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ARTICLE

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Prescribed fire placement matters more than increasing frequency and extent in a simulated Pacific Northwest landscape

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Abstract

Prescribed fire has been increasingly promoted to reduce wildfire risk and restore fire-adapted ecosystems. Yet, the complexities of forest ecosystem dynamics in response to disturbances, climate change, and drought stress, combined with myriad social and policy barriers, have inhibited widespread implementation. Using the forest succession model LANDIS-II, we investigated the likely impacts of increasing prescribed fire frequency and extent on wildfire severity and forest carbon storage at local and landscape scales. Specifically, we ask how much prescribed fire is required to maintain carbon storage and reduce the severity and extent of wildfires under divergent climate change scenarios? We simulated four prescribed fire scenarios (no prescribed fire, business-as-usual, moderate increase, and large increase) in the Siskiyou Mountains of northwest California and southwest Oregon. At the local site scale, prescribed fires lowered the severity of projected wildfires and maintained approximately the same level of ecosystem carbon storage when reapplied at a ~15-year return interval for 50-year simulations. Increased frequency and extent of prescribed fire decreased the likelihood of aboveground carbon combustion during wildfire events. However, at the landscape scale, prescribed fire did not decrease the projected severity and extent of wildfire, even when large increases (up to 10× the current levels) of prescribed fire were simulated. Prescribed fire was most effective at reducing wildfire severity under a climate change scenario with increased temperature and precipitation and on sites with north-facing aspects and slopes greater than 30°. Our findings suggest that placement matters more than frequency and extent to estimate the effects of prescribed fire, and that prescribed fire alone would not be sufficient to reduce the risk of wildfire and promote carbon sequestration at regional scales in the Siskiyou Mountains. To improve feasibility, we propose targeting areas of high concern or value to decrease the risk of high-severity fire and contribute to meeting climate mitigation and adaptation goals.

Our results support strategic and targeted landscape prioritization of fire treatments to reduce wildfire severity and increase the pace and scale of forest restoration in areas of social and ecological importance, highlighting the challenges of using prescribed fire to lower wildfire risk.

KEYWORDS
carbon stabilization, climate change, forest management, landscape modeling, prescribed fire, Siskiyou Mountains, wildfire risk reduction

INTRODUCTION

Consensus among land managers and scientists in the United States continues to converge on the need to increase the use of prescribed fires (i.e., fires set intentionally to accomplish treatment objectives) to manage or restore forest ecosystems and reduce wildfire risk (Kolden, 2019; Levy, 2022; Schultz et al., 2019; Stephens et al., 2020; Taylor et al., 2021). At the same time, Indigenous communities are increasingly asserting their sovereignty and traditions, which include revitalizing cultural burning practices (Adlam et al., 2021; Lake et al., 2017; Marks-Block & Tripp, 2021). As more partnerships form between land managers, Tribes, and other stakeholders to manage and/or restore ecosystems using prescribed fire (Davis et al., 2021; Lake, 2021), a key question remains to be addressed: how much prescribed fire is needed to meet social and ecological goals under ongoing and projected climate change? To answer this question, we conducted data-enabled simulations parameterized in the Siskiyou Mountains of northwest California and southwest Oregon, as a model system for western landscapes of the United States, to examine the frequency and extent of prescribed fire needed to maintain ecosystem carbon (C) stocks while reducing the severity and extent of wildfires under different climate change scenarios.

We argue that questions related to the use of prescribed fire are particularly important to ask for landscapes with mixed-severity fire regimes. Such landscapes are abundant across the western United States, yet implementing prescribed fire in forests poses a challenge; this is because forests with mixed-severity fire regimes experience a spectrum of fire severity ranging from low to high, and they are adapted to small and frequent fires that leave behind heterogeneous patchworks at various stages of succession (Hessburg et al., 2016). In the past, fires burning across this type of heterogeneous landscape were influenced not only by fuels, topography, and climate but also by differences in vegetative composition and structure within a mosaic of patches created by people and natural disturbances (Halofsky et al., 2011). The heterogeneity created by uneven land use and burning patterns plays a crucial role in the sustainability and resiliency of ecosystems in the western United States (Perry et al., 2011; Turner et al., 2013) as well as in other parts of the world where socio-ecological dynamics strongly influence forest ecosystem structure and function (Silva et al., 2021, 2022; Silva & Lambers, 2021). As a test case of feasibility for the Pacific Northwest, we focus on the Siskiyou Mountains, a heterogeneous landscape within the Klamath Mountains ecoregion that has been a focal point for understanding mixed-severity fire regimes (Halofsky et al., 2011; Taylor et al., 2021). This region encompasses biodiverse landscapes with potential for ecosystem shifts in structure and function (e.g., changes in vegetation, biomass, and C storage) driven by climate change, land use, and fire regime (Maxwell et al., 2018; Serra-Diaz et al., 2018; Tepley et al., 2017).

The Siskiyou Mountains also have a rich history of human use and stewardship principally in the form of Indigenous cultural burning and stewardship (Knight et al., 2022). These practices, developed over millennia by Indigenous peoples with intimate knowledge of fire effects on the landscape, took advantage of topographical, vegetation, and climatic gradients to modify the landscape in ways that promoted key focal habitat and resources (Anderson, 2018; Kimmerer & Lake, 2001; Long et al., 2021). Dendrochronological archives for the pre-Euro-American Contact Era suggest that median fire return intervals ranged from 8 to 20 years, with most fires occurring in spring and fall (Knight et al., 2022; Metlen et al., 2018; Taylor & Skinner, 2003). Indigenous stewardship persisted until its disruption by Euro-American settlement and fire suppression in the late 19th and early 20th centuries, which increased fire return intervals by an order of magnitude and reduced the area burned by one-twelfth to one-fourteenth of the historical fire regime in the Klamath Mountains (Haugo et al., 2019).

Despite widespread consensus that forests would benefit from increased low- to moderate-severity fire (Kolden, 2019), nearly 98% of wildfires continue to be suppressed and rapidly contained by the USFS and their partners (USDA Forest Service, 2015). By suppressing wildfires, federal fire managers are "preferentially selecting for more damaging fires that burn under more extreme conditions" (Dunn et al., 2020). Consequently, forested landscapes, especially in the western United States, are experiencing a "fire deficit" (Haugo et al., 2019; Marlon et al., 2012). When fires do burn in this landscape, they are larger and more severe than the estimated historic range of variation due to fuels buildup and climate change (Haugo et al., 2019; Parks & Abatzoglou, 2020), further exacerbating the climate crisis by increasing greenhouse gas emissions and diminishing long-term C storage (Jerrett et al., 2022). Alternatively, reintroducing low-to-moderate-severity fire results in numerous co-benefits such as wildfire risk reduction, improved forest resilience to disturbance, and more sustainable long-term C storage (Stephens et al., 2020).

While there is growing interest in managing western forests for C sequestration, questions remain about how much of that C is likely to stay under changing climate and future fire regimes. Under a high-emissions scenario, annual temperatures in the southwest Oregon are projected to increase by 4.2°C and most models predict increases in precipitation by the end of the century although summers are expected to be drier (Miller et al., 2022). Like much of the United States, western working lands are at the center of debates pertaining to increasingly frequent droughts, which have ancient forests on the threshold of shifting from carbon sinks to carbon sources (Baldocchi et al., 2018), whereas management decisions shifted landscapes toward denser and younger forests that require vast amounts of water and therefore exacerbate drought impacts (Perry & Jones, 2016), increasing the risk of catastrophic wildfire and related C emissions (Jerrett et al., 2022). Increasing the frequency of low-severity wildfires through prescribed fire, cultural burning, and wildfires managed for resource benefits (i.e., managed fires) alongside thinning treatments can reduce severity and spread rate of subsequent fires, decreasing extreme fire behavior by reducing the loading and continuity of fuels available to burn (Cochrane et al., 2012; Fernandes, 2015; Maxwell et al., 2020). This leads to decreased tree mortality (Kalies & Yocom Kent, 2016) and can help sustain ecosystem services such as water supply, wood production, and in some cases C sequestration, at local to regional scales (Chafe et al., 2024). Reintroducing low-severity wildfire in western landscapes could draw upon the long history of frequent prescribed burning in the southeastern United States. For example, restoration treatments of longleaf pine forests have maintained open canopies and wiregrass cover preferred by the endangered red-cockaded woodpecker (Gilliam & Platt, 1999; USFWS, 2003).

Although C storage may be immediately lowered following a prescribed burn due to combustion and mortality of younger trees, older trees storing larger amounts of C are more likely to survive in burned areas, thus maintaining C storage through time. For example, prescribed fire can result in mature forest structures with fewer fine to intermediate-sized fuels that are less likely to convert to a less productive or nonforested state following a wildfire event (Hurteau et al., 2019). While wildfire can lead to major losses in soil C through combustion and erosion, frequent low-intensity fires can induce the formation of pyrogenic C or fire-induced reductions in microbial priming of soil organic matter, favoring the accumulation of more stable forms of soil C (Pierson et al., 2021). In certain ecological and pedogenic contexts, low-intensity and high-frequency fire disturbances can lead to increased soil C densities and stability (Hunter et al., 2023; Silva, 2022). Models of ecosystem responses to disturbance that include erosional C losses or gains in stable soil pools can inform landscape prioritization for increased C storage across a broad range of spatial and temporal scales (Hunter et al., 2024; Roering et al., 2023) in addition to safer and more impactful adoption of prescribed fire in the management of western forests.

In this paper, we simulate aboveground and belowground C gains in response to different levels of prescribed fire through time and assess our results at multiple spatial scales (local, landscape, region). While the use of prescribed fire to maintain ecosystem services, restore fire-adapted ecosystems, and manage wildfire risk shows promise, current fuel mitigation treatments have not reached the pace and scale needed to do so (Kolden, 2019; Vaillant & Reinhardt, 2017). This situation could rapidly change with the passage of the 2021 Infrastructure Investment and Jobs Act by the US Congress as billions of additional dollars are slated for investment in land management over the next decade. For example, the 2022 USFS Wildfire Crisis Strategy aims to treat an additional 8 million ha (20 million acres) of National Forest lands and over 12 million ha (30 million acres) of other Federal, State, Tribal, and private lands. Strategically investing these funds and positioning treatments will be critical for addressing wildfire risk to ecosystems and communities across the United States; therefore, estimating the pace and scale needed to implement effective prescribed fire plans is now a research priority (USDA Forest Service, 2022b).

We built on existing numerical models and simulations to quantify the likely effects of increasing frequency and extent of prescribed fire on fire regimes and C stores under contrasting climate scenarios using a multiscale interaction framework and interpretive hypotheses for disturbance and climate impacts on C from plots to landscapes to regions (Silva & Lambers, 2021). Specifically, we designed simulations with increasing prescribed fire frequency and extent under different climate scenarios to assess the likelihood that (1) forest sites will lose or gain aboveground biomass and soil organic C, (2) forested landscapes will experience lower wildfire severity, and (3) the size of wildfires and fire-induced C losses are to decrease in the study region.

METHODOLOGY

Study area

The study area is comprised of the 171,179-ha Environmental Protection Agency Level III ecoregion within the Siskiyou Mountains (Figure 1) known as the "Serpentine Siskiyous" for their distinct nutrient-poor serpentine soils (Griffith et al., 2016). The Siskiyou Mountains are the northernmost range of the larger Klamath Mountains ecoregion and extend in an east–west direction along the California–Oregon border between the Coast and Cascade Ranges (Figure 1a). Elevation in the study area ranges from 27 to 1620 m above sea level (USGS, 2020). The study area is characterized by a Mediterranean climate with long, hot summers and cool, wet winters (Whittaker, 1960). Mean minimum January and maximum June temperatures across the study area between 1991 and 2020 were 1.7 and 28.9°C, respectively, with an average annual precipitation of 1803 mm (NCEI, 2020).

Vegetation in the Siskiyou Mountains is exceptionally diverse due to elevational and climatic gradients, soil parent materials, and mixed-severity fire regime, with a heterogeneous mixture of conifer and hardwood forests, shrublands, and prairies of perennial grasses and oak woodlands being present throughout (Agee, 1991; Whittaker, 1960). In the Serpentine Siskiyous, Douglas fir (*Pseudotsuga menziesii*) and western white pine (*Pinus monticola*) are common and Jeffrey Pine (*Pinus jeffreyi*), endemic shrubby oak species (*Quercus* spp.), Ceanothus (*Ceanothus* spp.), and many forb species have evolved to

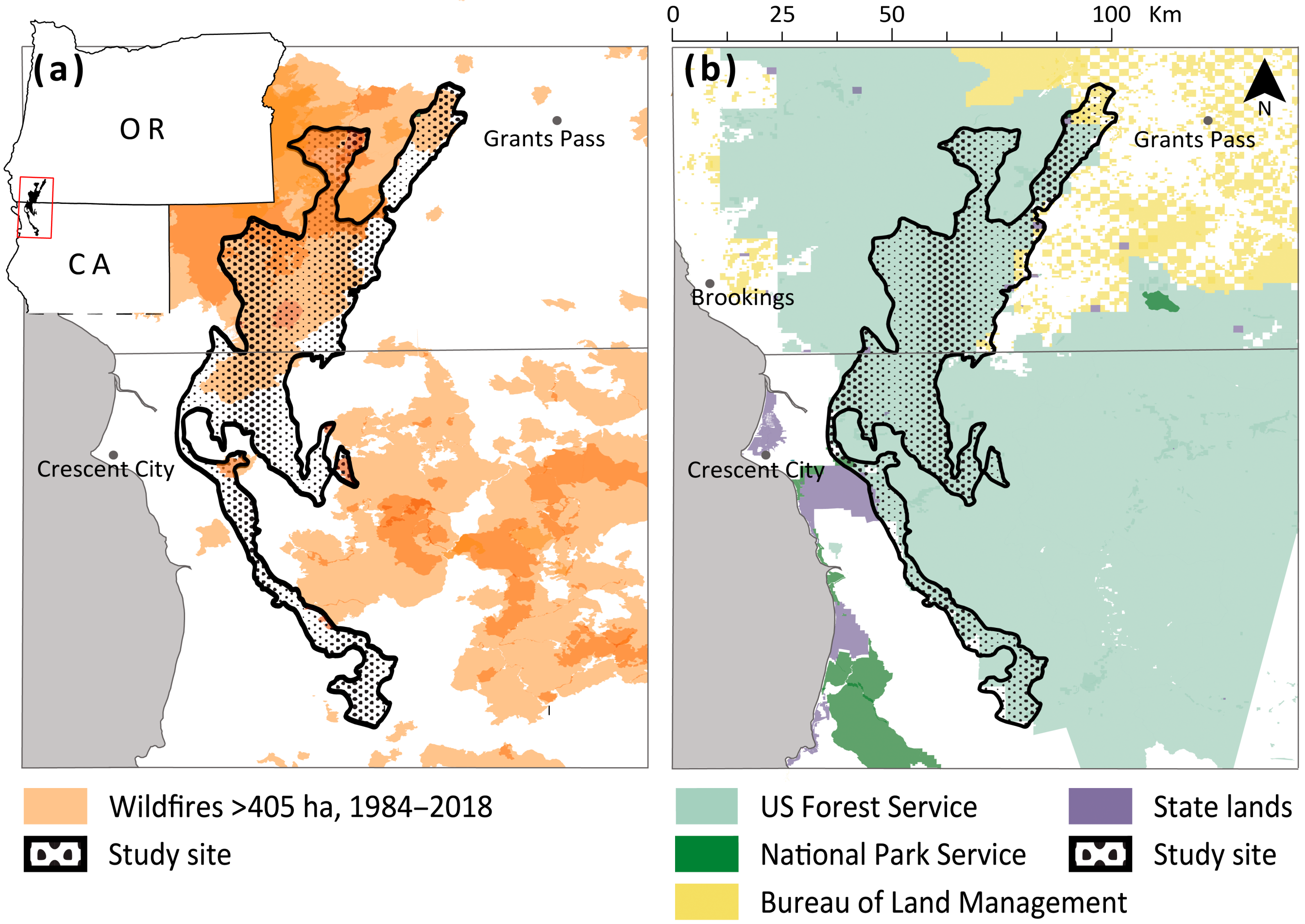

FIGURE 1 Simulated study landscape. (a) Wildfires greater than 405 ha (1000 acres) in size occurring across the study area between 1984 and 2018. Reburn areas are indicated by a darker hue on the map. *Source*: USDA Forest Service and US Geological Survey (2021a). (b) Land ownership of the study area and surrounding area. *Source*: USGS Gap Analysis Project (2020).

grow in the nutrient-poor soils. The study area is currently managed by the Rogue River and Six Rivers National Forests (91.4%), with a small portion of the remaining landscape managed by private entities (8.3%), the Bureau of Land Management (1.2%), and Oregon and California state parks and recreation departments (0.1%, Figure 1b). The landscape was traditionally stewarded by Indigenous peoples whose descendants are today members of the Coquille Tribe, Cow Creek Band of the Umpqua, the Confederated Tribes of the Siletz, the Confederated Tribes of Grand Ronde, the Tolowa Dee-ni' Nation, Karuk Tribe, Yurok Tribe, and the Shasta Indian Nation.

Overview of simulation model

Using the raster-based dynamic forest landscape model LANDIS-II (Scheller et al., 2007), we simulated changes in C storage and fire regimes within our study landscape in the Siskiyou Mountains. This model has been widely used to simulate forest succession and response to disturbance, treatment, and climate change scenarios in the western United States (Cassell et al., 2019; Duveneck et al., 2014; Liang et al., 2018; Serra-Diaz et al., 2018; Syphard et al., 2011). We chose the LANDIS-II modeling framework due to its unique ability to simulate the effects of climate change, prescribed fire, and wildfire on forest succession and C at a landscape scale over long time periods.

LANDIS-II uses species' life history attributes to simulate vegetation change driven by disturbance and succession (Mladenoff, 2004; Scheller et al., 2007). LANDIS-II simulates species-age cohorts, meaning species are discretely grouped into user-specified age bins that are altered simultaneously by disturbance, succession, and management. Each species is parameterized with its own life history attributes, such as shade and fire tolerance, longevity, and seed dispersal ability, and is responsive to changes in climate due to optimal temperature ranges and drought tolerance. Processes, such as competition, growth, and mortality, are simulated independently for each species-age cohort within each site, while other processes, such as fire and seed dispersal, are spatially interactive and are simulated both within and across sites.

We used the LANDIS-II core v7 with the Net Ecosystem Carbon and Nitrogen (NECN) succession extension v6.9 (Scheller, Hua, et al., 2011) to simulate forest growth, reproduction, and mortality. NECN tracks soil C and nitrogen pools and fluxes while limiting cohort growth based on leaf area index (LAI), soil water availability, temperature, growing space capacity, and nitrogen availability at monthly time steps (Lucash et al., 2018; Scheller, Van Tuyl, et al., 2011). Climate inputs to NECN include temperature, precipitation, relative humidity, and wind speed and direction.

Wildfire, prescribed fire, and forest harvesting were simulated across the landscape. The Social-Climate Related Pyrogenic Processes and their Landscape Effects (SCRPPLE) v3.2 extension was used to simulate natural, human-accidental, and prescribed fire as separate processes (Scheller et al., 2019). At daily time steps, the probability of wildfire ignition, spread, and mortality is calculated for each site based on fire weather index, topography, and vegetation dynamics. Fire spread and species mortality resulting from fire are based on user-defined inputs and algorithms in the model dictating ignition, intensity, and suppression for each of the three types of wildfires. To simulate forest harvest and management, we used the Biomass Harvest extension v4.4 (Gustafson et al., 2000). This extension simulates the removal of biomass through harvesting activities and the replanting of species following harvest. User-defined prescriptions dictate the amount of biomass removed from specified species-age cohorts within forest stands. The Dynamic Biomass Fuels Extension v3.0.1 was used to determine fuel types and amounts across the landscape (Syphard et al., 2011). This extension is required by the Biomass Harvest extension to inform where harvest occurs on the landscape based on fuel loads.

Model parameterization, validation, and calibration

All R scripts used to parameterize, validate, and calibrate model inputs are available in Deak and Lucash (2024). Data sources used to parameterize model inputs and perform calibration are included in Appendix S1.

Climate regions

NECN requires grouping sites throughout the study landscape into homogenous climate regions. Three climate regions were delineated within the study landscape based on 30-year average (1991–2020) precipitation, maximum temperature, and minimum temperature values for months during the growing season (i.e., months with an average temperature greater than 5°C) at 4-km resolution from the PRISM Climate Group (2021). Unsupervised classification using K-means clustering and Clustering Large Applications (CLARA) delineated three climate regions on the study landscape; the K-means clustering analysis produced a larger silhouette index (i.e., a measurement of how well clusters have been classified), indicating better overall performance. The output from this analysis was used to generate three climate regions from which homogenous daily climate is simulated (see Appendix S2 for workflow).

Simulated climate scenarios

Daily historical and future climate data were retrieved from the USGS Geodata Portal (https://cida.usgs.gov/gdp/) for each of the three climate regions. For our climate change scenarios, we used statistically downscaled global climate model (GCM) data from CMIP5 (Taylor et al., 2012) using a modification of the Multivariate Adaptive Constructed Analogs method (Abatzoglou & Brown, 2012). Predicted daily precipitation (in millimeters), minimum and maximum relative humidity (in percentage), maximum near-surface air temperature (in kelvin), wind speed (in meters per second), and wind direction (northing and easting) were obtained using area-weighted grid statistics for each of the three climate regions. We selected the CNRM-CM5 climate model to represent historical data (1950–2005) due to its availability through the USGS Geodata Portal and its strong predictive performance in the Pacific Northwest (Rupp et al., 2013). To simulate historical climate, annual data were randomly selected during each year of the simulation. We simulated two high-emissions (GCM 8.5) climate scenarios to capture the spectrum of predicted climate change across the climate regions identified on the landscape for the period 2021–2070. The first represents a large increase in annual precipitation with a moderate increase in temperature (henceforth, the “warmer/wetter” scenario). The second represents a large decrease in precipitation with a larger increase in temperature (henceforth, the “warmer/drier” scenario; Table 1).

Initial vegetative communities

We developed a map of initial species’ age and biomass by interpolating USFS Forest Inventory and Analysis (FIA) data (USDA Forest Service, 2022a) based on gradient nearest neighbor (GNN) maps developed by the Landscape Ecology, Modeling, and Mapping Analysis (LEMMA) group (Ohmann & Gregory, 2002). Species distribution, stand age, and forest type at a 30-m resolution from LEMMA were masked to the study landscape extent and FIA plots were iteratively assigned to each site based on whether species composition, forest type, and/or stand age within FIA plots matched the LEMMA GNN maps. Sites designated as developed, industrial, open water, and agricultural were made inactive. A total of 666 unique vegetative communities were distributed across the study area.

Shrub species (grouped by genus) identified within greater than 10% of FIA plots within the defined study landscape were simulated (see Appendix S3 for full list of species simulated). Tree ages were computed using the large tree height growth equations from the USFS Forest Vegetation Simulator (Keyser, 2019). Shrub ages were based on stand age from the corresponding FIA plot (see Appendix S4) because height growth equations were not available from the USFS Forest Vegetation Simulator. Initial tree biomass was estimated by FIA using the component ratio method (Woodall et al., 2010). Initial shrub biomass was calculated for each shrub functional group using allometric equations from Riccardi et al. (2007) based on plot-level FIA data for species height and cover percent (see Appendix S5 for initial aboveground C comparisons with FIA-derived aboveground C estimates). Species parameters were obtained from the literature and available datasets (see Appendix S1). The sources used to

TABLE 1 Simulated climate scenarios.

Climate scenario (years simulated) (CMIP5 climate model)	Climate region	Mean annual precipitation (mm)	Maximum temperature (°C)	Minimum temperature (°C)
Contemporary (1950–2005) (CNRM-CM5)	1	160	18.4	4.9
	2	267	17.7	5.6
	3	340	17.1	5.0
Warmer/drier (2021–2070) (GCM8.5 MIROC-ESM-CHEM)	1	−57	+4.1	+3.5
	2	−95	+3.4	+3.0
	3	−123	+4.0	+3.4
Warmer/wetter (2021–2070) (GCM8.5 CNRM-CM5)	1	+40	+2.8	+3.0
	2	+59	+2.3	+2.5
	3	+77	+2.6	+2.8

Note: For the climate change scenarios, the change in average annual precipitation, maximum daily temperature, and minimum daily temperature in the climate change scenarios for each climate region is shown. Changes in precipitation and temperature for climate change scenarios are the difference between the five-year averages of temperature variables at the beginning (2021–2025) and end (2066–2070) of the simulated climate change scenarios.

parameterize each functional group are available in Appendix S6.

We validated initial communities across the landscape by comparing the distributions of each site of the simulated landscape's LAI during June of the first time step to the MODIS Level-4 LAI product (Myneni & Park, 2015) and LAI values calculated from the ICESat-2 ATL03 product (Neumann et al., 2021) using the methods described by Zhang et al. (2021). LAI is a unitless measurement of canopy foliage, considered a reliable proxy for aboveground net primary productivity (ANPP) (Asner et al., 2003). The distribution of simulated LAI values fell within the range of values expected by these datasets, though spatial agreement was poor (for more information, see Appendix S7).

Soils

NECN requires soil inputs to simulate forest succession and calculate species growth within sites. Soil depth, drainage class, percent sand, and percent clay data were acquired from the UCDavis SoilWeb application (Walkinshaw et al., 2020). The UCDavis SoilWeb application aggregates current US Department of Agriculture Natural Resource Conservation Service soil survey data across all soil layers within 800-m grid cells. Soil C and nitrogen were calculated based on soil C estimates in 20-cm layers down to a 1-m depth from the Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics (West, 2014). These data were summed across depths; previously published ratios of C and nitrogen within each soil pool were used to divide the total soil pool into the active, slow, and passive soil pools in NECN (Parton et al., 1987, 1988). Field capacity and wilting point data were calculated using STATSGO shapefiles, based on the volumetric content of soil water retained at a tension of 1/3 bar and 15 bars, respectively (Schwarz & Alexander, 1995). The initial amount of belowground dead coarse roots was interpolated across the landscape from FIA data (USDA Forest Service, 2022a) based on C estimates from coarse roots greater than 2.54 m in diameter and multiplied by 44% based on the ratio from Mattson and Zhang (2019). Surficial dead woody material was derived from Wilson, Woodall, and Griffith's (Wilson et al., 2013) forest C stocks of the contiguous US dataset (2000–2009).

Fire

We derived lightning- and human-caused wildfires as well as prescribed fire parameters based on empirical data. Between 1992 and 2018, an average of seven wildfires were ignited within the study area annually, burning an average of 8243 ha/year (Figure 1b). Human-caused ignitions were the most common source, making up 65% of all ignitions (Short, 2021). Kernel density maps of historical ignition locations of lightning and human ignitions (Short, 2021) were used to determine each site's probability of ignition. Simulated wildfires (Figure 2) were calibrated to closely match annual area burned (mean: 8243 ha), size (mean: 1239 ha), and average severity (50% low, 26% moderate, 24% high) for the period 1984–2019 in the study area (see Appendix S8; USDA Forest Service and US Geological Survey, 2021b). Fire spread in SCRPPLE is based on an empirical relationship between historical daily fire spread and fire weather index, effective wind speed calculated from slope, uphill slope azimuth, wind speed, wind direction, and fine fuel loading in each site on the day of fire spread (Scheller et al., 2019). Spread is moderated based on user-defined suppression parameters. We parameterized maximum suppression to occur on sites within the wildland–urban interface (i.e., zones of transition between the developed and natural environments with higher wildfire risk), moderate suppression to occur on sites representing roads, and light suppression to occur on sites representing ridgelines. We parameterized the model so that fires ignited by lightning in wilderness areas would not be suppressed.

Fire severity in SCRPPLE is modeled as a nested process, representing severity as the differenced Normalized Burn Ratio (dNBR) for each site on the landscape burned during a fire event (Scheller et al., 2022); dNBR is a commonly used index calculated from remotely sensed imagery to assess wildfire severity based on changes in the spectral responses of vegetation in burned areas.

Mortality at the site scale is based on the relationship between mortality (USDA Forest Service and US Geological Survey, 2021a) and effective wind speed, the previous year's climatic water deficit and actual evapotranspiration (Abatzoglou et al., 2018), fine fuel loading (calculated by LANDIS-II), and ladder fuels (LANDFIRE, 2014) on the day of spread. Site-level mortality is scaled to approximate dNBR (Robbins et al., 2022). Species-age cohort mortality is derived based on species' bark thickness, a measure used by the model to determine species' susceptibility to mortality at different fire severities. Bark thickness was parameterized using empirical values from the Fire and Tree Mortality Database (Cansler et al., 2020) and bark thickness coefficients from the First Order Fire Effects Model (Hood & Lutes, 2017) when empirical values were unavailable.

The severity of wildfires and sites affected by wildfire were categorized using a dNBR threshold for low-, moderate-, and high-severity classes of fire severity

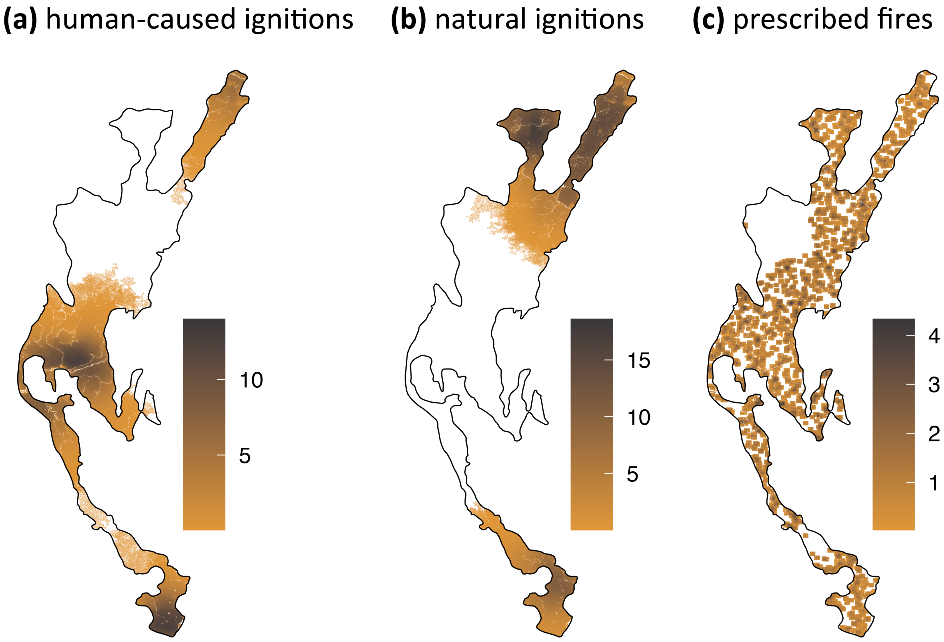

FIGURE 2 Mean number of (a) human-caused ignitions, (b) natural ignitions, and (c) prescribed fires on each site across all 50-year simulations. The simulated mean fire return interval for all scenarios was 8.5 years and the median fire return interval ranged from 2.7 to 4.2 years.

occurring within the study landscape. Fires occurring within a 1-km buffer of the study area from 1984 to 2019 were subset from the Monitoring Trends in Burn Severity (MTBS) fire occurrence dataset (USDA Forest Service and US Geological Survey, 2021b) and analyzed. Each fire in the MTBS dataset has significant burn-severity thresholds determined by analysts based on the range of dNBR and relativized dNBR values found (Eidenshink et al., 2007); dNBR values consistently less than 200 were identified as low severity, between 200 and 439 as moderate severity, and values equal or greater than 440 as high severity within the study landscape.

Prescribed fires were parameterized to burn at the lowest severity class and were randomly distributed across the landscape outside of wilderness areas (Figure 2c). Only one prescribed fire could be ignited each day and only during favorable climatic conditions based on relative humidity, fire weather index, wind speed, and temperature thresholds. Four prescribed fire scenarios were simulated, representing (1) no prescribed fire (henceforth the "No-Rx" treatment scenario), (2) business-as-usual, (3) a moderate increase, and (4) a large increase (Table 2). In the business-as-usual treatment scenario (1x-Rx), we simulated the average number and size of prescribed fires that occurred across the study area annually between 2002 and 2021 (five prescribed fires between 1.6 and 54 ha, with a mean size of 14 ha) based on historical data derived from the USGS National Fire Plan Operations Reporting System dataset (USGS, 2021). For the moderate increase treatment scenario (3x-Rx) and large increase treatment scenario (10x-Rx), the average number and size of prescribed fires were multiplied by 3 and 10 times, respectively. We chose the moderate increase scenario to examine how current treatment goals set by the USFS (USDA Forest Service, 2022b) may affect the study area and the large increase scenario to ensure the landscape experienced a strong response to prescribed fire. For context, under the 10x-Rx treatment scenario, an average of 0.84% of the landscape was prescribed burned annually while wildfires burned an average of 1.8% of the landscape annually under all scenarios. Given the shape and size of the simulated landscape, a larger increase in prescribed fire frequency and extent was not feasible.

Timber harvesting

Timber harvest was simulated using the business-as-usual scenario developed by Maxwell et al. (2020) based on 2012 county-level timber receipts and reports from National Forests within the Klamath ecoregion. Harvesting was parameterized to occur on private industrial lands in the form of clear cuts and on Federal lands with a goal of promoting old-growth characteristics through thinning operations. Harvest was parameterized to treat 278 ha of the landscape every five years within each of our model runs (see Appendix S9).

TABLE 2 Number and maximum possible size of prescribed (Rx) fires simulated during each treatment scenario and the mean and SD of annual area burned by prescribed fire across all simulated treatment scenarios.

Prescribed (Rx) fire scenario	No. Rx fires ignited annually	Maximum Rx fire size (ha)	Percentage of total landscape burned by Rx fires annually	Area burned by Rx fires annually	
				Mean	SD
No prescribed fire (No-Rx)	0	0	0	0	0
Business-as-usual (1x-Rx)	5	14	0.01	70	0.6
Moderate increase (3x-Rx)	15	48	0.08	629	6.3
Large increase (10x-Rx)	50	140	0.84	6686	534.0

Although mechanical treatments, such as thinning operations, are often a precursor to prescribed fire application (McIver et al., 2012; Stephens et al., 2012), our study was focused solely on the widespread application of prescribed fire, and the interaction between fire and thinning was outside the scope of this study.

Simulations and analysis

To isolate the effects of prescribed fire on vegetation and fire regimes under climate change, 12 scenarios were simulated using combinations of each climate and treatment scenario for a 50-year period. Each scenario was replicated three times for a total of 36 model runs (i.e., 3 climate scenarios × 4 prescribed fire scenarios × 3 replicates = 36 model runs).

All data processing, model parameterization, model calibration, and data analyses were completed using R v4.2.0 (R Core Team, 2022) in RStudio 2022.02.03 (RStudio Team, 2022) with the following packages: dplyr (Wickham et al., 2022), ggplot2 (Wickham, 2016), and terra (Hijman, 2022).

At the local scale of 30-m sites, the effect of prescribed fire was evaluated based on average annual C storage and wildfire burn severity. The effect of increasing prescribed fire frequency on C storage was analyzed by isolating sites with increasing frequencies of prescribed fire applied at specified and equal intervals to sites that had experienced a high-severity wildfire within the first five years of the simulation and calculating the mean aboveground, belowground, and total C storage within each site at each time step. Similarly, to evaluate the effect of prescribed fire on wildfire burn severity at the local scale, as measured by dNBR, we isolated sites across climate and treatment scenarios and compared the proportion of sites burned at high severity where wildfire was not preceded by prescribed fire with sites burned in wildfire events within the subsequent two decades following prescribed fire. Each burned site was further analyzed to find the slope, aspect, and dNBR value during wildfire events, considering landscape position (aspect and steepness) as first-order controls on biomass production (Quadri et al., 2021) and soil C storage (Hunter et al., 2023; Roering et al., 2023) in response to disturbance and climate. dNBR values were averaged across repetitions of simulations based on their slope (greater than or less than 30°), aspect (north- or south-facing), and climate region during the first and last 25 years of simulations by climate and treatment scenarios.

At the landscape scale, for each unique climate and management scenario, we analyzed the average total C (i.e., aboveground and soil organic C combined), belowground C (i.e., soil organic C), and aboveground C. We further assessed the mean cumulative aboveground C lost and area burned during all fires (i.e., prescribed fires and wildfires combined) and high-severity wildfires alone. ANPP and net ecosystem exchange (NEE) were calculated across the landscape for each repetition and analyzed by treatment and climate scenario. To understand how treatments affected wildfire spatially, we calculated the average number of hectares burned by wildfires and high-severity wildfires alone and the mean fire rotation across repetitions.

RESULTS

We simulated four prescribed fire scenarios, representing (1) no prescribed fire, (2) business-as-usual, (3) a moderate increase, and (4) a large increase. At the local "site" scale, prescribed fires lowered the severity of projected future wildfires and maintained carbon storage when reapplied three times over 50-year simulations. Prescribed fire was found to most effectively lower wildfire severity on north-facing aspects, on slopes less than 30°, and within areas that experience greater precipitation. At the landscape scale, increased frequency and extent of prescribed fire decreased the likelihood of combustion, thus increasing the likelihood of maintaining C storage, during wildfire events, but prescribed fire did not significantly decrease the projected severity and extent of wildfires at a landscape scale. At landscape to regional scales, we estimated limited benefits of prescribed fire even under large increases in extent (up to 10 times the current levels). Overall, our results show strong scale-dependency in ecosystem responses to prescribed fire, as follows.

Local scale

The effects of prescribed fire and high-severity wildfire were compared by analyzing sites where each fire type occurred within the first five years of the simulation, but wildfire and prescribed fire did not interact (Figure 3). One prescribed fire in the first five years of the simulation resulted in greater long-term increases in C storage relative to one high-severity wildfire in all climate scenarios. This was most notable in the warmer/drier climate scenario, where sites with one prescribed fire in the first five years experienced an average gain of 103 Mg C ha^{-1} in total C (above + belowground C) storage over the 50-year simulation. In contrast, sites with one high-severity wildfire within the first five years of the simulation only recovered an average of 78.2 Mg C ha^{-1}. These results demonstrate the threat high-severity wildfires pose to C storage in these ecosystems.

Generally, increased prescribed fire frequency on sites resulted in a greater decline in total and aboveground C and less accumulation of belowground C. Reductions in

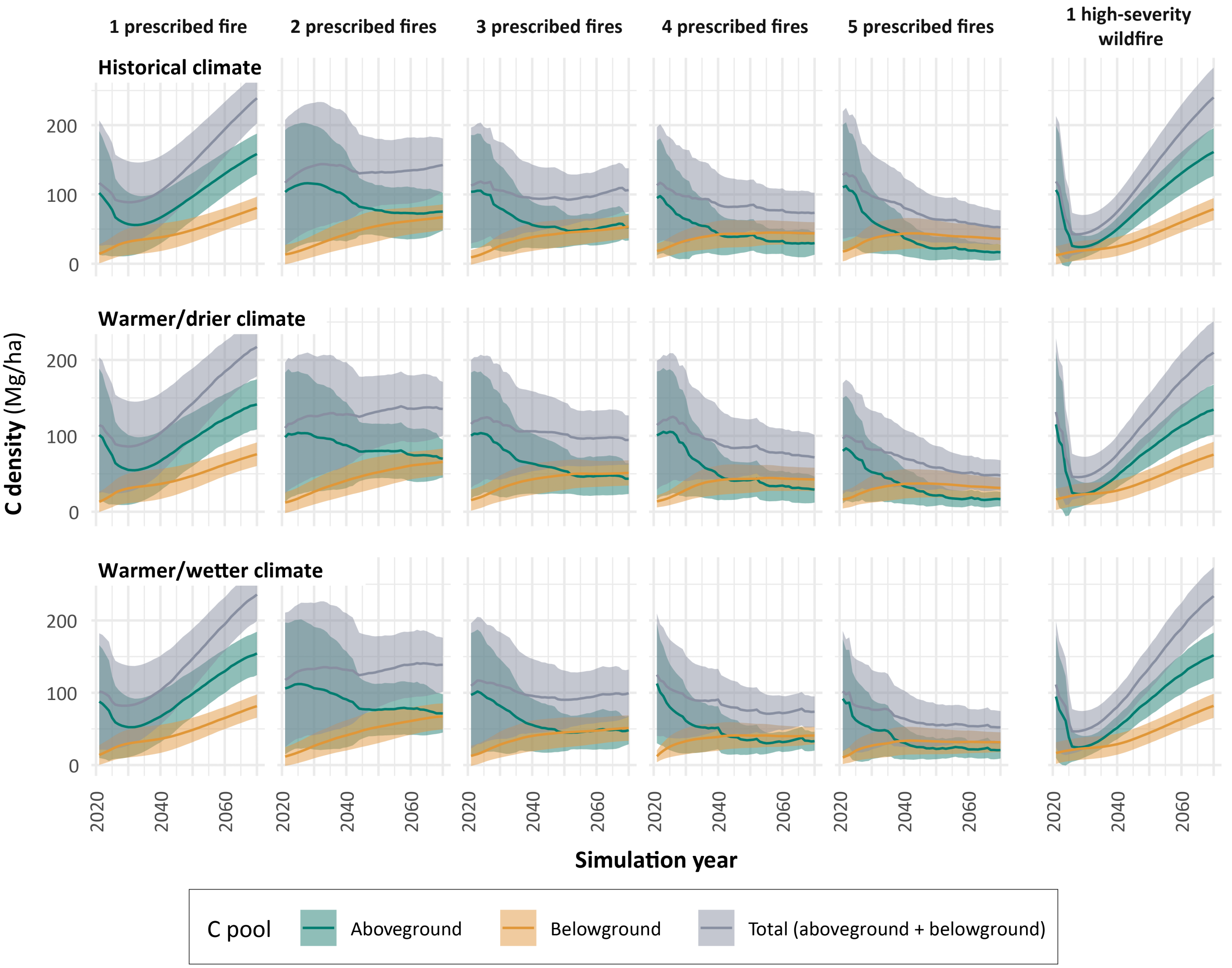

FIGURE 3 Site-level results for projected mean carbon (C) density in sites with increasing frequencies of prescribed fire and one high-severity wildfire through model year 2070. Sites analyzed with increasing frequencies of prescribed fire were not impacted by wildfire during the simulation and had prescribed fire applied at specified and equal intervals. Sites analyzed with one high-severity wildfire had only one wildfire occurrence during the first five years of the simulation. Plots are faceted vertically by climate scenario and horizontally by fire type and frequency. Ribbons of color represent ±SD across three replicates.

total C occurred on sites with more than two prescribed fires during simulations. While more than one prescribed fire on sites led to losses in aboveground C, belowground C storage increased despite increasing prescribed fire frequency. For example, the most significant declines in aboveground C storage occurred in cells with five prescribed fires in the historical climate scenario (mean of 93.8 Mg C ha^{-1}), but belowground C increased by an average of 18.2 Mg/ha. On average, the least change was seen in sites where three prescribed fires were applied (at roughly 15-year intervals), with declines of 6.6, 10.2, and 21.1 Mg C ha^{-1} in the historical, warmer/wetter, and warmer/drier climate scenarios, respectively.

Prescribed fire resulted in slight decreases in the likelihood of subsequent high-severity wildfire in all climate scenarios, but prescribed fire was least effective at lowering wildfire severity during the second decade following treatment (Figure 4). When the percentage of sites burned during high-severity wildfires was averaged across replicates, prescribed fire was most effective at limiting high-severity wildfire in the warmer/drier scenarios and least effective in the warmer/wetter scenarios (likely because of differences in precipitation altering regeneration and fuels accumulation under the differing scenarios). In the warmer/drier climate scenario, an average of 3.8% of sites without previous prescribed fire burned at high severity during wildfire events while 1.8% of sites with prescribed fire in the past 10 years burned at high severity. When burned within the second decade following a prescribed fire, an average of 2.2% of cells burned at high severity. In contrast, prescribed fire in a warmer/wetter climate scenario only reduced the average percentage of sites burned at high severity from 3.1% to 2.5% in the first decade following prescribed fire; in the second decade, this only increased by 0.1%.

To understand the interacting influence of topography and climate on wildfire severity at the local level of 30-m sites, the difference in mean dNBR during wildfire events was compared between the first and last 25 years of simulations across slope, aspect, and climate region (Figure 5). Sites in the climate region with the greatest annual precipitation had the largest average reduction in wildfire severity (dNBR) during 50-year simulations. In the historical climate scenario, there were minor reductions in severity during the No-Rx and 10x-Rx scenarios. However, increases in severity occurred on south-facing aspects in the wettest climate region (climate region 3) on south-facing aspects and on slopes greater than 30% in the No-Rx treatment scenario. Severity decreased across all topographies and climatic gradients in the 3x-Rx scenarios, with the greatest decreases in dNBR in the third (wettest) climate region on north-facing aspects and on slopes less than 30°. In a warmer/drier climate, severity decreased across nearly all climatic and topographical variables in the third climate region, except on sites with south-facing aspects, and there were notable increases in severity in the driest climate region. In a warmer/wetter climate scenario, severity also decreased across climatic and topographical

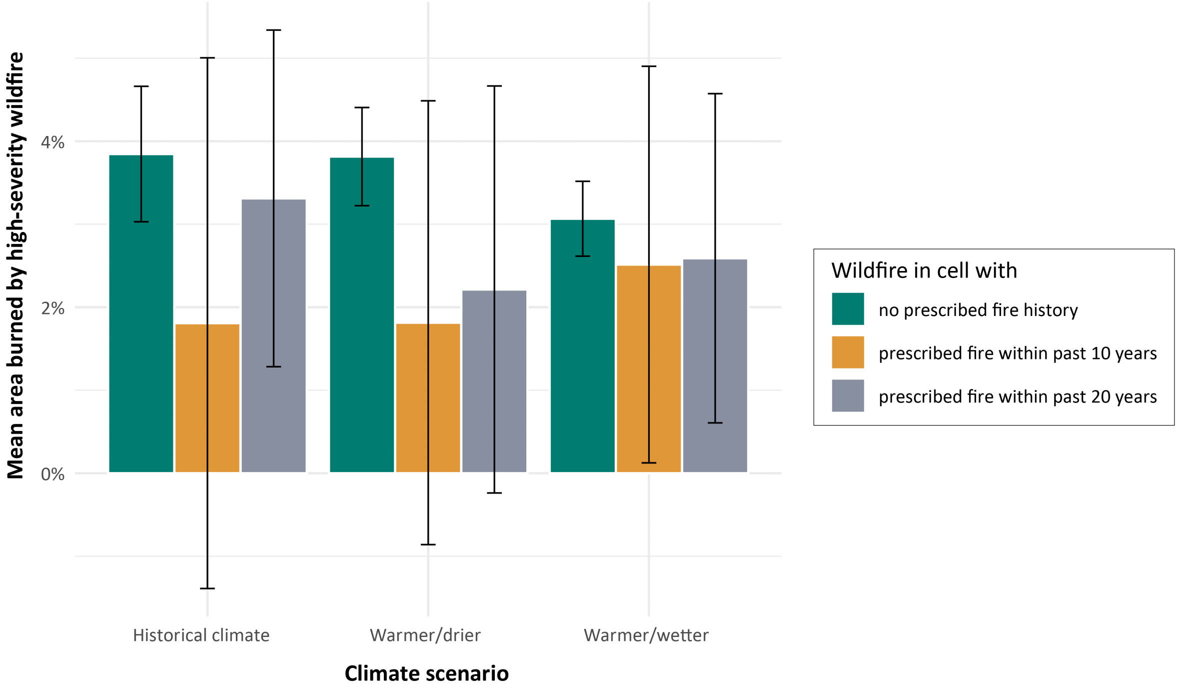

FIGURE 4 The mean proportion of area burned by high-severity wildfire without prescribed fire and within 10 and 20 years following a prescribed fire by climate scenario. Error bars represent ±SD across three replicates.

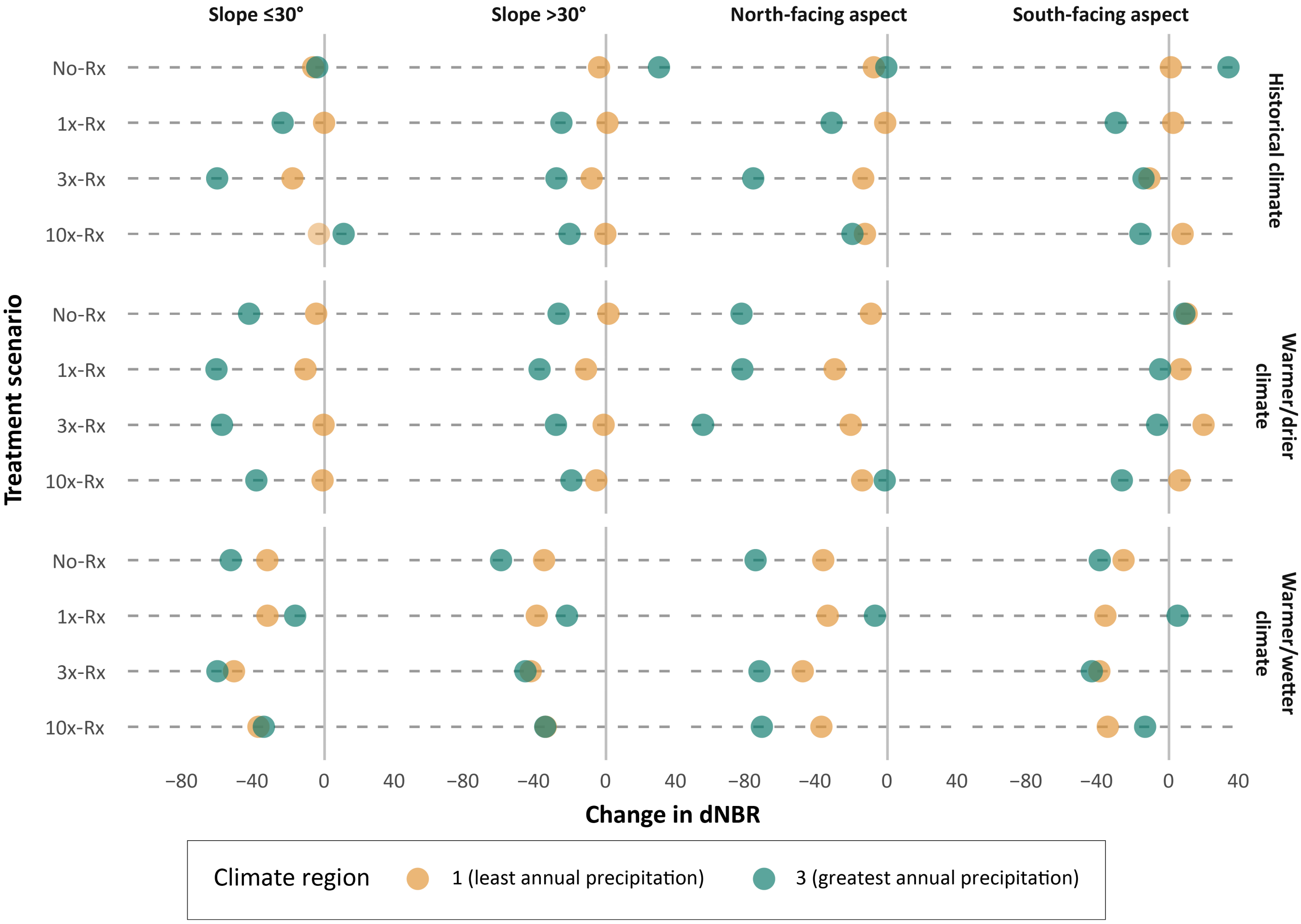

FIGURE 5 Change in mean burn severity (as calculated by differenced Normalized Burn Ratio [dNBR]) between the first and last 25 years of the simulation by treatment scenario and faceted by climate scenario and topographical variables (slope and aspect). The colors represent the climate regions with the least and greatest annual precipitation.

variables, although it slightly increased on south-facing aspects in the 1x-Rx scenario.

Landscape scale

At a landscape scale, aboveground C density declined across all climate and treatment scenarios, while belowground (soil organic) C increased over 50-year simulations (Figure 6). The least change in aboveground C density was produced from the No-Rx scenario under a warmer/drier climate (6.5% decrease) followed by the 1x-Rx scenario in the historical climate (9.4% decrease). Belowground C density showed similar trends in the No-Rx, 1x-Rx, and 3x-Rx scenarios, but the percent change in C density varied considerably, ranging from 224.5% in the 3x-Rx warmer/drier scenario to 255.7% in the No-Rx historical climate scenario. Overall, the largest decreases in aboveground C density and smallest increases in belowground C density occurred during 10x-Rx simulations, and this was most pronounced in a warmer/drier climate (47.1% decrease aboveground; 159.5% decrease belowground).

Combined, total C density increased across all scenarios, with the exception of the 10x-Rx scenario under a warmer/drier climate. The largest net increase in total C density occurred in the No-Rx warmer/wetter climate scenario (38.1%) followed by the 1x-Rx scenarios in the historical (36.5%) and warmer/wetter (35.8%) climate scenarios. Total C density in the 10-Rx warmer/drier climate scenario declined by 9.0%.

Similar to aboveground C density, ANPP declined most during the 10x-Rx scenario, with the greatest declines in the warmer/drier climate scenario (Figure 7). However, the landscape remained a net C sink in the 10x-Rx scenario across climate scenarios, as measured by NEE. NEE in the No-Rx, 1x-Rx, and 3x-Rx scenarios approached that of the 10x-Rx scenario, suggesting NEE may be lowered over the next 50 years in the study area, regardless of treatments due to lower ANPP and higher heterotrophic respiration.

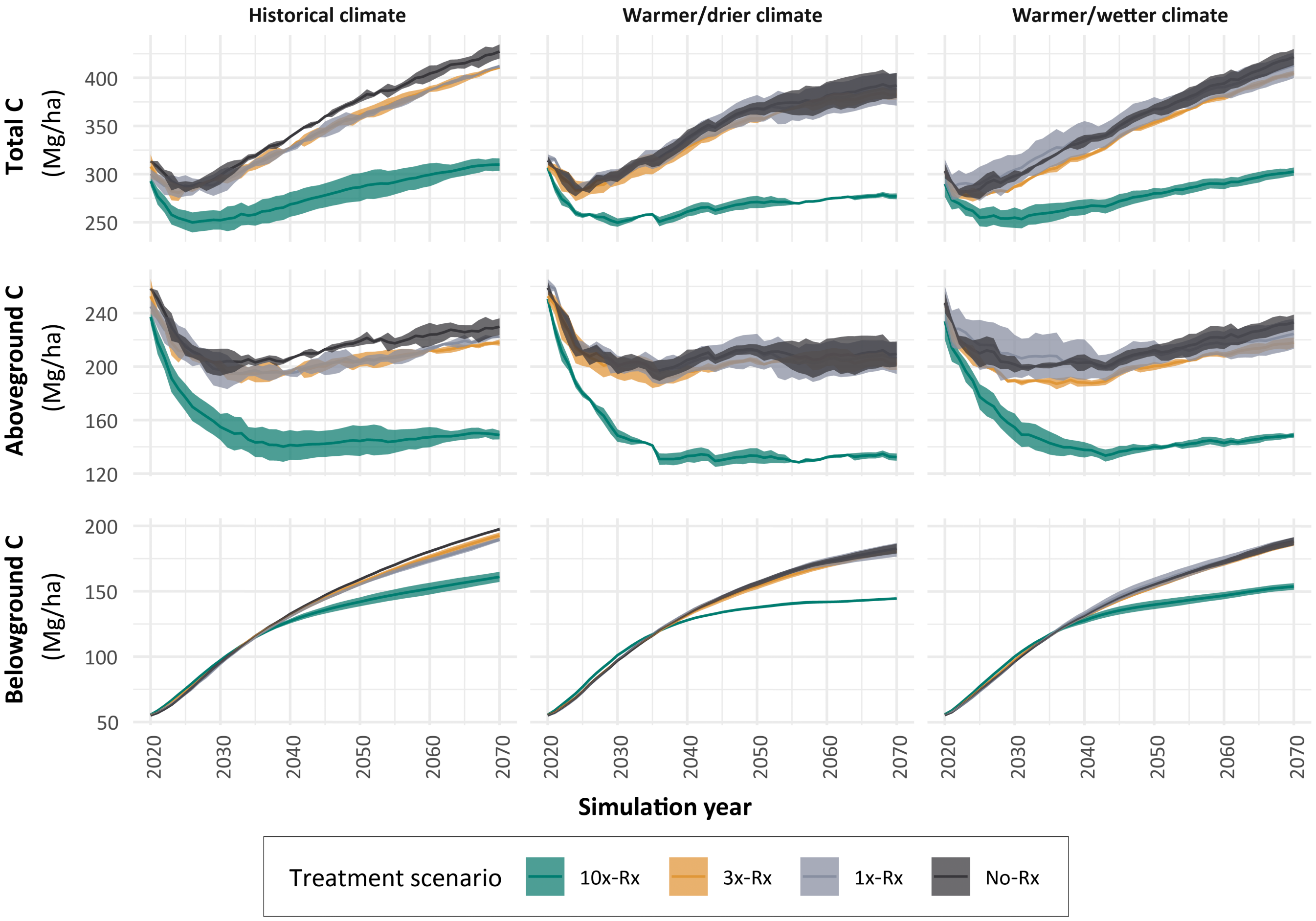

FIGURE 6 Landscape-scale results for carbon (C) density by climate and treatment scenario through model year 2070. Figure is faceted vertically by C pool, showing projected total (aboveground + belowground), aboveground, and belowground C density. Ribbons of color represent ±SD across three replicates.

The 10x-Rx simulations resulted in the greatest total aboveground C losses (i.e., emissions) resulting from all fires (both prescribed and wildfires combined), but the least loss from aboveground C consumption by wildfires alone (Figure 8). Total aboveground C consumed during all fires ranged from a mean of 1.7 million Mg in the 10x-Rx warmer/drier climate scenario to 1.1 million Mg in the No-Rx warmer/wetter climate scenario. The least amount of aboveground C was lost during the 10x-Rx historical climate scenario (8.7 million Mg) followed by the 10x-Rx warmer/wetter climate scenario (8.8 million Mg).

Mean cumulative area burned by wildfires was greatest in the warmer/drier scenario and least in the historical climate scenario, regardless of treatment scenario (Table 3). The lowest mean cumulative area burned by high-severity wildfires was in the 10x-Rx scenario in a historical climate (87,528 ha, 4.7% of area burned), No-Rx scenario in a warmer/wetter climate (98,810 ha, 4.6%), and 3x-Rx scenario in a warmer/drier climate (116,463 ha, 5.2%). The greatest average cumulative area burned by all wildfires (2,301,070 ha, 5.4%) was during the No-Rx warmer/drier climate scenario. Mean fire rotation, defined as the length of time for an area equal in size to the landscape to burn, only increased with increasing prescribed fire frequency in the historical climate scenario. Area burned at high severity, as measured by dNBR, was reduced by increasing prescribed fire under historical climate and the warmer/drier climate scenario, but this effect was dampened under the warmer/wetter climate scenario. The percentage of mean area burned by high-severity wildfire also declined under increasing levels of prescribed fire, except under the warmer/wetter scenario.

DISCUSSION

Understanding the effects of prescribed fire on ecosystem dynamics and C stocks is a critical step for the implementation of climate change mitigation and adaptation policies in the western United States. To advance the basic

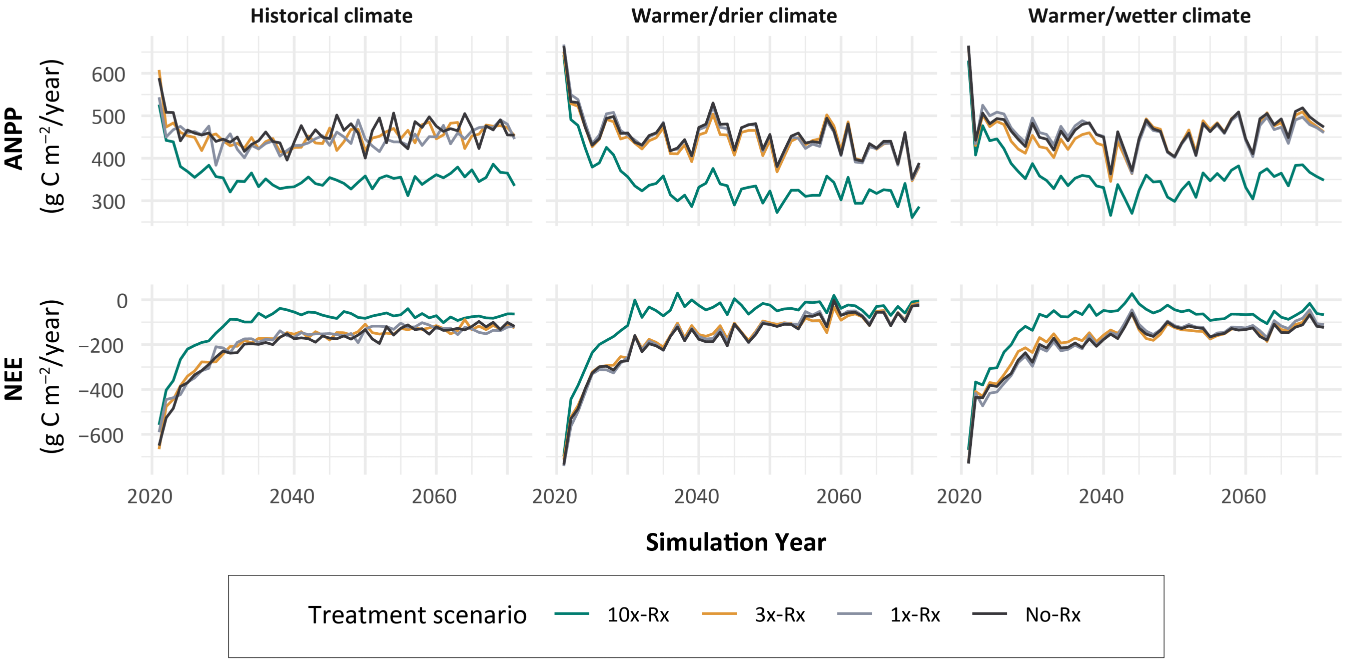

FIGURE 7 Landscape-scale results for mean aboveground net primary productivity (ANPP) and net ecosystem exchange (NEE) by treatment scenario through model year 2070. Figure is faceted vertically by climate scenario.

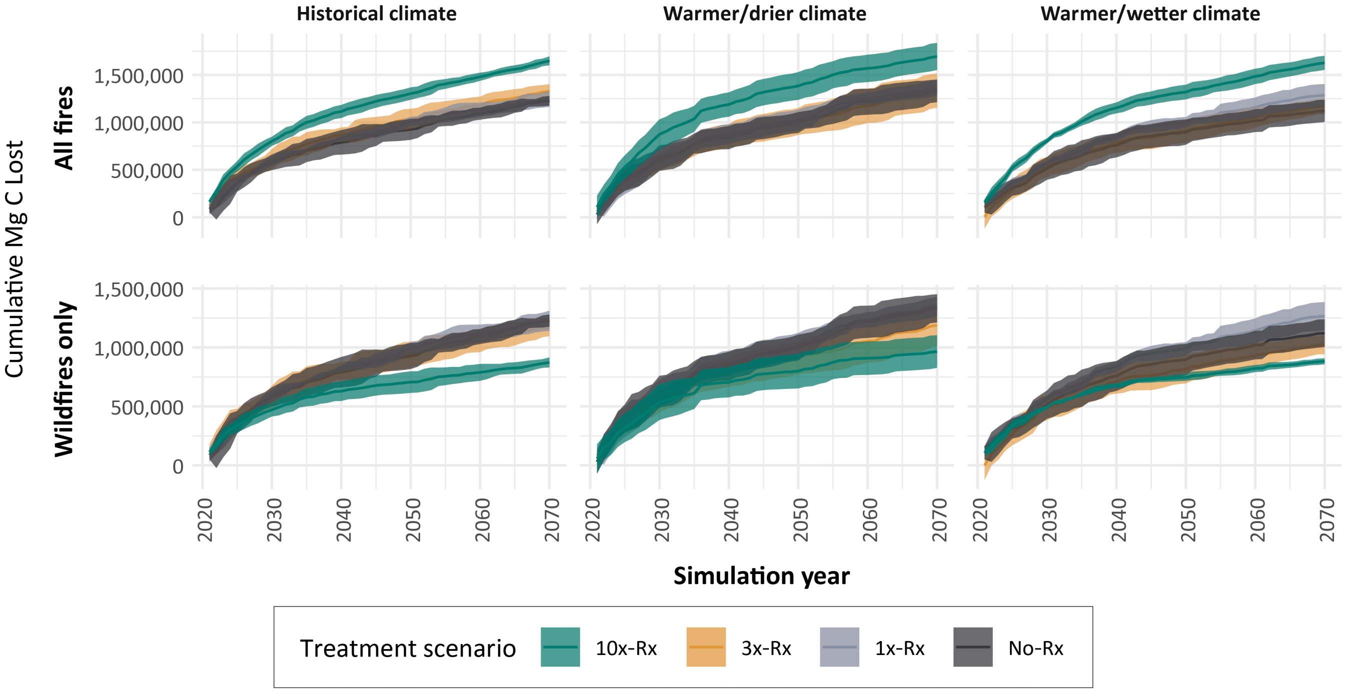

FIGURE 8 Landscape-scale results for cumulative aboveground carbon (C) lost due to all fires (both wildfires and prescribed fires) and wildfires alone, by climate and treatment scenario, through model year 2070. Ribbons of color represent ±SD across three replicates.

understanding and application of prescribed fires, we performed data-driven, process-based simulations to estimate how increasing the frequency and extent of prescribed fire in the Siskiyou Mountains of southwest Oregon and northwest California would affect fire regimes and C storage across a forested landscape. We expected a positive effect of high-frequency, low-severity prescribed fires on belowground C stocks and a reduction in high-severity wildfire. At the local site scale, our simulations confirmed our expectations, showing that prescribed

TABLE 3 Landscape-scale results for fire rotation (wildfires only) and cumulative area burned by all wildfires and high-severity wildfires over 50-year simulations across three replicates of each climate and treatment scenario (mean ± SD).

Climate scenario	Management scenario	Total area burned by wildfires (ha)	Mean fire rotation (years)	Area burned at high severity (ha)	Percent high severity
Historical	No-Rx	1,763,376 (±114,502)	13.7	87,748 (±6212)	5.0
	1x-Rx	2,039,422 (±105,356)	12.5	102,889 (±8679)	5.0
	3x-Rx	1,920,766 (±68,410)	13.3	93,390 (±6526)	4.9
	10x-Rx	1,867,858 (±20,598)	14.5	87,528 (±1047)	4.7
Warmer/drier	No-Rx	2,301,070 (±74,376)	11.4	124,887 (±5167)	5.4
	1x-Rx	2,284,365 (±148,222)	11.2	118,383 (±11,000)	5.2
	3x-Rx	2,226,134 (±102,105)	11.5	116,463 (±6338)	5.2
	10x-Rx	2,239,867 (±81,076)	11.1	116,524 (±5745)	5.2
Warmer/wetter	No-Rx	2,129,972 (±36,008)	11.4	98,810 (±859)	4.6
	1x-Rx	2,202,939 (±74,188)	11.6	100,273 (±4140)	4.6
	3x-Rx	2,201,803 (±45,114)	11.6	100,878 (±3755)	4.6
	10x-Rx	2,210,021 (±72,282)	11.4	101,196 (±4453)	4.6

Note: Percent high severity shows the proportion of mean area burned by high-severity wildfires throughout the 50-year simulations. Rx, prescribed.

fires lowered the severity of wildfires and maintained C storage when reapplied three times per 50-year simulation (i.e., at a roughly 15-year return interval). At the landscape scale, the frequency and extent of prescribed fire decreased the likelihood of C loss through combustion during wildfire events and maintained the landscape as a C sink, thus increasing the likelihood of maintaining C storage during wildfire events. Indeed, simulated biomass and soil C stocks showed little to no change, and in some cases continued to accumulate as expected with 10× the average frequency and extent of prescribed fire treatments.

Consistent with empirical studies of above- and belowground C responses to climate (e.g., Hunter et al., 2023; Quadri et al., 2021), we found that the climate region with the highest annual precipitation experienced the most significant change in wildfire severity, as indicated by differences in dNBR over 50 years. Under historical climate conditions, there was minimal change in wildfire severity in both the No-Rx (no treatment) and 10x-Rx (intense treatment) scenarios, except for increased severity on south-facing slopes and steep slopes (>30%) in the wettest climate region under the No-Rx scenario. When applying a 3x-Rx treatment scenario, which represents moderate management intervention, there was a decrease in severity across all topographies and climate gradients, with the most substantial reductions observed in the wettest climate region, particularly on north-facing slopes and gentler slopes (<30°). In scenarios simulating a warmer and drier climate, there was a general decrease in wildfire severity in the wettest climate region across most variables. However, this trend did not extend to south-facing aspects, and there was an increase in severity in the driest climate region. Conversely, in a warmer and wetter climate scenario, wildfire severity decreased across various climatic and topographical variables, but there was a slight increase in north-facing aspects in scenarios with standard treatment intensity (1x-Rx).

These findings suggest that climate and topography significantly influence wildfire severity, and that the effectiveness of fire management interventions varies depending on these environmental factors. Our results were also in line with previous studies finding topography as a strong influence on fire behavior in the Klamath-Siskiyou bioregion (Estes et al., 2017; Taylor & Skinner, 1998), with north- and east-facing slopes typically experiencing less severe wildfire effects given less direct solar insolation and higher fuel moisture values (Hessburg et al., 2016). Slope is also considered a critical variable affecting fire rate of spread, with steeper slopes rapidly increasing the rate of spread and fire intensity due to preheating of fuels upslope from the fire front (Butler et al., 2007). While slope position has been found to be a stronger predictor of fire behavior than slope within our study area (Alexander et al., 2006; Estes et al., 2017), our results showed prescribed fire may be a more effective treatment strategy on north-facing aspects and on slopes less than 30°, particularly in areas that experience greater precipitation.

Although prescribed fire was found to lower the severity of future wildfires at local scales, it was found to be relatively ineffective at decreasing the size of wildfires at a landscape scale when randomly simulated. Moreover, the effects of treatment on severity and area burned at a landscape scale were largely overshadowed by the effects of climate. Throughout our simulations, climate exerted a strong influence on mortality, fire spread, and severity, with distinct differences between climate scenarios. Under a warmer/drier climate, the landscape experienced greater area burned and C loss due to wildfire, likely due to differences in postfire conifer regeneration (as found by Serra-Diaz et al., 2018), drought pressures, and fire weather index on the day of ignition. However, prescribed fire was also found to be more effective for lowering wildfire severity at a local scale under a warmer/drier climate, offering a promising solution given the likelihood of this climate scenario. In our study area, the average annual temperature has already risen by 0.6°C since 1895, and most climate models predict greater overall warming and drier conditions during the summer (Miller et al., 2022).

As hypothesized, we found that increasing the application of prescribed fire by 3 and 10 times the contemporary prescribed fire frequency and extent reduced aboveground C emissions during wildfires alone (Figure 8). Although much of the public health concerns around smoke are related to $PM_{2.5}$ emissions (particulate matter less than or equal to 2.5 μm), 80%–90% of wildfire emissions are from carbon dioxide, and research has found organic C from biomass burning as a dominant component of summertime $PM_{2.5}$ emissions in the western United States (Jaffe et al., 2020). As greater attention is paid to public health issues stemming from long-duration hazardous air quality events during wildfire season, prescribed fire provides an opportunity to distribute emissions throughout the year when smoke may be regulated and more manageable due to more ideal burning conditions (D'Evelyn et al., 2022). Furthermore, implementing prescribed burns in southwest Oregon and northern California during these conditions may mitigate widespread and long-term smoke exposure to communities across the western United States (Kelp et al., 2023).

Our results also suggest that extensive prescribed fire treatments would be needed to significantly reduce wildfire risk and C emissions from wildfires at the landscape scale, but strategic and targeted landscape prioritization could be used as a tool to mitigate risks and promote stable C stores in critical areas. Increasing prescribed fire up to 10× current levels may be unrealistic as a mechanism for reducing C loss from wildfires and lowering wildfire severity regionally, but it could dampen wildfires, helping with the conservation of ecosystem C at the local to landscape scales. However, prescribed fire alone was not sufficient to significantly reduce the risk of wildfire at a landscape scale. Such a high level of prescribed fire is not new to the Siskiyou Mountains. As outlined above, Indigenous cultural burning and stewardship likely contributed significantly to the historical range of variability of the study area's forests by decreasing overall wildfire severity, limiting spread, and increasing heterogeneity of burned area mosaics. As a result of fire exclusion and the loss of widespread cultural burning, forests in the study region have experienced a nearly threefold increase in forest density that is increasingly vulnerable to large-scale, high-severity wildfire (Knight et al., 2022).

Reducing forest density through frequent prescribed fire promotes long-term C stability and increases the resilience of forests by reducing the vulnerability of forests to high-severity wildfire. However, this comes at the cost of short-term aboveground C storage and may only be realized if a wildfire interacts with treated areas (Goodwin et al., 2020; Krofcheck et al., 2019; Restaino & Peterson, 2013). Our results suggest these trade-offs at both landscape and site scales. Increased prescribed fire frequency and extent reduced cumulative C losses during wildfires (Figure 8), maintained the landscape as a net C sink (Figure 6), and slightly lowered the proportion of the landscape affected by high-severity wildfire in both the historical and warmer/drier climate scenarios (Table 3) but led to losses in total C storage at the landscape scale. At the local, site scale, the effectiveness of prescribed fire treatments for reducing wildfire severity declined with the length of time since treatment, with greater effectiveness during the first decade than second decade following treatment, but C storage decreased by nearly half when prescribed fire was applied at a frequency of 10 years. These results indicate that more prescribed fire is needed at appropriate intervals (~15 years) to reduce the impact of high-severity wildfires and to maintain forests, and the C they store, especially under an uncertain climate future. Given the unprecedented density of the region's forests due to fire exclusion, maintaining current C storage values may not be desirable for restoration. Higher rates of prescribed fire may be more appropriate to restore forests to the historic structure (characterized by greater heterogeneity and more open canopy structure) that led to their resilience (Hessburg et al., 2019), and our results demonstrate that these systems will continue to sequester C under these conditions.

Altogether, our simulations indicate that the implementation of prescribed fire must be informed by realistic system- or context-specific conditions, with attention paid to regional differentiation of social and ecological histories, as proposed for scalable climate change mitigation methods (Silva, 2022). Looking ahead, we propose targeting areas of high concern or value to decrease the risk of high-severity fire and to contribute to meeting climate mitigation in tandem with adaptation goals. Specifically, our results support the strategic and targeted landscape prioritization for prescribed fire to reduce

C emissions, reduce wildfire severity, and increase the pace and scale of forest restoration in areas of social and ecological importance. Our research builds on other simulation studies conducted in forests with mixed-severity fire regimes, finding the strategic and optimized placement of treatments effectively alters fire behavior across landscapes and could have the same effect with less area treated (Hessburg et al., 2016; Krofcheck et al., 2019; Loudermilk et al., 2014).

By targeting treatments (i.e., thinning, prescribed fire, and managed fire) through "pyrosilviculture," land managers have an opportunity to leverage existing treatments and take advantage of limited funding and capacity for fuels reduction projects to reduce wildfire risk at landscape scales (North et al., 2021; York et al., 2021). More targeted treatments using prescribed fires than simulated within our study, as well as the use of mechanical treatments to reduce fuel loading prior to prescribed fire, may also further the C benefits of prescribed fire application by reducing prescribed fire-related C losses (Krofcheck et al., 2019). Empirical research into the effectiveness and strategic placement of fuel treatments at a landscape scale remains lacking due to difficulties in design and implementation, and the use of modeling approaches is critical for understanding how treatments may be targeted to meet management objectives at a landscape scale (McKinney et al., 2022). We recommend future studies further investigate how treatments in the study area may be optimized for desirable landscape-level outcomes.

Caveats and limitations

Limitations are inherent with any modeling approach due to uncertainties in climate projections, parameterization with limited data, and simplification of ecological processes (Reyer et al., 2016). An apt example of this limitation is accounting for C within NECN does not include projections of pyrogenic C, a significant yet often overlooked C pool contributing to long-term C sequestration (Jones et al., 2020). It is also important to recognize that the study area exists within a larger landscape and was parameterized to only show the impacts of fires ignited within its borders. Although outside the scope of this study, forest management, climate change, and disturbance on the surrounding landscape also play a key role in determining the trajectory of fire regimes and vegetation within the study area and across the larger landscape. Lastly, due to the limited model repetitions and short modeling horizon of only 50 years, there remains much uncertainty in model projections, especially given the stochastic nature of wildfire.

CONCLUSION

As climate change mitigation strategies increasingly turn toward natural climate solutions, or the removal of carbon dioxide from the atmosphere through natural resources management techniques, forest management has received much attention for its ability to mitigate the global impacts of climate change through C sequestration (Chafe et al., 2024; Griscom et al., 2017). Although prescribed fire could be viewed as a threat to C storage given fire suppression has increased C storage in forests over the past century, current C stocks are increasingly vulnerable to combustion during high-severity wildfire events. Properly used at the correct frequency and locations, prescribed fire has the potential to maintain C storage while having tangible effects on other land management goals (Seipp et al., 2023).

The 2022 Wildfire Crisis Strategy (USDA Forest Service, 2022b) recognized the east slope of the Siskiyou Mountains as one of 29 landscapes at high risk for catastrophic wildfires with shovel-ready projects in the United States. It is important to consider how future treatments may impact the landscape, the appropriate frequency and extent of prescribed fire needed to restore fire-adapted ecosystems, and how differing climate change scenarios may affect how prescribed fire impacts the landscape. Our study showed that to meet wildfire risk reduction and climate change mitigation goals, more prescribed fire, including the revitalization of cultural burning, is needed in the Siskiyou Mountains. Our results suggest that by treating priority locations on public lands, forest managers can proactively reduce the likelihood that these areas will experience destabilizing effects on C storage, reduce the amount of C lost during wildfire events, and reduce the severity of wildfires. Coupling thinning treatments with prescribed fire and targeting topographical and climatic gradients were most effective for reducing wildfire severity (i.e., on north-facing aspects and slopes less than 30°) and may further improve the outcomes of these management actions under climate change. However, as prescribed fire was not enough to meaningfully reduce the severity and extent of wildfires at a landscape scale even at 10 times the current pace and scale of treatments, the pace and scale of treatments need to expand at a much faster rate to reduce wildfire risk.

AUTHOR CONTRIBUTIONS

Alison L. Deak conceived and designed the methodology and analysis, performed the analysis, and wrote the paper. Melissa S. Lucash, Michael R. Coughlan, and Lucas C. R. Silva contributed to the conception and design of the methodology, data analysis, and writing of this manuscript. Melissa S. Lucash and Shelby Weiss contributed to data and analysis tools.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Code and data (Deak & Lucash, 2024) are available from Zenodo: https://doi.org/10.5281/zenodo.10732408.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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