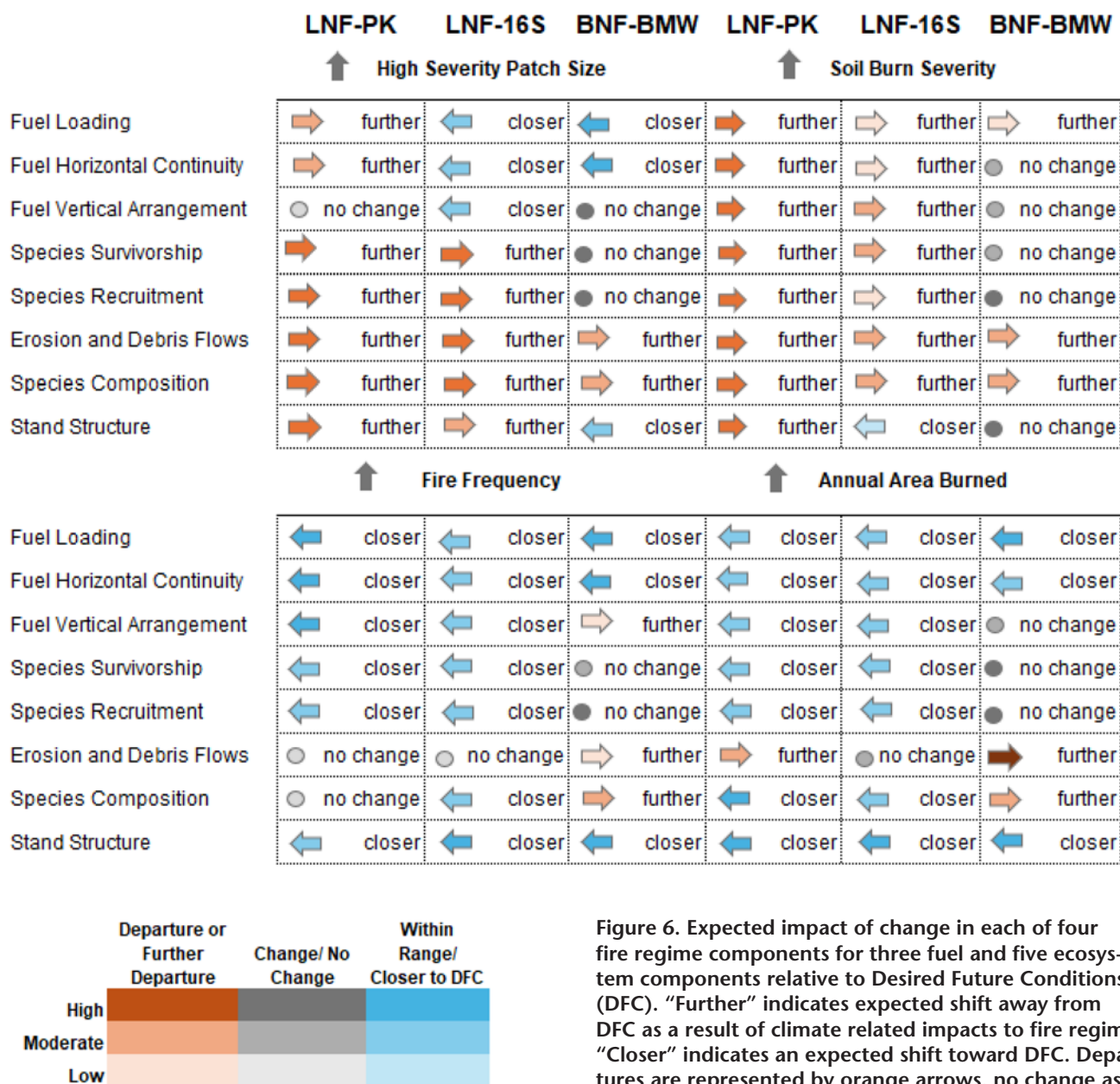


Figure 6. Expected impact of change in each of four fire regime components for three fuel and five ecosystem components relative to Desired Future Conditions (DFC). "Further" indicates expected shift away from DFC as a result of climate related impacts to fire regime. "Closer" indicates an expected shift toward DFC. Departures are represented by orange arrows, no change as grey circles, and improvements as blue arrows. Darker shade indicates greater confidence in outcome by user. LNF-PK= Lincoln National Forest- Perk-Grindstone Project; LNF-16S = LNF-16 Springs; BNF-BMW= Bighorn National Forest- Buffalo Municipal Watershed.

Response of Ecosystem and Fuel Components and Overall Vulnerability

Responses of ecosystem and fuel components to climate and fire regime changes produce impact scores that quantify vulnerability in the absence of management intervention (Table 1, Figure 2). Impact scores for project areas were generated based on expected responses of fire regimes and ecosystems to fire regime change and treatment options that were supplied by each group during half-day workshops (Figures 5, 6; [Supplementary Materials S1a, 3](#)). As evaluated by participants, most ecosystem components

in the LNF project areas were negatively impacted by increased high-severity patch size and soil burn severity expected under a climate change scenario (Figure 6) but were less negatively impacted by increases in fire frequency and annual area burned. Fuel components were negatively impacted by increased high-severity patch size in LNF-PK but not LNF-16S. For fuel components for both project areas, increased soil burn severity increased departure from DFC, but increased fire frequency and annual area burned brought areas closer to DFC. In the BNF-BMW, forest structure and two of three fuel components

Table 3. Treatments and effectiveness of treatments for reducing vulnerability within three project areas within Lincoln National Forest (Perk-Grindstone, LNF-PK; 16 Springs, LNF-16S) and Bighorn National Forest (Buffalo Municipal Watershed BNF-BMW). Higher values before treatment indicate greater vulnerability. Each fire regime, ecosystem, and fuel component is evaluated under each treatment, and scores are recalculated based on whether the treatment moves conditions closer to or farther from Desired Future Conditions (DFC). Movement toward DFC lowers the score, whereas movement away from DFC does not change the score. Post-treatment scores that remain close to initial vulnerability values indicate limited improvement. Treatments differ between forests and are not directly comparable across all sites.

	Vulnerability Score No Treatment (-10 to +10)	Score After Treatment 1 (-10 to +10)	Score After Treatment 2 (-10 to +10)	Score After Treatment 3 (-10 to +10)
		Mechanical thinning + single prescribed burn	Mastication of fuels + single prescribed burn	Single entry prescribed burn only
LNF-PK	5.3	-1.5	3.3	0.5
		Multiple prescribed burns and managed fire use	Lop and scatter. Slash treatment left onsite followed by prescribed fire	Lop and scatter. Slash removed
LNF-16S	4.4	-1.4	-0.1	-2.9
		Clearcuts > 16 ha (40 ac)	Mechanical thinning only	Prescribed fire with two entries
BNF	1.8	-4.7	-2.5	-3.2

were considered likely to benefit from fire regime change expected under a climate change scenario (Figure 6). Many fuel and ecosystem components were not expected to change in response to climate-fire interactions, but erosion and debris flow disturbance and species composition tended to depart from DFC for each predicted fire regime change (Figure 6).

Individual impact scores generated for each ecosystem and fuel component are summed to create an overall vulnerability score for each project area (Friggens et al. 2019). Within the LNF, LNF-PK had a higher vulnerability score (greater vulnerability) than LNF-16S (Table 3) due to a greater number of sensitivity factors, which collectively increased impact scores. Though not directly comparable, the BNF-BMW vulnerability score was close to neutral, indicating an expected less negative impact from climate driven changes in fire regimes (Table 3).

Treatment Effects

The effectiveness of a treatment for reducing vulnerability (reducing potential departure from DFC) represents the extrinsic adaptive capacity of system (AC_E ; Figure 2c). Extrinsic adaptive capacity is evaluated by ranking the expected impact of each treatment on each ecosystem and fuel component on a scale of “no effect” to “excellent.” Rankings are then used to modify vulnerability scores for each component where low ranking treatment outcomes result in no change in vulnerability and treatments with excellent outcomes result in a measured reduction in vulnerability score (Figure 2, Table 4). For each project area, managers identified three treatment alternatives based on treatment strategies commonly implemented in fuel reduction projects (Table 3). Considering each treatment,

managers then assessed whether those activities would have a measurable change on ecosystem and fuel response.

Treatments outlined by managers during workshops led to reduced vulnerability scores for all project areas (Table 3). More intensive treatments (e.g., clearcutting >16 ha [40 acres] with prescribed fire in BNF-BMW) demonstrated a broad capacity to bring multiple landscape components closer to DFC. As implemented, the Fire-CLIME VA distinguished between treatment effectiveness among different ecosystem and fuel components for each project area (Supplementary Materials S2), allowing users to differentiate between treatments for achieving specific or targeted management goals. For example, within the LNF-16S, Treatment 2 lowered the overall vulnerability score and was the most effective of the three treatments for reducing impacts associated with soil burn severity but was less effective for reducing impacts for the remaining fire regime components (Table 3, Supplementary Materials Figures S2b and S2c). Variations in confidence scores indicate gaps in our knowledge of fire-ecosystem interactions under different management scenarios (Supplementary Materials Figure S2a).

Discussion

Restoration is defined as the process of assisting the recovery of an ecosystem that has been degraded, damaged, transformed, or destroyed (SER 2004), ultimately resulting in benefits for biodiversity and human well-being (Nelson et al. 2024). Most forests within the western U.S. are in a degraded state in terms of departure from historical fire regimes (Littell et al. 2009) and thus are targets for potential restoration actions. Restoration targets for these

Table 4. Comparison of the attributes outlined in the Ecological Recovery Wheel (ERW) and comparable metrics in the FireCLIME Vulnerability Assessment (VA), where similar measures are represented as Intrinsic Sensitivities and Component Responses. It is important to remember that the intent of these two tools is different: The ERW identifies attributes used to gauge the recovery of a system compared to a reference model and is typically applied to field data. In contrast, the FireCLIME VA uses these metrics to determine a vulnerability score representing susceptibility of a system to climate and fire regime change. Following this baseline assessment, outcomes are compared under management (restoration) alternatives. Management alternatives are evaluated in terms of how well they reduce vulnerability scores. The FireCLIME VA is conducted using data from research studies and models, expert opinion, or some combination of these.

Attributes Outlined by the Ecological Recovery Wheel (Gann et al. 2019)	Metrics Used by FireCLIME VA to Measure Vulnerability (Friggens et al. 2019)
ATTRIBUTE 1. Absence of threats	
Over-utilization	Intrinsic Sensitivity: Other disturbances, Historic Management Regime
Invasive species	Intrinsic Sensitivity: Invasive species
Contamination	Intrinsic Sensitivity: Other disturbances
ATTRIBUTE 2. Physical conditions	
Substrate physical	Component Response: Stand structure, Fuels
Substrate chemical	NA
Water chemo-physical	Climate Scenario; Fire Regime Response; Desired Future Conditions (DFC); Component Response: Drought sensitivity
ATTRIBUTE 3. Species composition	
Desirable plants	DFC; Component Response: Species composition
Desirable animals	NA
No undesirable species	Intrinsic Sensitivity: Invasive species
ATTRIBUTE 4. Structural diversity	
All strata present	Component Response: Fuels, Stand structure
All trophic levels	Component Response: Stand structure
Spatial mosaic	Intrinsic Sensitivity: Ecotone; Component Response: Stand structure, Horizontal continuity, Species composition
ATTRIBUTE 5. Ecosystem function	
Productivity, cycling	Component Response: Species survivorship, Species recruitment
Habitat & interactions	Intrinsic Sensitivity: Invasive plants, Ecotone, Dispersal limitations, Projected declines in suitability; Component Response: Species composition
Resilience, recruitment	Intrinsic Sensitivity: Current departure, Historic management regime; Component Response: Species survivorship, Species recruitment
ATTRIBUTE 6. External exchanges	
Landscape flows	Component Response: Erosion and debris flows
Gene flows	NA
Habitat link	Intrinsic Sensitivity: Invasive plants, Ecotone, Dispersal limitations, Projected declines in suitability

forests are commonly based on historical conditions (e.g., HRV), which may also serve as desired outcomes of restoration activities (Allen et al. 2002). However, managing for changing fire regimes under the interactive effects of a changing climate, land use change, and other stressors such as invasive species and insect epidemics may require a shift from traditional management and restoration practices that focus on pre-European conditions (Sample et al. 2022, Mueller et al. 2024). For landscapes subject to novel or alternative future states, strategies based on historical conditions may no longer be adequate or achievable (Flatley and Fulé 2016, Vaillant and Reinhardt 2017, Coop et al. 2020; Figure 1). The field of restoration ecology also notes the need to consider future change in the determination of goals and actions (Gann et al. 2019). Vulnerability

assessments, along with modeling and adaptive management, provide an approach to managing the inevitable uncertainty associated with forest management in a changing climate (Adger et al. 2007, Morrow et al. 2025).

Natural resource management is inherently complex and requires systems and tools that can navigate those complexities and accommodate uncertainty (Stein et al. 2013, Golladay et al. 2016). The incorporation of local, expert knowledge (such as that represented by the natural resource managers who comprised our study groups) into land management decision-making processes has been identified by researchers, communities, and agencies as important for achieving effective outcomes (Lieberknecht et al. 2024). In each of our case studies, managers chose to consider restoration among their preferred management

actions. Specifically, actions were assessed for their potential to achieve the two primary goals outlined in DFC: 1) reduce risk of catastrophic fire, and 2) facilitate a future fire regime where fire is integrated into ecosystems, and used as a management tool. There was considerable support among our study groups for actions that would lead to the re-establishment of historical fire regimes within NFs. These actions reflect a synergy with standards and principles of restoration ecology (SER 2004) to increase the potential of native species and ecosystems to recover and continue to adapt and evolve on their own, as similarly identified in recent discourse within the fire ecology community (Ingalsbee 2017). Even actions aimed at reducing the risk of catastrophic fire might be considered on the spectrum of restoration, where they create more “natural” fuel loads or improve ecosystem resilience (Ren and Coffman 2023). Thus, ecological restoration, already identified as a powerful tool for enhancing ecosystem resilience to climate change (Shannon et al. 2019), is equally important for long term wildlife risk reduction and restoration of fire as a natural ecological process (Ren and Coffman 2023).

Commonalities between the fields of restoration ecology and climate adaptation support the use of vulnerability assessment tools such as the FireCLIME VA for restoration planning (Table 4). For example, the operational framework of the FireCLIME VA aligns with four key principles outlined for ecological restoration (Gann et al. 2019) including engaging stakeholders, using various types of knowledge, developing clear goals and objectives, and gaining cumulative value when applied at large scales. Two additional restoration principles (Gann et al. 2019) can be integrated into the VA via incorporation of DFC: 1) Principle 3, “Ecological restoration is informed by native reference ecosystems while considering environmental change,” and 2) Principle 4, “Ecological restoration supports ecosystem recovery processes.”

In our study, project areas within the LNF were found to be further departed from historical conditions than the forests within the BNF-BMW, with greater opportunity for management actions to reduce vulnerability by bringing ecosystem and fuels components closer to DFC (Figures 4–6, Table 3). Within both NFs, climate-driven changes in ecosystem and fire regime components were not always expected to lead to further departure from DFC (Figs 5, 6). For example, in the LNF, increased fire frequency and annual area burned did not contribute to increased vulnerability because they are likely to move dry ponderosa pine forests toward desired future conditions consistent with characteristic historical fire regimes for this forest type (Swetnam and Betancourt 1998). However, the manner in which these fires occur is of critical importance because in forests that are adapted to frequent, low-severity fire, fires with large high-severity components can result in regeneration failure, soil erosion, and conversion from forest to shrubland or grasslands (Reynolds et al. 2013,

Singleton et al. 2019, Mueller et al. 2020). In the BNF-BMW, managers assessed that climate driven increases in fire frequency moved tree species composition, fuel loads, and fuel horizontal continuity closer to DFC, but negative impacts were expected for erosion and debris flows and stand structure, in part reflecting assumptions that some of these fires would also lead to large high-severity patch sizes and greater soil burn severity (Tables 2, 6). This outcome is consistent with studies indicating that positive effects of increased fire do not always outweigh the potential ecological risks associated with high-severity fire, such as potential alterations in the vegetation community type, longer recovery time, increased risk of erosion, and increased risk of non-native species invasion (Miller et al. 2009, Cansler and McKenzie 2014).

Soil-related components consistently showed high vulnerability to climate and fire regime changes across project areas, and erosion and debris flows typically contributed to the highest impact scores (Figure 6). This finding is not surprising but perhaps has never explicitly been compared with other landscape factors before. Soil burn severity is a large driver of post-fire hazards; for example, monsoonal rains following several high severity wildfires, including the 2010 Shultz Fire near Flagstaff, AZ, the 2011 Las Conchas Fire in the Jemez Mountains, NM, the 2022 Hermit’s Peak/Calf Canyon Fire in NM, and the 2024 South Fork fire near Ruidoso, NM, led to unprecedented flooding, soil erosion and loss, and decreased watershed function, damaging homes and property below, altering habitat conditions for plants and wildlife, and reducing the ability of the slopes to recover naturally (Neary et al. 2012, Valdez 2023). Not surprisingly, the results of this study demonstrate that strategies to stabilize soil and prevent erosion and debris flow events were considered a primary avenue for reducing vulnerability to climate-fire impacts for all project areas.

The FireCLIME VA is a decision support tool that incorporates knowledge from a diverse set of sources to facilitate discussion and identification of action alternatives among diverse groups. A common goal for VA is to organize and communicate information in a way that enables strategic management planning even under uncertainty (Friggens et al. 2013). Although our study groups were comprised of different manager groups and addressed different ecosystems, common themes existed across the studies. Summarized from discussions and materials from each workshop, three themes emerged. First, the decision to implement treatments within a landscape requires managers to balance expected treatment benefits with the cost and feasibility of management actions. Cost can be associated with the risk of wildfire and climate change for forest ecosystems, which relates to the degree of forest and tree susceptibility, permanence of effect or likelihood of type shift, and values (importance of stand or forest type). Feasibility has as much to do with logistics (can we access and treat this area?) as with the likelihood that treatment will have a measurable

effect to reduce risk. Second, long-term planning is important for success. Returning to historical fire conditions requires intensive and sometimes sustained management while at the same time considering both immediate fire risk reduction and long-term ecosystem resilience. Third, not all outcomes will be undesirable, and some issues are more problematic than others. Managers noted that while some ecosystem components are at risk, others may improve due to changing fire regimes. In terms of restoration, this type of information is important to make decisions that attempt to balance actions that reduce risks associated with catastrophic fire with those that facilitate the incorporation of fire back into fire-adapted ecosystems.

The FireCLIME VA led participants through a process to evaluate ecosystem and fuel component responses under different treatment and climate scenarios and, in our case studies, facilitated discussions that weighed short-term risk reduction through mitigation-based strategies (fuel treatments) against long-term resilience-focused (ecosystem components) actions needed to produce the effective outcomes over time. In its current form, interpretation of potential management interventions using the FireCLIME VA is limited to those landscape components considered within the tool and the result of any single evaluation reflects the quality of information used to characterize future conditions and the perspectives of users who provide responses. Our studies were focused on USFS projects and exclusively considered fuel treatment strategies. Future studies that address a greater range of ecosystem types and restoration actions can improve our ability to interpret a larger range of potential impacts and strategies, and help further evaluate the role of tools like FireCLIME VA in resource planning.

Acknowledgments

We would like to thank workshop participants and facilitators from the Lincoln and Bighorn National Forests. B. Bornog and C. Wilcox coordinated communication for workshops and reviewed initial reports and results. K. Chaudhry provided editing and contributed to final reports. M. Sample helped to facilitate initial workshops. Two anonymous reviewers provided helpful feedback to improve early versions of this manuscript. This work was funded by the Joint Fire Science Program (Project 15-1-03-26, Landscape Impacts of Fire and Climate Change in the Southwest: A Science-Management Partnership, "SW FireCLIME" or Southwest Fire-Climate-Landscape Interactions in Montane Ecosystems). This research was supported in part by the U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

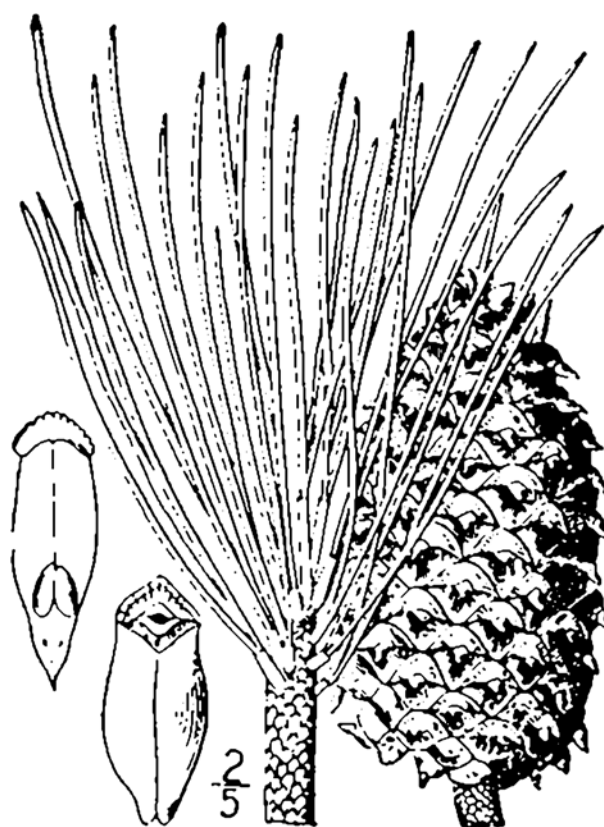
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