Research, part of a Special Feature on The Many Facets of Forest Resilience in the Lake Tahoe Basin

Comparing smoke emissions and impacts under alternative forest management regimes

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ABSTRACT. Smoke from wildfires has become a growing public health issue around the world but especially in western North America and California. At the same time, managers and scientists recommend thinning and intentional use of wildland fires to restore forest health and reduce smoke from poorly controlled wildfires. Because of the changing climate and management paradigms, the evaluation of smoke impacts needs to shift evaluations from the scale of individual fire events to long-term fire regimes and regional impacts under different management strategies. To confront this challenge, we integrated three widely used modeling tools to analyze smoke impacts across different management scenarios within a future of changing climate. We applied this multi-stage framework to a case study analysis in the Lake Tahoe basin, in which managers proposed scenarios that involved varying levels of hand- and mechanical-thinning treatments and prescribed fires. We began by using the LANDIS-II model to project daily emissions of fine particulate matter from wildland fires under various climate and management scenarios over a century. We also modeled dispersion and health impacts based upon individual wildfire events selected to be representative of different management scenarios. For those events, we modeled smoke conveyance to downwind communities from representative future fires using the BlueSky smoke dispersion model. Lastly, we estimated human health impacts resulting from the modeled smoke using the U.S. Environmental Protection Agency's BenMAP model. Our results suggest that emissions from wildfires will substantially increase in future decades; however, increased levels of forest thinning could substantially reduce those emissions and harmful health impacts from large wildfires. We also found that increased use of prescribed burning could reduce the health impacts associated with large wildfires but would also increase the frequency of low levels of emissions. Furthermore, the modeling results suggested that individual prescribed fires could have substantial health impacts if dispersion conditions are unfavorable. Our results suggest that increased management is likely to yield important benefits given expected increases in wildfire activity associated with climate change. However, there remain many challenges to projecting the effects of alternative management regimes, especially ones that involve substantial increases in intentional burning.

Key Words: *air quality; climate change; emissions; fine particulate matter; economics; health impacts; Lake Tahoe West; management regimes; modeling; prescribed burning; pile burning; wildfire smoke*

INTRODUCTION

Smoke exposure from wildfires is a growing problem in California and North America because of impacts to public health and associated social and economic values including outdoor recreation (Fann et al. 2018, Chen et al. 2021, Gellman et al. 2022). This health risk is expected to grow substantially over the coming decades due to climate change (Li et al. 2020, Burke et al. 2021). Wildfires are a significant concern within the Lake Tahoe basin because of their potential to damage forest and aquatic ecosystems, life and property, and air quality (Stevens et al. 2016, Abelson et al. 2021). The basin is prone to inversions that trap smoke from both local fires and fires in other parts of California (Gertler et al. 2010). Wildfire emissions add to other air pollutants originating within and being transported from long distances into the basin (Gertler et al. 2010). Consequently, smoke impacts have become a major concern for both land and fire managers and residents in the basin and wider region (Cisneros et al. 2018) (Fig. 1).
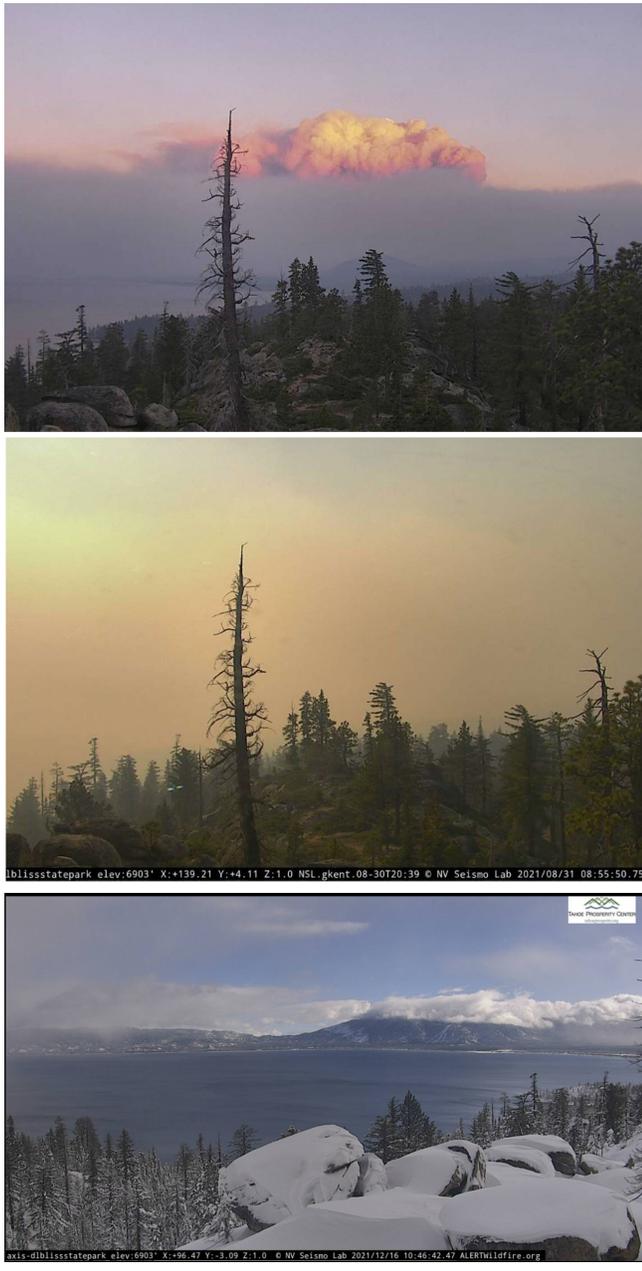
Managers and scientists have recommended treatments such as forest thinning and the use of wildland fire to restore forests, which in turn would reduce the health impacts of smoke from poorly controlled wildfires (Schweizer and Cisneros 2017, Schweizer et al. 2019, D'Evelyn et al. 2022). Thinning for forest restoration under such recommendations, and as typically applied in the basin, refers to the harvest of smaller trees along with reduction

of the resulting "activity fuels" through pile burning, mastication, or removal off-site (Safford et al. 2009, Harrison et al. 2016, Low et al. 2021). Use of wildland fire can include prescribed burning, management of naturally-ignited wildland fires to achieve resource objectives (North et al. 2021), and cultural burning by Indigenous fire practitioners (Long et al. 2021) (Fig. 2). Previous studies have compared smoke impacts from individual wildfires under alternative treatment scenarios (Navarro et al. 2016, Stevens et al. 2016, Schweizer et al. 2020). Calls to ramp up use of wildland fire, as well as expected increases in unplanned wildfires, require that evaluations shift from the scale of individual fire events to decades or centuries of landscape fire dynamics under different management strategies.

Our research was part of a broader evaluation of different management approaches for the Lake Tahoe West Restoration Partnership (https://www.nationalforests.org/who-we-are/regional-offices/california-program/laketahoewest). We sought to answer two questions that were important to managers and the broader public. First, how would different management scenarios compare in terms of smoke emissions over the long term? Second, under different management scenarios, how might emissions from extreme wildfire events (those producing the most intense emissions), as well as typical prescribed burn events, impact downwind human communities?

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Fig. 1. Visibility in the Lake Tahoe basin, as viewed by a webcam at D. L. Bliss State Park (within the study area) during the Caldor Fire on August 30 and 31, 2021, and on a relatively clear day on December 16, 2021. Credit: Alertwildfire.org.

Fig. 2. View of Baldwin Meadow following a prescribed burn, looking toward the Lake Tahoe West area, with the Emerald wildfire of 2016 visible in the background; meadows like this one are a priority for restoration and were traditionally burned by Indigenous Washoe people.

year of smoke dispersion poses a substantial computing challenge. To make an analysis of trade-offs more tractable, we sought metrics that could be computed relatively easily to approximate smoke impacts.
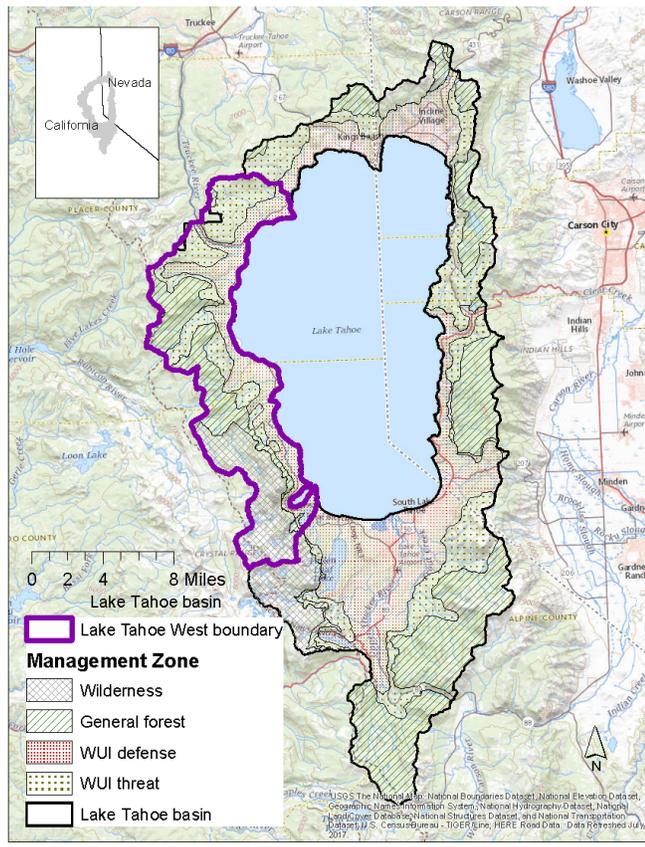
Projections of health impacts entail wide uncertainty due to variable dispersion and resulting population exposure (Long et al. 2018, Mueller et al. 2020). For example, smoke from the early summer Angora wildfire of 2007 was trapped in the basin and caused extreme particulate levels at locations directly within the plume (Cahill 2009). However, due to the ventilation dynamics in the Lake Tahoe basin, smoke emissions in the summer commonly disperse more than during the late fall, which has traditionally been the preferred period for prescribed burning (Cahill 2009). Low-intensity fires may not generate sufficient energy to loft smoke high into the air column where it can be more widely dispersed. Physiochemical processes cause the smoke emissions of wild and prescribed fires to differ in ways that are complex to model (Williamson et al. 2016). Accounting for dispersion is important, although it adds greater complexity to modeling effects of smoke. To demonstrate how different levels of $PM_{2.5}$ emissions may translate into health impacts, we modeled dispersion and health impacts of events that we selected to be representative of different management scenarios. As a final metric to help managers evaluate different management approaches, we considered the number of days of prescribed burning, both understory burning and pile burning, under each scenario.

METHODS

Study Area
The Lake Tahoe basin lies in the Sierra Nevada mountains along the boundary between California and Nevada, USA (Fig. 3). The basin includes approximately 134,000 ha ranging in elevation from 1900 to 3050 meters, with 36% of the area occupied by Lake Tahoe itself and 7% of the area occupied by urban development. The remaining surrounding lands are dominated by conifer forests with smaller areas of shrublands, meadows, aspen groves, and riparian areas. The United States Forest Service manages

We analyzed several metrics of smoke emissions that had been suggested as effective representations of air quality and potential health impacts in previous studies (Long et al. 2018, Striplin et al. 2020). Alternative management scenarios should be evaluated over long periods to account for the potential of treatments to mitigate future wildfire impacts. However, modeling the thousands of fires that are expected to burn over many decades is extremely computationally intensive; even modeling a single

Fig. 3. Map of the Lake Tahoe Basin, featuring the Lake Tahoe West study area and designated management zones.

Modeling fire and management regimes, emissions, and smoke impacts
We constructed our analysis based upon a previously proposed three-step framework (Long et al. 2018): 1) project daily smoke emissions, 2) project daily smoke dispersal based upon weather conditions, and 3) project smoke impacts on air quality conditions in health or economic terms (Fig. 4). This framework is comparable to one proposed by Williamson et al. (2016). Each step was associated with a different model, and we connected each step to evaluate overall outcomes. As a foundational step, we first needed to simulate the forest dynamics, including burning, that drive smoke emissions and impacts.

Fig. 4. Framework for modeling air quality impacts.
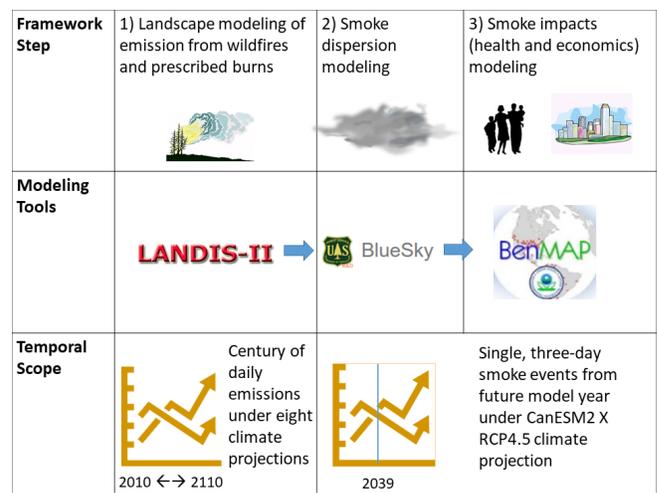
Projecting landscape dynamics based upon climate and management scenarios
We began by using the LANDIS-II integrated landscape change model (https://www.landis-ii.org/home) to forecast forest vegetation change and fire dynamics over a century (2010–2110) across different climate and management scenarios. LANDIS-II is a process-based simulation model that integrates forest growth and succession, climate change, and disturbances (Scheller et al. 2007). The model has previously been used to model landscape dynamics in the basin. As part of the Lake Tahoe West collaborative modeling effort, we ran the LANDIS-II model with the Net Ecosystem Carbon and Nitrogen (NECN) succession extension (v. 6.1)(Scheller et al. 2011), the Social-Climate Related Pyrogenic Processes and their Landscape Effects (SCRPPLE) fire extension (v. 2.1)(Scheller et al. 2019), and biomass harvest extension (v. 2.0) to simulate management activities and natural processes, and their interaction, over the century across the entire Lake Tahoe basin landscape. We ran the model with each pixel representing 100 m by 100 m (1 ha). Wildfires in the model are stochastic with ignitions varying spatially and temporally across the landscape. Reflecting complex terrain, shifting wind directions, and variable fuels, the model can simulate complex burns with patchy fire intensity including unburned patches (Scheller et al. 2019). The model generates outputs of burned areas with variable fire intensity classes that are considered

about 75% of the land area in the basin, with various state, local, private, and tribal landowners managing the rest. The basin lies in the heart of the ancestral territory of the Washoe Tribe of California and Nevada, which owns several parcels in the basin and also has been actively involved in cooperative restoration of meadows in the Lake Tahoe basin, including preparation to reestablish cultural burning (Davenport 2019). Forests at lower elevations in the basin burned frequently due to both lightning ignitions and burning by Washoe people to cultivate desired resource conditions, however, fire suppression since Euro-American colonization displaced both types of ignitions (Lindstrom 2000).

The Lake Tahoe West (LTW) study area includes over 23,600 ha on the western part of the basin. Like the rest of the basin, LTW has a high proportion of Wildland-Urban Interface (WUI) zones, which delineates developed areas amidst forests. Draining from the eastern slope of the Sierra Nevada, LTW has a higher proportion of wilderness (about one-quarter of its area) than the basin as a whole (Fig. 3), and it tends to have more mesic site moisture conditions (Beaty and Taylor 2008) than sites on the east side of the basin (Taylor 2004).

Table 1. Summary of management scenarios.

Scenario number	Summary	Annual average treatment of vegetated landscape	Forest thinning[†]		Prescribed burning		Wildfire management
			WUI Zones	Non-WUI Zones	Pile burning	Understory burning	
1	Fire suppression only	0%	None	None	None	None	Suppression of all wildfires in all zones
2	Wildland-urban interface (WUI) thinning	1.8%	Yes	No	Hand thinned areas	None	Suppression of all wildfires in all zones
3	Extensive and intensive thinning	6.7%	Yes	Yes	Hand thinned areas	None	Suppression of all wildfires in all zones
4	Fire-based approach	4.0%	Yes	No	Hand thinned areas	Target of 220 ha/y across all zones	Suppression of all wildfires in WUI zones, but ~40 ha/y of "managed wildfires," representing less active suppression of naturally-ignited fires in non-WUI zones
5	Extensive fire-based approach	7.2%	Yes	No	Hand-thinned areas	Target of 1050 ha per year across all zones	

[†]Forest thinning involved mechanical equipment with removal of biomass in areas near roads or thinning by hand-crews followed by pile burning in less accessible areas. Thinning treatments were limited from recurring no more than every 20 years in scenarios 2, 4, and 5, while they could recur every 11 years under scenario 3.
See the Supplemental materials for additional background on the LANDIS-II modeling of the management scenarios.

functionally equivalent to severity (Scheller et al. 2019). Multiple instances of the model are run to account for the effects of stochasticity on fire location and severity. This replication is important for better understanding of the impacts of management and climate scenarios on landscape fire behavior, as well as smoke emissions and air quality impacts.

The five management scenarios
The five management scenarios were developed through a collaborative process by an interagency team of resource managers that developed integrated goals and targets with input from agency decision-makers, technical experts, and stakeholder committees representing conservation, fire protection, recreation, homeowners and businesses, and local governments (Lake Tahoe West Restoration Partnership 2019). The management scenarios were intended to represent contrasting management approaches, rather than to precisely emulate specific sequences of treatments. Nevertheless, we obtained and used extensive input from managers to ensure that assumptions were generally consistent with likely practices. Scenario 1 involved no treatment other than suppression; scenario 2 emulated the recent history of thinning in WUI areas; scenario 3 represented more intensive and extensive thinning in all zones, while scenarios 4 and 5 included prescribed understory burning at modest and high levels, along with thinning at a rate like that in scenario 2. Key differences among the scenarios in terms of thinning, prescribed burning, and wildfire suppression within WUI and non-WUI zones are shown in Table 1, and additional details about the modeling are included in the supplemental materials.

Representing thinning and residual fuel treatments
The LANDIS-II model operates using species–age cohorts for computational tractability, so the size limits associated with treatments were translated into age classes. Analyses of recent fuel treatments within the basin were used to estimate the volume of biomass removed by species and age cohorts. Mechanical treatment was applied to represent whole removal of larger trees (generally up to 76 cm DBH, although some larger trees up to 97

cm DBH were removed in the most intensive thinning in scenario 3) in areas that were generally accessible based upon slope and distance to roads, while hand thinning was limited to smaller trees (less than 36 cm DBH). Managers suggested that residuals from hand-thinning treatments would be burned in piles but that mechanical treatments could have biomass removed off-site since those areas would be closer to roads and generate economic returns that could offset hauling costs. We assumed that such biomass removals would result in no local emissions of $PM_{2.5}$. These assumptions reflect expected practices in the basin, although pile burning has often predominated due to the costs of removing the thinned biomass, even including boles of medium and large trees. Managers were hopeful that there would be opportunities to remove forest slash for bioenergy production, which could reduce emissions of $PM_{2.5}$ and other pollutants (Springsteen et al. 2011).

Use of wildland fire
Two "fire-focused management scenarios" were developed to represent use of prescribed understory burning. These burns were fixed to burn at a low intensity within single days with various assumptions regarding timing, size, and fire weather based upon input from managers (Table 2). The simulated understory burns result in compact square shapes since they spread in a less sophisticated way than wildfires in the model to ensure that they attain a desired target size. Scenario 5 was added after the first four to compare effects of using more prescribed burning to achieve the high treatment levels that scenario 3 achieved using thinning. To facilitate the increase in prescribed burning compared to scenario 4, prescribed burns in scenario 5 were expanded to 73 ha/day and they were allowed to burn whenever fire weather conditions were suitable. These burns were concentrated in the spring and fall (consistent with typical practices), but some occurred throughout the year. A notable difference between the understory burns and thinning treatments is that prescribed fires could occur in vegetation types that were not dominated by trees, i.e., in shrub-dominated areas. Wildfire

Table 2. Prescribed fire parameters used in fire-focused management scenarios 4 and 5.

Prescribed fire parameters	Scenario 4	Scenario 5
Maximum wind speed	6.6 (m/s)	6.6 (m/s)
Maximum Fire Weather Index[†]	55 (unitless)	55 (unitless)
Minimum Fire Weather Index[†]	10 (unitless)	10 (unitless)
Maximum Fire Intensity	1 (low)	1 (low)
Number of fires allowable per year within the Lake Tahoe Basin area	30 (fixed)	364, subject to suitable weather
Allowable days	October 15–November 15	Any day, subject to suitable weather
Target size	40 (hectares)	72 (hectares)

[†]Canadian Fire Weather Index; see Scheller et al. (2019) for more details.

suppression was also modified under scenarios 4 and 5 to represent management of wildfires to achieve resource objectives outside of WUI zones, although manager guidance suggested that such practices would be highly constrained (in part because only 42% of Lake Tahoe West is not designated as WUI, and that includes large rocky areas at high elevations where large fires are unlikely to start and spread). As a result, only relatively small areas (about 40 ha/yr) experienced such burns.

Climate assumptions
The LANDIS-II model incorporates climate projections to inform future landscape disturbances. The main landscape modeling effort used four general circulation models (GCMs) that were recommended in California's Fourth Climate Change Assessment (Pierce et al. 2018) including Hadley Center Global Environment Model (HadGEM2), Canadian Earth System Model (CanESM2), Centre National de Recherches Meteorologiques (CNRM5), and Model for Interdisciplinary Research on Climate (MIROC5). These climate projections included those GCMs run under two representative concentration pathways (RCP) 4.5 and 8.5, which respectively represent projections for medium emissions, representing substantial emissions mitigation policies, and "higher emissions, representing a continuation of current emissions policies (Pierce et al. 2018, Schwalm et al. 2020). LANDIS-II results were obtained for three replicates under each of the eight combinations of GCM and RCP, for a total of 24 runs of outputs for each management scenario. We present emissions results based upon the average of those runs. However, smoke dispersion and impacts are inherently spatial, so it was not possible to average the many LANDIS-II outputs from the dozens of replicates based upon different climate projections. Instead, we limited our analysis to a smaller set of runs from an initial round of modeling that was based upon a single climate change projection (the combination of CanESM2 GCM and RCP 4.5 emissions pathway) that was replicated 10 times for management scenarios 1 through 4. While Pierce et al. (2018) recommended working with a broad range of climate projections to address uncertainty, they regarded the CanESM2 GCM as being closest to the "average" projection.

Quantifying total and daily smoke emissions under different management scenarios using LANDIS-II
We focused on emissions of fine particulate matter (airborne particles less than 2.5 microns in diameter, or $PM_{2.5}$) because it is one of the pollutants of chief concern for human health in the region (Cisneros et al. 2014), it is used as an epidemiologic proxy

for health impacts of smoke (Williamson et al. 2016), and it is expected to be strongly influenced by wildfire emissions under climate change (Jacob and Winner 2009, Williamson et al. 2016). Studies have shown that fuels, burn rate, and intensity, which combine to yield daily emissions, are key factors that influence smoke impacts on populations. For example, Schweizer et al. (2019) found that "wildfires at lower-intensity and burn rates limit the smoke extent and largely capture emission on forest land while large high-intensity fires transport further and impact large high-density populations"; they added that "high burn rates" of more than 250 hectares per day were associated with a 10-fold increase in person-days of exposure per hectare compared to slower-burning wildfires and about a 73-fold increase compared to prescribed fires. Because of such relationships, daily emissions of $PM_{2.5}$ could be a useful, albeit imperfect, proxy indicator for health impacts (Long et al. 2018). They are also a useful indicators because they can be generated from landscape-scale disturbance models that projects burn extent and intensity for each day.

We calculated both total and daily emissions of $PM_{2.5}$ over time under the various management scenarios. We quantified smoke emissions based upon 1) the footprint and severity of wildfires and prescribed understory burns; 2) the biomass consumed within those fire footprints; and 3) emissions of $PM_{2.5}$ released from the biomass consumed during the fire events. We estimated area burned and biomass available to burn for each simulated fire over the full century for each management scenario based on the LANDIS-II modeling conducted across the Lake Tahoe West landscape (Maxwell et al. 2022). For each simulated fire, we estimated fuel consumed in the flaming phase and smoldering phase for each fuel component, based upon fire severity, as shown in Table 3, with consumption values informed by previous work by Drury et al. (2014). Fire severity is determined within the SCRPPLE extension to LANDIS-II based upon fuel loads (fine and ladder) and neighborhood effects such that high-intensity fire spreads from pixel to pixel as high-intensity fire (Scheller et al. 2019). The Net Ecosystem Carbon Nitrogen (NECN) extension to LANDIS-II keeps track of biomass that moves through pools of litter, duff, dead woody biomass, and live woody biomass. When a fire occurs, LANDIS-II, the SCRPPLE generates maps of flaming and smoldering consumption based on the biomass pools from NECN and standard emissions factors for wildfires in conifer forests in the northwest (Urbanski 2014). Smoldering emissions are associated with duff, organic soils, and rotten logs (Ottmar 2014). Wildfire emissions often extend across multiple days with a gradual shift from flaming to smoldering. However, there is no established method for allocating emissions across multiple days (Long et al. 2018), so we applied professional judgment informed by Drury et al. (2014) to allocate the fine particle emissions over three-day periods with declining smoldering consumption in the duff and dead wood fuel components (Table 3). Specifically, we assigned all the flaming emissions and 50% of the smoldering emissions to the Julian date LANDIS-II reported the pixel burned (burn day 1). Thirty percent of the smoldering emissions were assigned to one day after LANDIS burn date (burn day 2) and 20% of the smoldering emissions were assigned to burn day 3. During multiday burn periods when multiple pixels were burned, the total emissions estimated to be released on that day included flaming emissions from pixels that burned on day 1 and smoldering emissions from day 2 or day 3 released from surrounding pixels in the modeling

Table 3. Assumptions regarding consumption of LANDIS-II biomass fuel components by fire intensity class and associated PM2.5 emissions factors used in modeling emissions from prescribed fire and wildfire in the Lake Tahoe basin.

Fuel component	Biomass consumed categorized by fire severity				Flaming phase		Smoldering phase	
	Unburned	Low	Moderate	High	Proportion	Emission factor (g/kg)	Proportion	Emission factor (g/kg)
Litter	0%	100%	100%	100%	100%	23.2	0%	N/A
Duff (soil organic matter)	0%	100%	100%	100%	0%	N/A	100%	50
Dead wood	0%	5%	20%	40%	35%	23.2	65%	33

space. We calculated both total and daily emissions of $PM_{2.5}$ over time under the various management scenarios.

Adding pile burning to annual emissions
LANDIS-II does not directly model emissions from pile burning or from wood that is removed from the landscape. However, accounting for those emissions can provide valuable information for evaluating management strategies. We did not include emissions removed off-site under mechanical harvest; such material could be processed into wood products or used for energy production. Previous research from the region indicated that using the waste material in a biomass power cogeneration facility would reduce $PM_{2.5}$ emissions by 98% compared to pile burning (Springsteen et al. 2015). We calculated how pile burning associated with hand thinning would add to annual fine particle emissions. To convert biomass harvested by hand thinning into $PM_{2.5}$ emissions, we used the pile burn emissions calculator tool (Fire and Environmental Research Applications Team 2022), which had been developed with input from experts within the Tahoe basin. We entered values for typical pile shape (half-ellipsoid) and median dimensions (3.1-m diameter and 1.2-m high) based upon recent field sampling of piles within the Tahoe basin (Hubbert et al. 2013) and the tool's default consumption value of 90%. This yield applied an emissions factor of 6 kg $PM_{2.5}$ per Mg of biomass harvested via hand thinning, which is slightly higher than the average of 5.3 kg $PM_{2.5}$ per Mg of "dry forest slash" reported by (Springsteen et al. 2015). We added these emissions to the annual totals from wildfires and prescribed understory burns simulated in LANDIS-II (although in practice there would typically be a few years lag between harvest and pile burning to allow the cut biomass to dry). We did not include pile burning emissions in analyses at the daily scale, since we assumed that managers could time such burns to avoid creating daily impacts based upon manager guidance and previous work (Malamakal et al. 2013).

Evaluating daily emissions
Given a lack of established criteria for evaluating daily emissions, we thought it would be useful to categorize them into bins to highlight the levels of emissions that have been observed to more frequently cause smoke impacts. We developed those bins (Table 4) based upon guidance from Leland Tarnay, an ecologist with the U.S. Forest Service Region 5 Remote Sensing Lab, who has extensive experience monitoring and modeling fire emissions (Fusina et al. 2007, Preisler et al. 2015, Mueller et al. 2020) and studying air quality in the Lake Tahoe basin (Tarnay et al. 2005). In addition, we drew upon results from a previous study of different types of fires (Long et al. 2018), which found that daily

emissions of $PM_{2.5}$ from prescribed burns in the Yosemite area remained below 200 Mg $PM_{2.5}$/day, while resource objective wildfires sometimes had localized smoke impacts when emissions were between 200 Mg and 500 Mg $PM_{2.5}$/day. Resource objective wildfires may have greater impacts than prescribed burns because they may burn faster, across larger areas, and with less emphasis on minimizing smoke impacts (Schweizer et al. 2020). The extreme Rim Fire of 2013, however, frequently exceeded 500 Mg $PM_{2.5}$ and peaked at nearly 10,000 Mg $PM_{2.5}$/day (Long et al. 2018), causing widespread smoke impacts across the region. The Rim Fire and other extreme smoke events, including the Caldor Fire of 2021, have affected the Tahoe basin (Fig. 1). Schweizer et al. (2019) concluded that a high wildfire burn rate of 250 ha/day would be more likely to cause smoke impacts. Multiplying that daily threshold by an emissions rate of 0.45 Mg $PM_{2.5}$/ha, which is associated with relatively heavy forest fuels (Long et al. 2018), yields a threshold of 120 Mg $PM_{2.5}$/day, which falls into the "high daily emissions" bin (Table 4). Specific relationships between burn rates and smoke impacts could vary substantially from airshed to airshed due to different topography, dispersion, and fuels. Consequently, we urge caution in extending these criteria to other regions.

Table 4. Classes used to categorize daily PM2.5 emissions.

Class	Daily emissions of $PM_{2.5}$ in Mg
Negligible	0 < 10
Low	10 < 30
Moderate	30 < 60
High	60 < 200
Very High	200 < 500
Extreme	> = 500

Projecting smoke dispersion
We used the BlueSky Playground (2.0 beta, https://playground.airfire.org/) to model dispersion of fine particulate matter ($PM_{2.5}$). Fusina et al. (2007) previously demonstrated the platform's utility in predicting emissions and $PM_{2.5}$ concentrations at surface stations from wildfires in Northern California. The BlueSky system requires a dispersion model; a weather forecast; and the location, timing, amount, and composition of emissions. For the smoke dispersion model, we selected the HYSPLIT option which has been shown to provide good predictions within areas of complex topography such as the Lake Tahoe basin (Malamakal et al. 2013). However, the HYSPLIT option limits users to the weather forecasts hardwired into BlueSky Playground rather than customizing meteorological conditions. To represent three smoke-dispersal forecasts for each fire event we modeled, we used dates

of fire emissions discussed previously and then applied fire weather data for the same Julian dates corresponding to the three most recent years of data (2016, 2017, 2018) from the highly resolved (2-km scale) Weather Research and Forecasting (WRF) forecast for California and Nevada (https://cansac.dri.edu/). For the emissions, BlueSky Playground allows for customizing data on fuel consumption and emissions when measured data are available. For each BlueSky Playground run, we created a default emissions scenario based on modeled fire locations from LANDIS-II runs and then substituted our values for emissions and energy release from LANDIS-II. This approach provided more precise data for projecting the lofting of emissions into the atmosphere. We estimated the energy produced during the flaming and smoldering phases of combustion using the inherent heat content of forest fuels of 18608 Kj/kg of fuel consumed. The energy released simulates the lifting of emitted particles into the air where the particles enter the dispersion model.

To demonstrate how our modeled projections might translate into smoke impacts, we winnowed our LANDIS outputs down to a more manageable subset of data that represented alternative management scenarios under the CanESM2 climate projection that appeared to generate average results (Pierce et al. 2018). We extracted results from a single model year 30 (2039 on the LANDIS-II temporal scale) for our modeling exercise based upon the assumption that 30 years into the future was a reasonable period to allow for different management scenarios to influence fuels and fire regimes across the landscape. For this step, we did not model scenario 5, representing increased burning, since it had not yet been developed when we conducted the dispersion modeling. LANDIS-II modeling produced ten replicates for each management scenario under the selected climate projection. To approximate both the extreme and more typical outcomes, we ranked the replicates from 1 to 10 based on the maximum daily emissions in year 30 and then analyzed the air quality impacts associated with the worst days of emissions from the 1st, 5th, and 6th ranked replicates. The replicate with the highest maximum daily value represented the worst outcome for each scenario, while results from the 5th and 6th ranked replicates can be averaged to represent median outcomes.

As a general comparison, we also modeled a fall season prescribed burn under scenario 4. Previous research has suggested that prescribed burns, including pile burns, in the Lake Tahoe basin may cause minor smoke impacts (e.g., less than a standard of 35 μg $PM_{2.5}$ m^{-3} over 24 h) but are unlikely to cause serious impacts because typically only relatively small areas have been burned during favorable dispersion windows (Malamakal et al. 2013, Striplin et al. 2020). Furthermore, managers tend to favor fall season burns because spring burns are considered out-of-season burns, may be less effective in consuming fuels (Striplin et al. 2020), and may conflict with regulations to protect wildlife breeding. We did not attempt to model dispersion of pile burns or spring prescribed understory burning because of the expectation that those practices would not typically cause significant smoke impacts and because of computational constraints. These assumptions and potential outcomes warrant further attention if prescribed burning is greatly expanded.

Evaluating smoke impacts
In the third step in our analysis, we followed the methodology described in Jones et al. (2016) and used the BenMAP-

Community Edition tool to model health impacts and associated economic values (Sacks et al. 2018, U.S. EPA 2021). The user provides the model with gridded pollution data and a region of interest for assessing impacts. For this study, the gridded pollution data was $PM_{2.5}$ data obtained from fires simulated using BlueSky in step two.

We estimated both morbidity and mortality impacts of smoke using a willingness to pay (WTP) approach. We first estimated the physical impact of the smoke exposure and then translated those impacts into a monetary value using an estimate of willingness to pay to avoid the mortality or morbidity damages of the smoke exposure. BenMAP also allows users to estimate the expected expenditures associated with specific health endpoints, such as respiratory conditions, after pollution exposure. This is often referred to as a cost-of-illness approach and generally represents a lower bound estimate of the economic damages of pollution (Jones et al. (2016) for a comparison of the two approaches in the context of wildfire smoke). When data are available, the WTP approach is preferred since it assesses the economic costs of pollution more fully (Jaafar et al. 2018).

The BenMAP model first estimates the physical impact of the pollution on user-specified non-overlapping health endpoints. For each health endpoint, the user can choose to either utilize predetermined health impact functions (also referred to as dose-response functions) or provide their own from the literature. For this study, we used minor restricted activity days (MRADs) as the health endpoint for the non-fatal health impacts of smoke exposure. As noted in Jones et al. (2016), MRADs are defined as "any day on which an individual was forced to alter his or her normal activities due to minor illnesses, including both respiratory and non-respiratory conditions." The health impact function for estimating MRADs is taken from Ostro and Rothschild (1989) and input directly into BenMAP. For the all-cause mortality health endpoint, we used the dose-response function estimated in Johnston et al. (2011).

The final step in the BenMAP analysis is to assign an economic value to the physical health endpoints. For a non-fatal MRAD health endpoint, we used a marginal WTP estimate from Jones et al. (2016). Based on a survey of residents in Albuquerque, New Mexico, the authors found the residents would be willing to pay $130.79 to avoid adverse health effects associated with wildfire events. We used this estimate after updating it for inflation to 2018 values. This WTP estimate of general willingness to pay for avoided health damages aligns conceptually with the MRAD health endpoint. To estimate the economic cost of all-cause mortality, we used the value of a statistical life (VSL) concept. The value of a statistical life is a commonly used money metric for valuing willingness to pay to reduce mortality risk at the population level in cost-benefit analysis (Kniesner and Viscusi 2019). The BenMAP manual (U.S. EPA 2021) recommended using a VSL of $7.4 million (2006 dollars), which we adjusted for inflation to $9.3 million in 2018 equivalents.

For each simulated event in this modeling space, we estimated the health impact associated with three days of $PM_{2.5}$ exposure generated in Step 2. After three days, we assumed that wildfire smoke would be fully dispersed with negligible additional health effects, recognizing that this was a simplifying assumption (and not representative of many giant wildfires that have occurred primarily outside of the Lake Tahoe basin in recent years). While

Fig. 5. Cumulative total fine particulate emissions (A: wildfires and understory prescribed burning, B: pile burning, C: combined) for each management scenario over a 100-year period for the Lake Tahoe West landscape (central line is the average, and ribbon is the standard deviation, calculated over three replicates for eight climate projections).
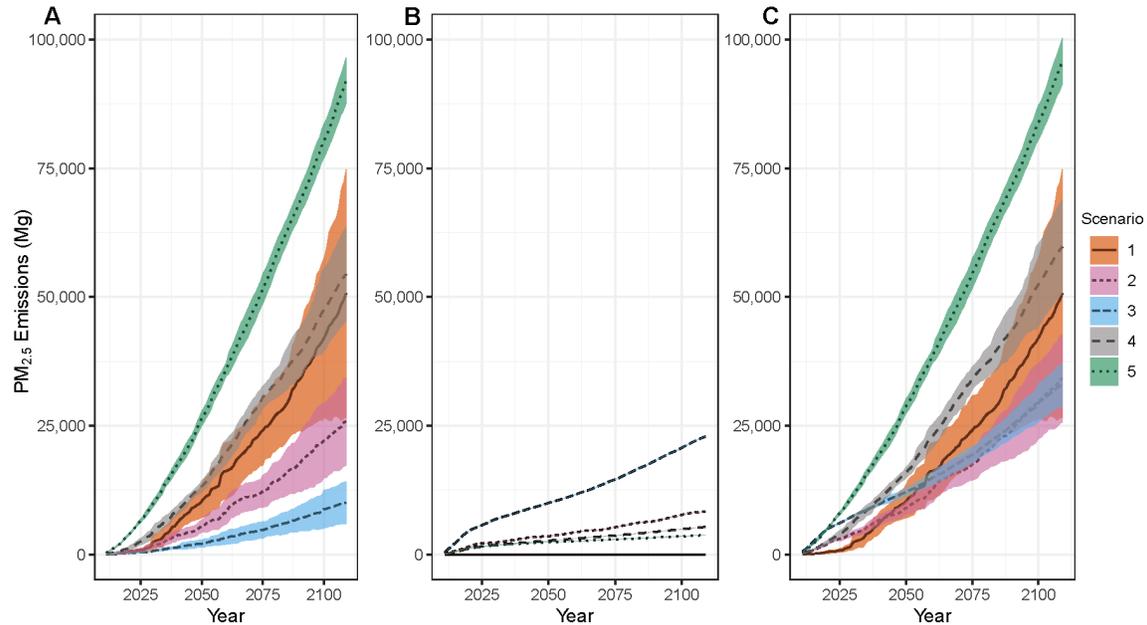
some wildfires burned longer in LANDIS-II, the ones with highest emissions tended to drop rapidly after they peaked. The three replicates were ones with the first (highest), fifth, and sixth (median) peak daily emissions out of the 10 replicates generated with LANDIS-II modeling for year 2039. In total, we ran 108 BenMAP simulations of wildfire smoke days (3 replicates × 3 weather patterns × 4 management scenarios × 3 days) and 9 BenMAP runs for the single prescribed fire under scenario 4 (3 weather patterns × 3 days).

Modeling frequency of prescribed burning
As a supplementary analysis to evaluate the feasibility of prescribed burning, we compared the number of days of prescribed and pile burning compared to the number of days historically considered suitable for such burns. First, we counted days with prescribed understory burns simulated in LANDIS-II. Then, we divided the area treated by hand thinning each year, as reported in the LANDIS-II results, by 125 acres (50.6 ha) per day; managers in the advisory group suggested that daily rate would be a reasonable constraint. That value is slightly higher than the typical amount of less than 40 ha reported by Malamakal et al. (2013); however, it was twice as large as the largest prescribed burn (24 ha) reported through Prescribed Fire Information Reporting System (PFIRS, https://ssl.arb.ca.gov/pfirs/) for Lake Tahoe during the years 2014–2017. Many factors, including proximity to homes, staffing within different land management organizations, weather, and air quality, govern how such burns are accomplished or might be accomplished in the future, but we thought the results would be clearer if we applied the same rate to all management scenarios. We assumed that days allocated for pile burning and understory burning would be additive since pile burning might effectively displace prescribed understory burning

(especially if relatively large areas were being burned) and because pile burning can occur during winter when understory burning is not feasible.

We then compared the resulting average number of burn days under each management scenario against the number of "available burn days." Striplin et al. (2020) determined that there was an average of 96 days available for prescribed burning in the Lake Tahoe basin based upon three conditions: approval by air regulators for burning ("approved burn day"), suitable fire weather and fuel moisture ("within prescription"), and sufficient availability of firefighting resources. We did not attempt to analyze whether each day of burning would be feasible on a day-by-day, or season-by-season basis, although the LANDIS-II model did constrain prescribed understory burning to days of suitable fire weather (Scheller et al. 2019).

RESULTS

Cumulative emissions of fine particulate matter
We projected that while annual emissions of fine particulate matter would greatly increase over the next century across most management scenarios, the choice of management scenario would strongly influence those trajectories. Figure 5 compares the mean and standard deviation for cumulative emissions from wildfires and prescribed burns under each of the five scenarios (emissions from wildfires and prescribed understory burns are shown in 5A; emissions from hand piles are shown separately in 5B, and the total is shown in 5C; average values are shown in Supplemental Table S8). As an example of how wildfire emissions would accelerate, under scenario 2, such emissions over the late decade of the modeled century were nine times greater, on average, than under the first decade. Under the suppression-only scenario 1,

wildfire emissions over the last decade were nearly 20 times greater than during the first decade.

For all scenarios that involved harvest (scenarios 2–5), emissions from pile burning (5B) raised total emissions while mitigating emissions from wildfires (5A). For example, the no-treatment scenario 1 resulted in 96% greater cumulative emissions from wildfires but only 48% greater cumulative emissions after accounting for pile burning emissions in scenario 2. Under the high thinning scenario 3, most emissions would result from pile burning of residual materials; it reduced the cumulative emissions from wildfires relative to scenario 2 by 61%, but only by 3% after accounting for pile burning emissions.

Adding understory prescribed burning in scenarios 4 and 5 raised total emissions compared to the other scenarios while tamping down on wildfire emissions, especially later in the century as wildfires become more widespread. Scenario 4 resulted in total cumulative emissions that were 69% greater than under scenario 2 and 14% higher than under scenario 1. Meanwhile, dramatically increasing prescribed understory burning under scenario 5 resulted in the highest total emissions compared to other scenarios; for example, total average emissions were 187% greater than under scenario 2.

However, both scenarios involving high levels of treatments (scenarios 3 and 5) reduced the variation in emissions across replicates and climate projections compared to the other three scenarios. Indeed, scenario 1 had the highest variation across replicates and climate projections, so that some replicates under no-treatment scenario resulted in higher total emissions than under scenario 4, even though scenario 4 had a higher average.

Daily emissions of fine particulate matter
We found that increased treatment reduced days of very high and extreme emissions of fine particulate matter from wildfires while increasing use of prescribed fire (scenarios 4 and 5) would increase days of more modest emissions (Fig. 6). Consequently, prescribed fires effectively shifted emissions into more frequent releases of lower daily emissions. Suppression-only management (scenario 1) averaged over 10 days of very high or extreme emissions per decade, while scenarios with the most treatment (scenarios 3 and 5) reduced the average number of such days below two per decade. Scenario 3 with the most thinning reduced the risk of very high emission days, while scenario 1 with no treatment greatly increased that risk. More modest levels of treatment (scenarios 2 and 4) were intermediate, averaging 7 and 5.5 days per decade, respectively, because each scenario resulted in comparable levels of treatment. Our results suggested that air quality would deteriorate due to fire activity over time under all scenarios. However, high emission days did become more frequent in earlier decades under scenarios 1, 2, and 4, while greatly increasing overall treatment (scenarios 3 and 5) sharply reduced the incidence of such days in early decades.

Our analysis of conditions in a single future year (Fig. 7) indicated that greatly increasing the amount of treatment under scenarios 3 and 4 resulted in lower peaks and fewer days of very high fine particulate emissions compared to scenarios 1 and 2. Prescribed understory burns resulted in more frequent, low-level emissions concentrated in late fall under scenario 4. Those patterns are reflected in increased days of "moderate" emissions in Figure 5.

Fig. 6. Days of fine particulate matter (PM2.5) emissions per decade, categorized into the highest four daily emission levels (30–60 and 60<200 Mg at top, 200–500 and >500 Mg at bottom, note change in Y-axis), derived from LANDIS-II modeling across the Lake Tahoe West landscape for each of five management scenarios over a full century modeling period based upon the average of eight different climate projections.
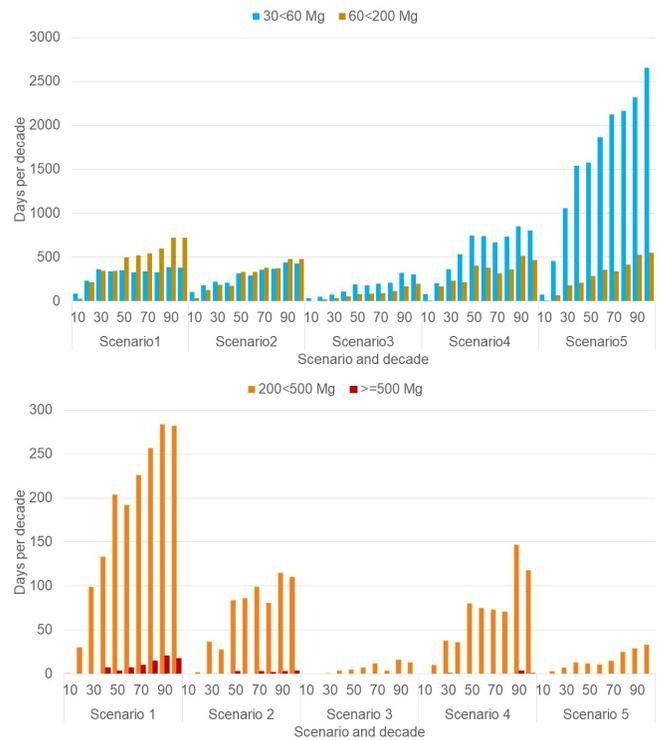

Fig. 7. Fine particulate matter (PM2.5) from wildland fires in the Lake Tahoe West landscape for a single future year (2039) from a typical replicate under each of the first four management scenarios derived from LANDIS-II modeling.
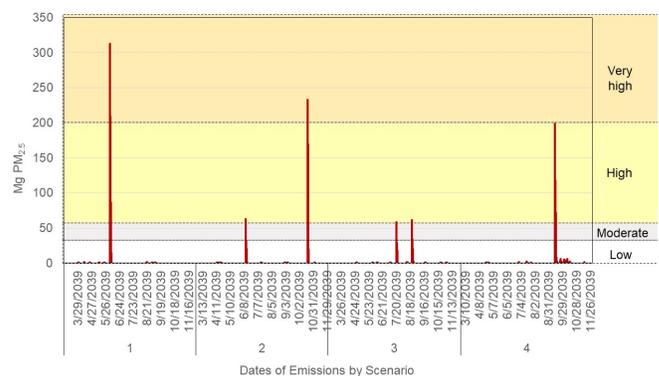

Figure 8 shows the maximum daily emissions within that future model year (2039) for each of the ten replicates run for the first four management scenarios under a single climate change projection (the CanESM2 GCM × RCP4.5 emissions pathway). The results

Fig. 8. Maximum daily emissions of fine particulate matter (PM2.5) within a future model year (2039) for each of the ten replicates run for four management scenarios.
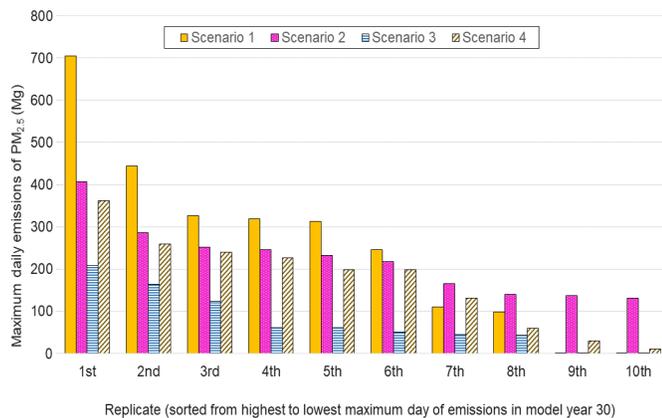
show that daily maximum emissions varied substantially across replicates, from 705 Mg down to a negligible 2 Mg. Scenario 3 consistently generated the lowest maximum emissions across the 10 replicates compared to the other scenarios, indicating that it would consistently abate high impacts. Scenario 1 resulted in higher daily maximums than any other scenario for the worst 6 replicates, while scenario 2 had higher daily maximums than other scenarios for the four best replicates. The results in Figure 8 represent only a single future model year, but they appear consistent with the full-century trend (Fig. 6), in which increased thinning treatment under scenario 3 reduced maximum daily emissions, while the lower treatment scenarios (1 and 2) risked incurring higher maximum daily emissions.

Smoke impacts
Our analysis of select future wildfire events indicated that increases in treatment would likely reduce the resulting smoke impacts from future wildfire events. Our BlueSky modeling depicted the effects of individual fire events on downwind particulate matter levels relative to standards to protect human health. It revealed how the most extreme wildfire in a future model year (2039) would have more regionally extensive and severe impacts than a modest prescribed burn, although the latter could still elevate pollution in populated areas within the Lake Tahoe basin and nearby greater Reno area (Fig. 9). Figure 10 spatially depicts results for the fifth-ranked replicates (approximating a median outcome for that future year), while highlighting the projected fine particle levels in the urban centers of Reno and Carson City (notably without factoring in background levels or other potential pollutant sources) across each of the first four management scenarios. This figure illustrates that huge areas could be affected by emissions from large wildfires especially under scenarios 1 and 2, which involved the least amount of fuel reduction treatment. Scenario 3, which involved the most extensive and intensive thinning, was projected to result in much more mild smoke impacts. This comparison of representative events reinforces the emission days analysis in illustrating how increased treatment would effectively reduce the incidence of extreme smoke events overall and on potential impact to large urban populations.

Health impacts and associated economic costs
Our results indicate that increases in treatment would reduce health impacts from future wildfire events. Higher levels of daily particulate emissions are associated with increased economic impacts, measured in terms of WTP to avoid mortality and morbidity impacts (Fig. 11). We found that extreme wildfires could have very large health impacts on downwind communities, with potential for single large wildfires in the basin to cause up to $80 million of economic losses based upon health risks alone. Those estimates are dominated by the value of a statistical life, with mortality accounting for 96% of total value if one uses WTP for morbidity and more than 99% if one uses COI estimates for morbidity. The results of the representative events analysis indicated that future wildfires under the suppression-only scenario would likely result in much greater harm than wildfires under scenarios with high levels of treatment. However, our rendition of a single prescribed burn also indicated that there could be substantial impacts especially if conducted under less favorable wind patterns.

Annual days of prescribed burning
The average number of days of prescribed burning per year associated with implementing each scenario increased substantially from management scenario 1 through to scenario 5 (Table 5). For scenarios 2 and 3, these values reflected increased levels of hand thinning compared to no thinning under scenario 1. Because the modeled size of pile burning operations was higher than the levels reported in recent PFIRS data, it may not represent "business-as-usual" but instead a more optimistic scenario of expanded burning. The levels of hand thinning, and hence pile burning under scenarios 4 and 5, were comparable to scenario 2, but those scenarios involved understory burning of 30 days per year under scenario 4 and 92 days under the more aggressive scenario 5. Indeed, the 99.1-day average estimated in scenario 5 was slightly higher than a reference value of 96 available days, which was the historical average of one-day windows available for burning reported by Striplin et al. (2020).

DISCUSSION
This study demonstrates an approach for projecting the smoke impacts of alternative management regimes. We had to adopt numerous simplifying assumptions to model a very complex and dynamic social-ecological system. Further investigations could refine key assumptions regarding consumption and emissions and

Table 5. Average days of prescribed burning (pile burning and understory burning) per year by management scenario.

Management scenario	Pile burning	Understory burning	Total
1	0.0	0.0	0.0
2	9.4	0.0	9.4
3	28.1	0.0	28.1
4	7.0	30.0	37.0
5	6.9	92.2	99.1

expand the temporal and spatial scope. Specific results should not be regarded as forecasts, but rather they spotlight key trade-offs. Because there are no consensus yardsticks for evaluating air quality impacts of management regimes, our results suggest how emissions of fire particles, as well as smoke impacts, are likely to vary over near and long terms under different management approaches. We

Fig. 9. Projected concentrations of fine particulate matter (PM2.5) over three days under an extreme wildfire in a management scenario with no treatment (left) compared to a prescribed burn (right) in a management scenario that used prescribed fire as a primary management tool.
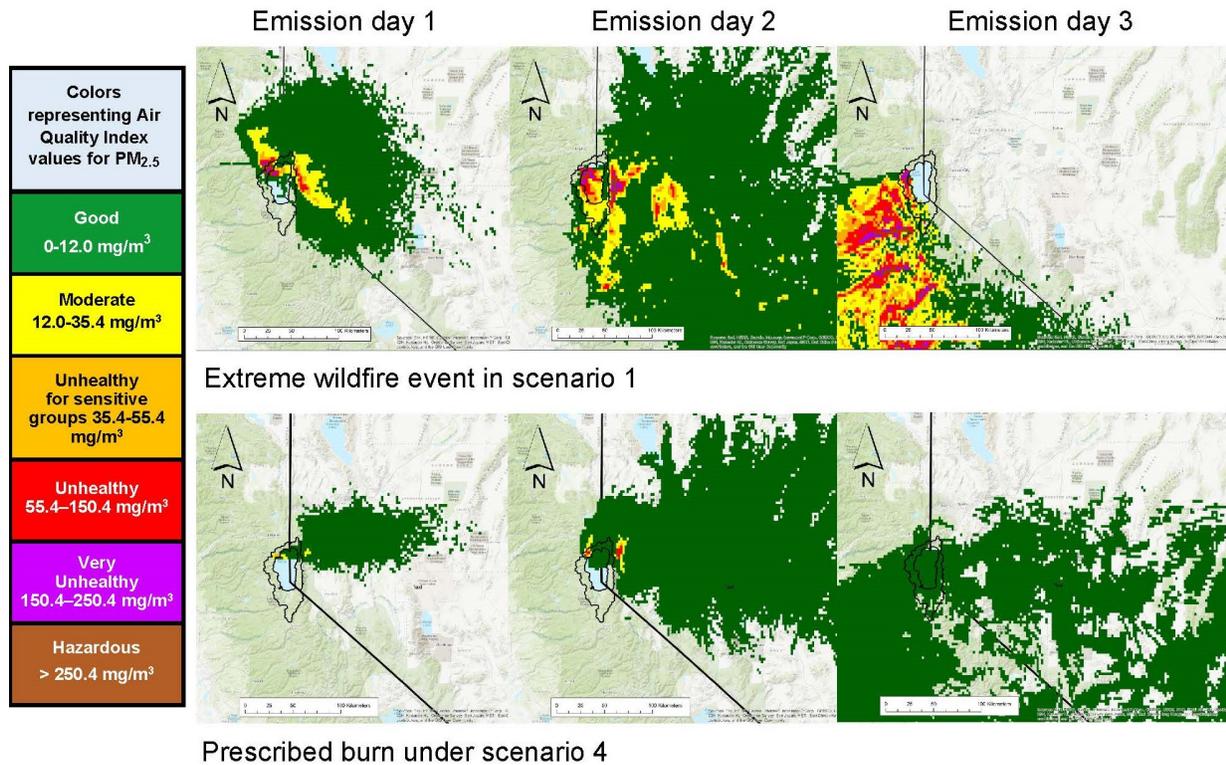

Fig. 10. Examples of smoke dispersion and resulting levels of particulates at Reno and Carson City from median wildfire events under four different management scenarios in year 2039, based on LANDIS-II modeling results for the Lake Tahoe West landscape.
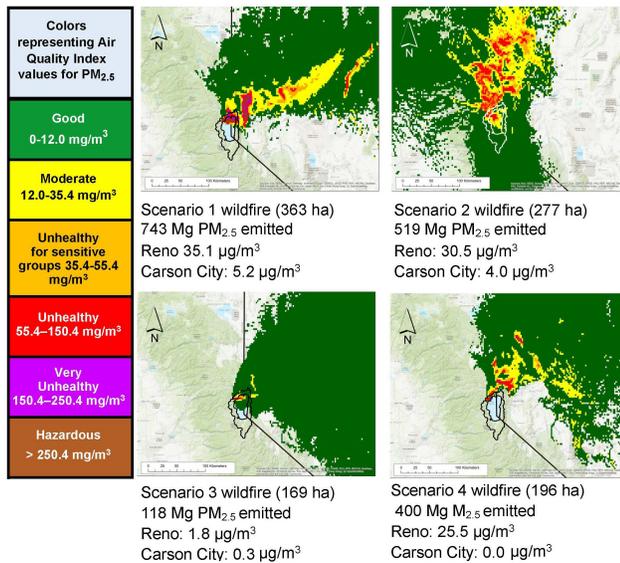

Fig. 11. Economic impacts of smoke (measured in terms of willingness-to-pay to avoid mortality and morbidity impacts) from modeled wildfires under various replicates for each of four management scenarios derived from LANDIS-II modeling across the Lake Tahoe West landscape. Trend lines show the relationship between cost and emissions for different weather years.
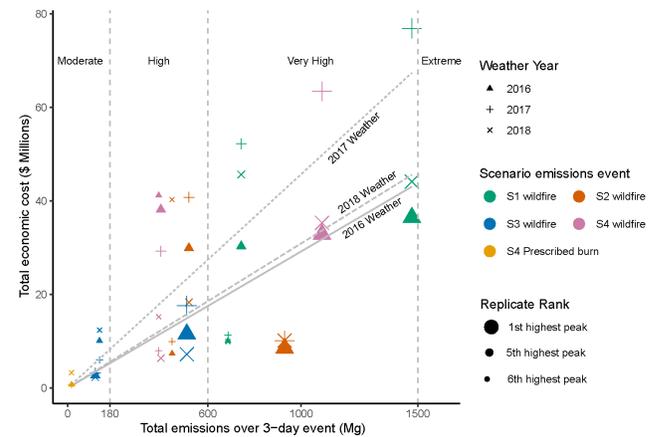
first discuss how our findings suggest that increased treatment could provide multiple benefits, and then we note challenges associated with increasing prescribed burning. We then consider methodological challenges in evaluating air quality effects of management regimes and the increasing opportunities to better project long-term smoke impacts.

Management implication: treatments are likely to yield benefits
Our findings indicate that increasing forest treatment, both thinning and prescribed burning, would reduce expected emissions from wildfires, days of very high emissions associated with wildfire events, and economic impacts of such events. Mitigating wildfire emissions from the study area appears likely to benefit air quality for heavily populated areas including the greater Reno–Sparks metropolitan area and the Central Valley in California. Management that expands thinning (scenario 3) appeared particularly effective in reducing wildfire emissions by reducing the amount of fuel to be consumed in such events. This finding is consistent with previous modeling of management regimes on carbon emissions (Hurteau and North 2008, Loudermilk et al. 2017) and field studies of wildfires (North and Hurteau 2011). The air quality benefits of such a strategy would be greatest when cut materials could be used in controlled biomass or energy production rather than being disposed of through pile burning, as suggested by previous field studies (Springsteen et al. 2011, Springsteen et al. 2015).

We found that strategies that rely heavily on increased prescribed burning would also be effective in reducing extreme daily emissions and associated smoke events. Ecologists have championed increasing use of wildland fire in the Sierra Nevada, particularly to maintain areas treated initially by thinning, to promote a variety of resource objectives (North et al. 2012, D'Evelyn et al. 2022). Previous research in the Lake Tahoe basin suggested that prescribed burns would be effective in mitigating smoke impacts from wildfire (Cahill 2009, Malamakal et al. 2013). As reported by managers and in research by Malamakal et al. (2013), both pile burning and understory burning are expected to remain within daily burn targets, which results in many days of low emissions but avoids high daily emissions. Schweizer et al. (2019) suggested two important mechanisms that are reflected in our findings: 1) that spreading emissions across many days keeps smoke levels below thresholds that are expected to harm both sensitive and general populations, and 2) that favoring more localized, managed burns tends to reduce the number of people exposed to smoke by reducing the potential for large wildfires that resist suppression and impact large urban populations. We found that increases in prescribed fire, in conjunction with modest thinning, would also reduce high daily emissions from wildfires, but that very frequent prescribed burning would greatly increase overall fine particulate emissions. A recent global review of studies that compared prescribed fire and wildfire regimes similarly concluded that increased use of prescribed fire can reduce total wildfire emissions by reducing the size and intensity of wildfires, but also that such regimes often increase the total amount of fire and emissions within a landscape over time (Hunter and Robles 2020). However, they found few studies that evaluated effects on economics or resilience and did not report any that specifically compared effects on air quality. This dearth of literature on this important topic may reflect the challenges in modeling such complex systems.

Climate change and opportunities for adaptation
Our analysis of emission and smoke impacts focused on differences among management scenarios rather than differences under climate change scenarios. As reported in other work in this special issue (Maxwell et al. 2022), the LANDIS-II modeling projected substantial increases in wildfire activity (in addition to drought-related tree mortality) across management and climate scenarios as conditions become warmer. However, there was also considerable variation in fire regimes across individual climate projections; specifically, some projections resulted in different combinations of drier and warmer conditions, which intensified wildfire disturbances (Maxwell et al. 2022). However, the projection based upon the CanESM GCM × RCP4.5 emissions pathway appeared to be a "middle-of-the-road" projection out of the ones examined in the LANDIS-II modeling (Maxwell et al. 2022). These findings suggest that our results are reasonable projections in light of what we might expect from climate change, and they are consistent with research regarding future impacts of climate change on air quality (Jacob and Winner 2009). Our modeling projections suggest what the future could bring, but managers can adapt their strategies as climate change unfolds, as fuel conditions change, and as weather changes. For example, they could shift their use of fire from year-to-year and decade-to-decade.

Challenges with increasing burning
Our results suggest that substantial increases in prescribed burning would also face implementation challenges. We found that the high level of prescribed burning under scenario 5 would often exceed the number of days historically likely to be available for such burning. More prescribed burning could be accomplished within those constraints by burning even larger areas than the 73 ha per day assumed in our model, but such large burns could still require multiday burn windows in the fall. Therefore, implementing scenario 5 would be difficult without policy changes to facilitate more burn days during those critical periods. In addition, warmer, drier conditions and greater wildfire activity resulting from climate change may further winnow the opportunities for burning or force relaxation of the criteria for burning, which could entail greater risks to various objectives for public health, safety, biodiversity conservation, restoration, and air quality (Kupfer et al. 2020).

Recent research on burn day windows in the Lake Tahoe basin suggested that increasing availability of specialized fire personnel in the fall and spring and adjusting prescriptions to burn more in the spring might be necessary to substantially increase burning (Striplin et al. 2020). An even more recent analysis (York et al. 2021) at the Blodgett Forest Research Station, to the west of Lake Tahoe, suggested that burning opportunities would be even narrower than Striplin et al. (2020) had indicated, particularly because larger prescribed understory burns would require longer windows of dry fuels to be successful. In contrast, pile burns can be completed even under relatively wet conditions when the residual materials are kept dry under plastic sheets (Aurell et al. 2017). Additional research may be warranted to evaluate potential effects of conducting more burning in winter and spring, since such practices have not been widely studied and air quality may also be a constraint in the winter (York et al. 2021).

While our results suggest that increasing treatments would achieve substantial benefits in terms of averting extreme wildfire emissions, we did not identify a point at which increasing prescribed burning might no longer improve net air quality and associated economic costs. Implementing the scale of prescribed burning under scenario 4, and especially scenario 5, would increase the probability that some of those burns would result in smoke impacts especially for communities near treated areas within the basin, despite efforts by managers to mitigate them. The probability of impacts likely would increase if managers used more marginal burn days to achieve those targets. Our results demonstrated that a prescribed burn during unfavorable weather conditions could result in unhealthy air quality in some downwind areas. For example, a small (8 ha) prescribed understory burn in the west side of the basin resulted in elevated levels of $PM_{2.5}$ in Tahoe City in November 2019 when a nighttime inversion inhibited dispersion (Hobbs 2020).

Limitations in evaluating emission impacts of fire regimes
We highlight several sources of uncertainty in modeling smoke impacts under alternative fire regimes. The first concerns fuels consumption and emissions from fires of different types over time, including prescribed burns, wildfires managed for resources objectives, and extreme wildfires. Recent work in the 2013 Rim Fire, which burned over 1 km^2 of mixed conifer forests where fire had been excluded for many decades, suggested that emissions were similar across low, moderate, and high severity burn areas (Harris et al. 2019). They noted that most of the fuel consumed was in surface fuels (litter, duff, and small wood), that consumption of those fuels was high across burn severities, and that consumption of live trees did not vary enough to produce substantial differences in direct emissions (Harris et al. 2019). However, other researchers have noted that fires are managed for resource objectives only under less extreme weather, which would moderate consumption (White 2017). Another study in a repeatedly prescribed burned forest found that fuel loads were nearly two times higher in the first burn than in the second and third, and that percent fuel consumption (compared to pre-burn levels) was highest (65%) for the first burn but dropped for the second (45%) and third (29%) burns (Levine et al. 2020). Our landscape modeling used a simplifying assumption that rates of consumption would be consistent regardless of how recently the area had burned. We also did not apply different emissions factors to wildfires versus prescribed burns or to different seasons of burning. Research has suggested that $PM_{2.5}$ concentrations might be higher in smoke from prescribed fires, although that reported difference may reflect that prescribed fire smoke was measured closer to the burns (Navarro et al. 2018). Other research has noted that emissions rates vary seasonally (Hiers et al. 2020). These factors suggest opportunities to refine modeling tools to better represent the complexities of fuels, consumption, and emissions and translate those into projections of future smoke impacts.

Our analysis accounts for changes in climate on fire activity including warming and drying, which are likely to be a dominant driver of changing fire effects (Williams et al. 2019); however, we did not attempt to account for changes in wind patterns or human populations. Because the analysis only evaluated effects of fires occurring within the Lake Tahoe West landscape, it does not directly consider how fire activity in other parts of the basin, and smoke from outside of the basin, could also impact air quality

and the ability of managers to use fire within the basin. These sources of uncertainty are likely to affect the absolute projections of impacts, but they are less likely to alter the relative performance of different management regimes.

Other sources of uncertainty associated with physical and social factors pose challenges to simulating intentional burning regimes. There is great uncertainty in modeling the location, timing, and smoke dispersion from such burns over decades, which is necessary to understand how a regime based upon frequent and large prescribed burns, or other applications of managed wildland fire, would affect air quality in downwind communities. Research studies are being initiated to help to better quantify the smoke effects of large burns (Prichard et al. 2019), but there are few examples to draw upon from the Lake Tahoe basin and surrounding areas. Furthermore, mitigation strategies can be used by managers to minimize smoke impacts by timing and constraining managed fires and providing advanced warning of potential smoke impacts, particularly for sensitive groups (Long et al. 2018). Such practices are increasingly being incorporated into operations and policies, although our models did not encompass such sophisticated mitigations. Ideally, projections would account for smoke transport patterns and constraints such as crew availability when modeling individual burns.

Improving understanding of health impacts
Recent extreme wildfire seasons have provided opportunities for researchers to better understand and quantify the health impacts of extreme wildfire events. Such investigations are revealing that health impacts from wildfires are likely to have unprecedented costs and to increase dramatically with a hotter climate (Johnston et al. 2021). Our results were consistent with a recent study of the California wildfires of 2018, which reported over $32.2 billion in health costs, with much of those damages occurring in densely populated locations very distant from the fires (Wang et al. 2021). That study similarly found that increased mortality was the dominant portion of those costs. Continued study of such extreme events, as well as cumulative effects across a range of events magnitudes, will help to improve estimates of health and economic impacts of long-term regimes. There could be thresholds or other non-linear relationships that are important to consider when comparing infrequent but extreme smoke events with frequent but low-level emissions. Such information would be useful in comparing trade-offs between highly contrasting management scenarios.

CONCLUSIONS
Our results reveal how management regimes that rely on increased thinning with fuels treatment are likely to benefit air quality and human health by reducing impacts from future wildfires. Our results suggest that increases in prescribed burning can also reduce the impacts of wildfires, but they result in much more frequent, low-level particulate emissions overall. Consequently, management regimes that would greatly increase prescribed burning could be challenging to implement. Our analysis represents an initial approximation of health impacts; a more complete analysis would require processing the full duration of multiple fire events within years and over many decades. Advances in computing power and modeling frameworks will enhance the capacity to model the air quality benefits from alternative forest management regimes. Adaptive management that includes monitoring of actual burns

will help to better understand how fire can be used effectively while minimizing smoke impacts. In the meantime, averting threats to public health in fire-prone regions could depend on careful planning and execution of intentional burning and proactive engagement with affected communities.

Data Availability:

Coding and data used to generate the results are available here: https://github.com/LANDIS-II-Foundation/Project-Lake-Tahoe-2017, which has been archived here: https://doi.org/10.5281/zenodo.4644579

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1 **This file includes:**
2   <u>Supplementary methods</u>
3   <u>Tables S1 to S8</u>
4   <u>Figures S1 to S9</u>
5   <u>Supplementary references</u>

Supplemental Methods:

Climate projections

A combination of 8 projections were used from 4 different global change models (GCMs) at two relative concentration pathways (RCPs). The RCPs chosen were 4.5 and 8.5, the former representing an emissions-controlled future, while the latter represents an uncontrolled emissions future. The particular combination is based on recommendations from Pierce et al. 2016. The LANDIS model utilizes the following climatological variables: daily precipitation (Figure S1 and S2), daily maximum temperature (Figure S3), daily minimum temperature, daily average windspeed, and daily average wind direction that are averaged across the Level II EPA ecoregions in the study area.

Forest succession

NECN (v6.5) simulates both above and belowground processes, tracking C and N through multiple live and dead pools, as well as tree growth (as net primary productivity--a function of age, competition, climate, and available water and N). Soil moisture, as well as movement across the dead pools: wood and litter deposition and decomposition, soil accretion and decomposition are based on the CENTURY soil model (Parton et al. 1983, Scheller et al. 2011). Carbon estimates by pool were validated against Wilson et al. (2013) at the ecoregion level, where the model overestimated total C for only one region but was within one standard deviation for all others (see supplemental figure S4). Forest growth estimates using the climate data for year 2010-2015 for the region were calibrated against the MODIS 17a3 product annual mean for 2000 – 2015 (Figure S5). Mean landscape value for MODIS was 393 g C/m ^{2} (sd 134), while for LANDIS the mean value was 320 g C/m^2 (sd 312). Reproductive success is dependent on temperature and water.

Fire modeling

The SCRPPLE extension (v2.1) models ignitions by drawing the number of ignitions from a zero-inflated Poisson distribution and allocates them across the landscape with a weighted ignition surface for each type of fire modeled (Scheller et al. 2019). The weather influence on fire is based on the Fire Weather Index (FWI) measures created by the Canadian Fire Prediction System (1992). There are three categories of fires that can be modeled: lightning, accidental (i.e., human started), and prescribed fire. The extension also includes the ability to explicitly set fire suppression effort levels across the landscape as well as by ignition type, where the suppression parameter reduces the probability of fire spread from one cell to another. Effort levels can range from 0 to 3, where 0 is no suppression attempted, to 3 which represents high effort and was designed to mimic current suppression efforts in the Basin (Figure S6). However, suppression effectiveness can be limited by weather as well, a maximum wind speed parameter can limit suppression to days only when resources can be deployed safely. That parameter was set at wind speeds of 11 meters per second (~25 miles per hour) in consultation with regional fire personnel. Prescribed fires follow a set of weather prescriptions for when fires can occur (Table S2).

Contemporary wildfires (2000-2016, from CalFIRE FRAP) were used to parameterize fire spread and size from the Central Sierra Nevada in order to increase the sample size of fires. Mean annual fire area (in ha) for observed data was 117 hectares per year (SD = 309), for modeled data, the mean value was 122 hectares per year (SD = 210). In order to move from fire intensity to fire severity (to encompass the mortality associated with fire), five fire experts working in the LTB provided their estimates of mortality for varying species, age, and intensity combinations. More details about the parameterization of the fire extension are found in Scheller

52   et al. (2019). Suppression effort and fire spread are calibrated at the same time in order to try to
53   account for both forces in recreating the contemporary fire regime.
54   The model calculates three levels of fire intensity, roughly corresponding to flame lengths of: 1)
55   less than 4 ft, 2) between 4 ft. and 8ft., and 3) greater than 8ft. While ignitions are based off of
56   climate, fire intensity is based off of fuel loading within each cell. LANDIS calculates fuel
57   loadings based on the current year's litter, duff, and downed and dead woody debris. When a
58   threshold of fine fuels is exceeded in a cell, the fire intensity increases. This threshold is based
59   off a value of ~1100g/m^2 or about 5 tons per acre of fine fuels. The other threshold is based on
60   ladder fuels: a combination of specific species, under a certain age, and over a certain amount of
61   biomass per area, contribute to intensity. Those species contributing to ladder fuels are: Jeffrey
62   Pine, white fir, and incense-cedar, and the cohorts in the cell have to be younger than 40 with a
63   biomass greater than 2000g/m^2 (9 tons per acre). When one threshold is exceeded, fire intensity
64   increases. When both thresholds are exceeded, fire intensity is at its highest. High intensity fire
65   spreads as high intensity fire. To validate fire intensity for the Basin, the targeted fire intensity
66   value for any of the larger multi-day fires was 40% high, 40% mid, and a 20% low intensity,
67   with high intensity less than 60% of the total fire area. These targets are based on long-term
68   averages calculated for the Northern half of the Sierra Mountains (which includes the Lake
69   Tahoe footprint) using the Monitoring Trends in Burn Severity Composite Burn Index data.
70   Over the entire data period (1984-2020), the percentage of area burned at high severity was 41%
71   each year (with 36% and 22% for moderate and low severity respectively), with up to 58% of
72   area burning at high severity in 2007, see Table S7.
73   *Insect modeling*
74   A modified version of the Biological Disturbance Agent extension (Biomass BDA v.2.0)
75   (Sturtevant et al. 2009) was used to simulate insect outbreaks for three species of insects: Jeffrey
76   pine beetle (*Dendroctonus jeffrey*), mountain pine beetle (*Dendroctonus ponderosae*), and fir
77   engraver beetle (*Scolytus ventralis*). The extension requires insect-specific resource
78   requirements and assigns a species-specific vulnerability that varies by age. Cells are
79   probabilistically selected for disturbance based upon the species host density at a given site and
80   the presence of non-hosts reduce disturbance probability. The parameters for spread and
81   mortality are outlined in Kretchun et al. (2016), see Table S5 and Table S6 below. Mortality at
82   an outbreak site is subsequently determined by species' age and host susceptibility probabilities
83   based from empirical field studies (Egan et al. 2010, 2016) and expert opinion, see Table 2
84   below. The insects had differing rates of spread per year from previous outbreaks. Mountain
85   Pine Beetle had positive neighbor effects, where pheromones promoted more rapid spread when
86   there were neighboring populations. All insects were able to exploit recently burned stands up to
87   10 years after a fire. Following mortality, dead biomass remains on site and moves to the
88   downed woody debris C pool and the fine woody debris C pool.
89   However, unlike Kretchun et al. (2016), the trigger for an outbreak was changed to be responsive
90   to climate signals. This is because for many beetle species climate influences outbreaks in three
91   ways: low winter temperatures cause beetle mortality; year-round temperatures influence
92   development and mass attack; and drought stress reduces host resistance. Here, we modeled
93   climate influences as a function of drought and mean minimum winter temperature, recognizing
94   that the full suite of climatic influences is necessary for a fully mechanistic model. So long as
95   annual climatic water deficit exceeded a set threshold, in conjunction with mean winter
96   minimum temperatures exceeded a certain threshold, outbreaks could occur. A comparison
97   between the modeled and observed outbreak dataset (USFS Aerial Detection Survey:

98   https://www.fs.fed.us/foresthealth/applied-sciences/mapping-reporting/index.shtml) found an
99   overestimation of frequency of occurrence but an underestimation of area impacted by insects
100 (Figure S7). However, there was unprecedented mortality across the Sierras due to the drought
101 in California that lasted from 2012-2016, and the cause of the mortality has not been definitively
102 attributed to insects or drought given that field studies are retrospective (e.g., Fettig et al. 2019,
103 Restaino et al. 2019). While the ADS data were the main source of such insect mortality data;
104 there are significant limitations with the data. Not all areas receive a fly-over each year and very
105 few areas that are marked as having mortality receive on the ground verification. A newer
106 dataset developed by the R5 Remote Sensing Research Team uses LANDSAT images to assess
107 changes in canopy cover through time. From personal communication with Michele Slaton
108 (USFS) who helped develop this data product, the amount of area affected by insects is far less
109 than what is reported by the Aerial Detection Survey possibly due to the limited accuracy of fly-
110 over mapping. However, these data are still provisional as their manuscript is in review.
111
112 *Pile burn emissions factor calculation*

Pile Group Data:

Group No.	Group Name	No. Piles	Pile Type	Pile Shape	Pile Dimensions (m)	Soil %	Packing Ratio	Pile Composition	Pile Quality	Consumption
1	PileGroup1	1	Hand	Half ellipsoid	W1: 3.1 H1: 1.2 L1: 3.1	N/A	N/A	Conifer	N/A	90%

Pile Group Results:

Pile Group No.	Pile Group Name	Species Comp.	Gross Volume (m³)	Adjusted* Volume (m³)	Wood Density (g/cm³)	Pile Biomass (Mg)	Consumed Fuel (Mg)	Emissions by pollutant (Mg) PM	PM10	PM2.5	CO	CO2	CH4	NMHC
1	PileGroup1	Conifer	6.04	4.92	na	0.3011	0.271	0.0003	0.00021	0.00018	0.0103	0.4508	0.00008	0.0006
TOTAL			6.04	4.92		0.3011	0.271	0.0003	0.00021	0.0018	0.0103	0.4508	0.00008	0.0006

113
114 *Adjusted volume for hand piles is corrected to account for the difference between the gross
115 volume of a geometric shape and the actual volume of the pile.
116 Machine pile adjusted volume of solid wood is determined by subtracting the amount that is soil
117 from the gross volume and applying the appropriate packing ratio.
118
119 Piled Fuels Biomass and Emissions Calculator (https://depts.washington.edu/nwfire/piles)
120

129 **Supplemental Tables:**

130 Table S1. Suppression effort levels and effectiveness on fire spread probability.

Fire Type	Fire Weather Index Thresholds		Effort Level		
	Low-mod	Mod-high	Low	Moderate	High
Accidental	40	60	0	5	10
Lightning	40	60	0	5	10
Rx	40	60	0	0	0

131

132 Table S2. Prescribed fire parameters used for scenarios 4 and 5.

Prescribed Fire Parameters	Scenario 4	Scenario 5
MaximumRxWindSpeed	6.6 (m/s)	6.6 (m/s)
MaximumRxFireWeatherIndex*	55 (unitless)	55 (unitless)
MinimumRxFireWeatherIndex*	10 (unitless)	10 (unitless)
MaximumRxFireIntensity	1 (low)	1 (low)
NumberRxAnnualFires	30 (fixed)	364, subject to suitable weather
FirstDayRxFires	289 (first Julian day for allowable fire)	1 (first Julian day for allowable fire, subject to fire weather)
TargetRxSize	40 (hectares)	72 (hectares)

133   *Canadian Fire Weather Index, see Scheller et al. (2019) for more details.

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135   Table S3. Species parameters used in modeling.

Name	Longevity	Sexual maturity age	Shade tolerance	Fire tolerance	Seed effective dispersal distance (meters)	Maximum dispersal distance (meters)	Vegetative Reproduction Probability	Minimum age veg reproduction	Maximum age veg reproduction	Post-fire regeneration
Pinus jeffreyi	500	25	2	5	50	300	0	0	0	none
Pinus lambertiana	550	20	3	5	30	400	0	0	0	none
Calocedrus decurrens	500	30	3	5	30	1000	0	0	0	none
Abies concolor	450	35	4	3	30	500	0	0	0	none
Abies magnifica	500	40	3	4	30	500	0	0	0	none
Pinus contorta	250	7	1	2	30	300	0	0	0	none
Pinus monticola	550	18	3	4	30	800	0	0	0	none
Tsuga mertensiana	800	20	5	1	30	800	0.0005	100	800	none
Pinus albicaulis	900	30	3	2	30	2500	0.0001	100	900	none
Populus tremuloides	175	15	1	2	30	1000	0.9	1	175	resprout
Non-N fixing, Resprouting	80	5	2	1	30	550	0.85	5	70	resprout
Non-N fixing, Seeding	80	5	2	1	30	1000	0	0	0	none
N fixing, Resprouting	80	5	1	1	30	500	0.75	5	70	resprout
N fixing, Seeding	80	5	1	1	30	800	0	0	0	none

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138   Table S4. Harvest removals prescription tables.

		Abies concolor	Calocedrus decurrens	Pinus jeffreyi	Abies magnifica	Pinus contorta	Pinus lambertiana	NonnResp	NonnSeed	FixnResp	FixnSeed
Hand Thinning	Age range	1-60	1-64	1-52	1-60	1-73	1-52	10-200	10-200	10-200	10-200
Scenario 1 - 5	Percent removed	-66%	-66%	-66%	-66%	-66%	-66%	-5%	-5%	-5%	-5%
Trees up to 11" dbh	Age range	61-70	65-78	53-68	61-75	74-88	53-64				
	Percent removed	-39%	-39%	-39%	-39%	-39%	-39%				
Mechanical Thinning		Abies concolor	Calocedrus decurrens	Pinus jeffreyi	Abies magnifica	Pinus contorta	Pinus lambertiana	NonnResp	NonnSeed	FixnResp	FixnSeed
Scenario 1, 2, 4, 5	Age range	1-60	1-64	1-52	1-60	1-73	1-52	10-200	10-200	10-200	10-200
Trees up to 24" dbh	Percent removed	-93%	-93%	-93%	-93%	-93%	-93%	-30%	-30%	-30%	-30%
	Age range	61-65	65-71	53-60	61-68	74-80	53-58				
	Percent removed	-70%	-70%	-70%	-70%	-70%	-70%				
	Age range	66-70	72-78	61-68	69-75	81-88	59-64				
	Percent removed	-65%	-65%	-65%	-65%	-65%	-65%				
	Age range	71-75	79-84	69-76	76-82	89-96	65-70				
	Percent removed	-57%	-57%	-57%	-57%	-57%	-57%				
	Age range	76-80	85-91	77-85	83-90	97-105	71-77				
	Percent removed	-45%	-45%	-45%	-45%	-45%	-45%				
	Age range	81-84	92-99	86-95	91-97	106-115	78-83				
	Percent removed	-32%	-32%	-32%	-32%	-32%	-32%				
	Age range	85-89	100-107	96-105	98-104	116-125	84-90				
	Percent removed	-23%	-23%	-23%	-23%	-23%	-23%				
	Age range	90-93	108-115	106-115	105-112	126-136	91-97				
	Percent removed	-17%	-17%	-17%	-17%	-17%	-17%				
	Age range	94-98	116-125	116-126	113-120	137-148	98-104				
	Percent removed	-13%	-13%	-13%	-13%	-13%	-13%				
	Age range	99-103	126-135	127-138	121-127	149-161	105-112				
	Percent removed	-8%	-8%	-8%	-8%	-8%	-8%				
	Age range	104-108	136-145	139-151	128-135	162-176	113-120				
	Percent removed	-4%	-4%	-4%	-4%	-4%	-4%				

Mechanical Thinning		Abies concolor	Calocedrus decurrens	Pinus jeffreyi	Abies magnifica	Pinus contorta	Pinus lambertiana	NonnResp	NonnSeed	FixnResp	FixnSeed
Scenario 3	Age range	1-60	1-64	1-52	1-60	1-73	1-52	10-200	10-200	10-200	10-200
Trees up to 38" dbh	Percent removed	-95%	-95%	-95%	-95%	-95%	-95%	-30%	-30%	-30%	-30%
	Age range	61-65	65-71	53-60	61-68	74-80	53-58				
	Percent removed	-95%	-95%	-95%	-95%	-95%	-95%				
	Age range	66-70	72-78	61-68	69-75	81-88	59-64				
	Percent removed	-85%	-85%	-85%	-85%	-85%	-85%				
	Age range	71-75	79-84	69-76	76-82	89-96	65-70				
	Percent removed	-85%	-85%	-85%	-85%	-85%	-85%				
	Age range	76-80	85-91	77-85	83-90	97-105	71-77				
	Percent removed	-85%	-85%	-85%	-85%	-85%	-85%				
	Age range	81-84	92-99	86-95	91-97	106-115	78-83				
	Percent removed	-75%	-75%	-75%	-75%	-75%	-75%				
	Age range	85-89	100-107	96-105	98-104	116-125	84-90				
	Percent removed	-70%	-70%	-70%	-70%	-70%	-70%				
	Age range	90-93	108-115	106-115	105-112	126-136	91-97				
	Percent removed	-60%	-60%	-60%	-60%	-60%	-60%				
	Age range	94-98	116-125	116-126	113-120	137-148	98-104				
	Percent removed	-35%	-35%	-35%	-35%	-35%	-35%				
	Age range	99-103	126-135	127-138	121-127	149-161	105-112				
	Percent removed	-20%	-20%	-20%	-20%	-20%	-20%				
	Age range	104-108	136-145	139-151	128-135	162-176	113-120				
	Percent removed	-10%	-10%	-10%	-10%	-10%	-10%				
	Age range	109-120	146-180	152-240	136-180	177-230	121-160				
	Percent removed	-10%	-10%	-10%	-10%	-10%	-10%				
	Age range	121-125	181-200	241-252	181-190	231-250	161-180				
	Percent removed	-5%	-5%	-5%	-5%	-5%	-5%				

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140   Table S5. Insect disturbance inputs by insect.

	Fir Engraver		Jeffrey Pine Beetle		Mountain Pine Beetle	
	Parameter	Source	Parameter	Source	Parameter	Source
Dispersal Rate	1000 m/year	Jactel (1991)	600 m/year	Egan (personal comm.)	400 m/year	Safranik (2006)
Neighborhood Effect	N/A	USFS Fir Engraver Facts (2017)	N/A	N/A	Yes, 2x	Safranik (2006)
Disturbance Modifier	Fire: 100%, 10 years	Schwilk 2006	Fire: 100%, 10 years	Schwilk 2006	Fire: 100%, 10 years	Schwilk 2006

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143   Table S6: Insect disturbance parameters by insect by host species.

|		Susceptibility			Mortality			
	Target Species	*Age Class 1*	*Age Class 2*	*Age Class 3*	*Age Class 1*	*Age Class 2*	*Age Class 3*	*Source*
Fir Engraver	*Abies concolor*	0-10, 0%	10-60, 65%	60+, 75%	0-10, 0%	10-60, 8%	60+, 12%	Ferrell 1994, Schwilk 2006, Egan (personal comm)
	Abies magnifica	0-10, 0%	10-60, 45%	60+, 55%	0-10, 0%	10-60, 8%	60+, 12%	
Jeffrey Pine Beetle	*Pinus jeffreyi*	0-20, 10%	20-30, 80%	30+, 80%	0-40, 5%	40-120, 18%	120+, 8%	Egan et al. 2016
Mountain Pine Beetle	*Pinus albicaulis*	0-20, 33%	20-60, 66%	80+, 80%	0-20, 5%	20-60, 15%	80+, 20%	Safranik (2006), Cole and Amman (1980)
	Pinus lambertiana	0-20, 33%	20-60, 66%	80+, 80%	0-20, 5%	20-60, 25%	80+, 30%	
	Pinus contorta	0-20, 33%	20-60, 66%	80+, 80%	0-20, 5%	20-60, 15%	80+, 20%	
	Pinus monticola	0-20, 33%	20-60, 66%	80+, 80%	0-20, 5%	20-60, 25%	80+, 30%	

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147 Table S7. Percent of fire severity type by class based on MTBS thematic burn severity for the Northern Sierras.

|	1984	1985	1986	1987	1988	1989	1990	1991	1992	1994	1996	1997	1999	2000	2001	2002	2003	2004
High severity	23%	16%	21%	32%	39%	37%	41%	6%	68%	48%	21%	17%	28%	45%	50%	31%	8%	42%
Moderate severity	30%	17%	52%	39%	35%	41%	35%	52%	23%	29%	56%	41%	49%	36%	37%	41%	51%	36%
Very low/low severity	47%	67%	27%	29%	27%	22%	24%	42%	9%	22%	23%	42%	24%	19%	13%	29%	41%	23%
	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**		**Total**
High severity	32%	27%	58%	30%	20%	15%	5%	34%	42%	54%	45%	36%	38%	38%	37%	50%		41%
Moderate severity	42%	52%	29%	48%	39%	45%	39%	48%	37%	24%	32%	43%	37%	40%	39%	26%		36%
Very low/low severity	26%	21%	12%	22%	41%	39%	56%	18%	22%	21%	23%	22%	26%	21%	24%	24%		22%

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149 Table S8. Cumulative emissions of PM2.5, averaged across all replicates and climate projections (combinations of RCP4.5 and
150 RCP8.5 emission scenarios and four GCMs).

151

| Scenario	1	2	3	4	5
Wildfire and understory Rx emissions	50697	25807	10028	52389	92060
Wildfire and understory Rx emissions as % of Scenario 2	96%	0%	-61%	103%	257%
Pile burning emissions	0	8363	23117	5388	3924
Total	50697	34170	33145	57776	95984
Total as % of Scenario 2	48%	0%	-3%	69%	181%

152

Supplemental Figures:
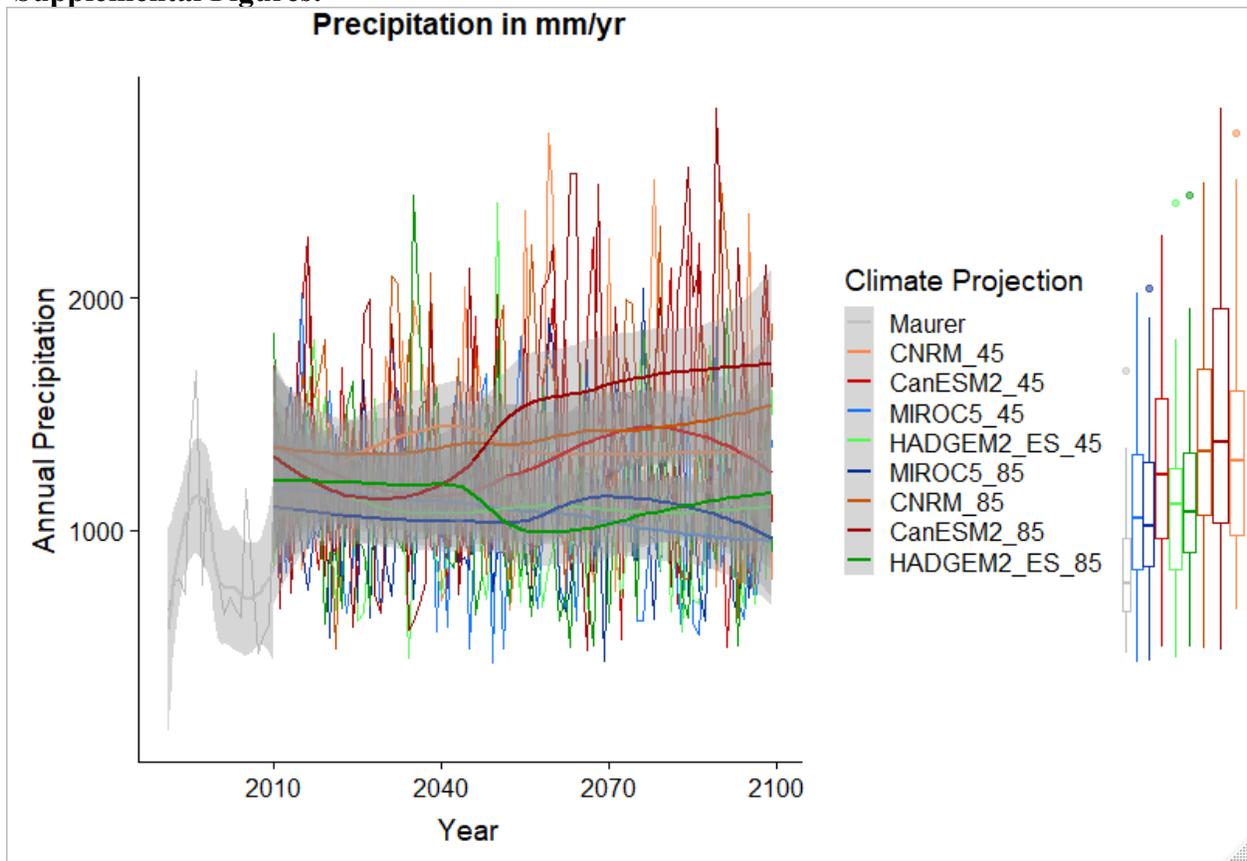
Figure S1. Projected precipitation in mm yr^{-1}, lines of best fit are GAM estimated, and boxplots
represent distribution of annual precipitation for the years 2090-2100.

Number of consecutive days with precipitation less than 0.1mm
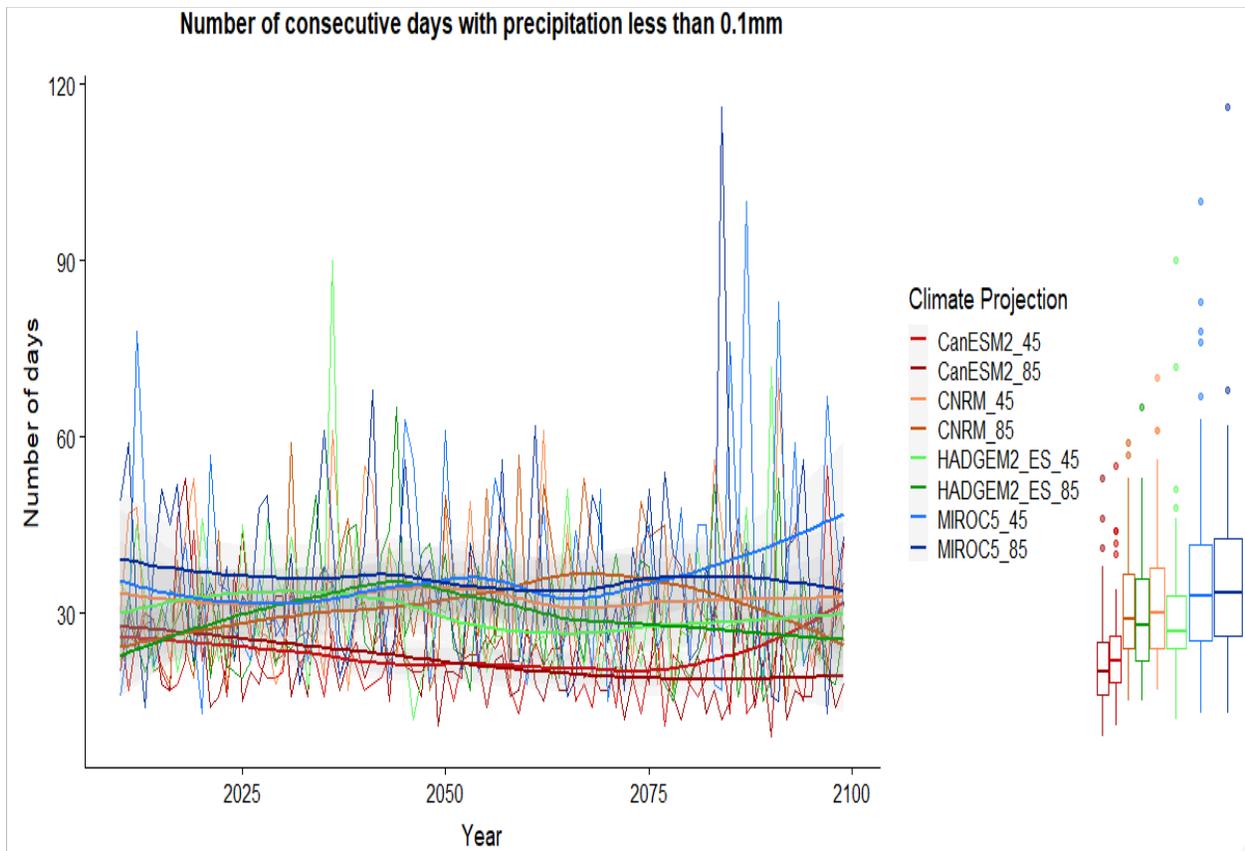
157
158 Figure S2. Projected number of consecutive days with no precipitation, lines of best fit are GAM
159 estimated, and boxplots represent distribution of consecutive days per year for the years 2090-
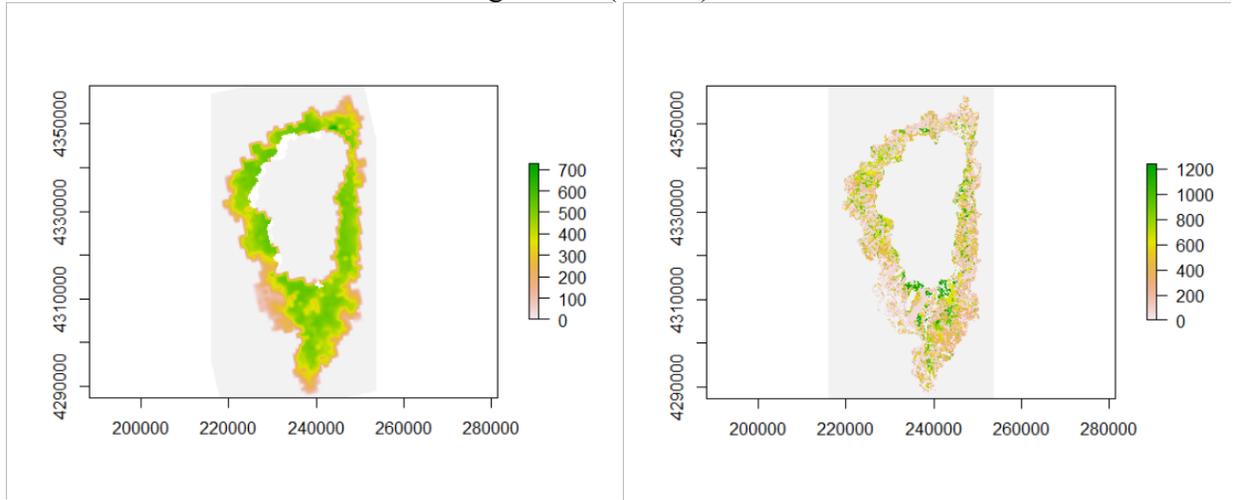160 2100.
161
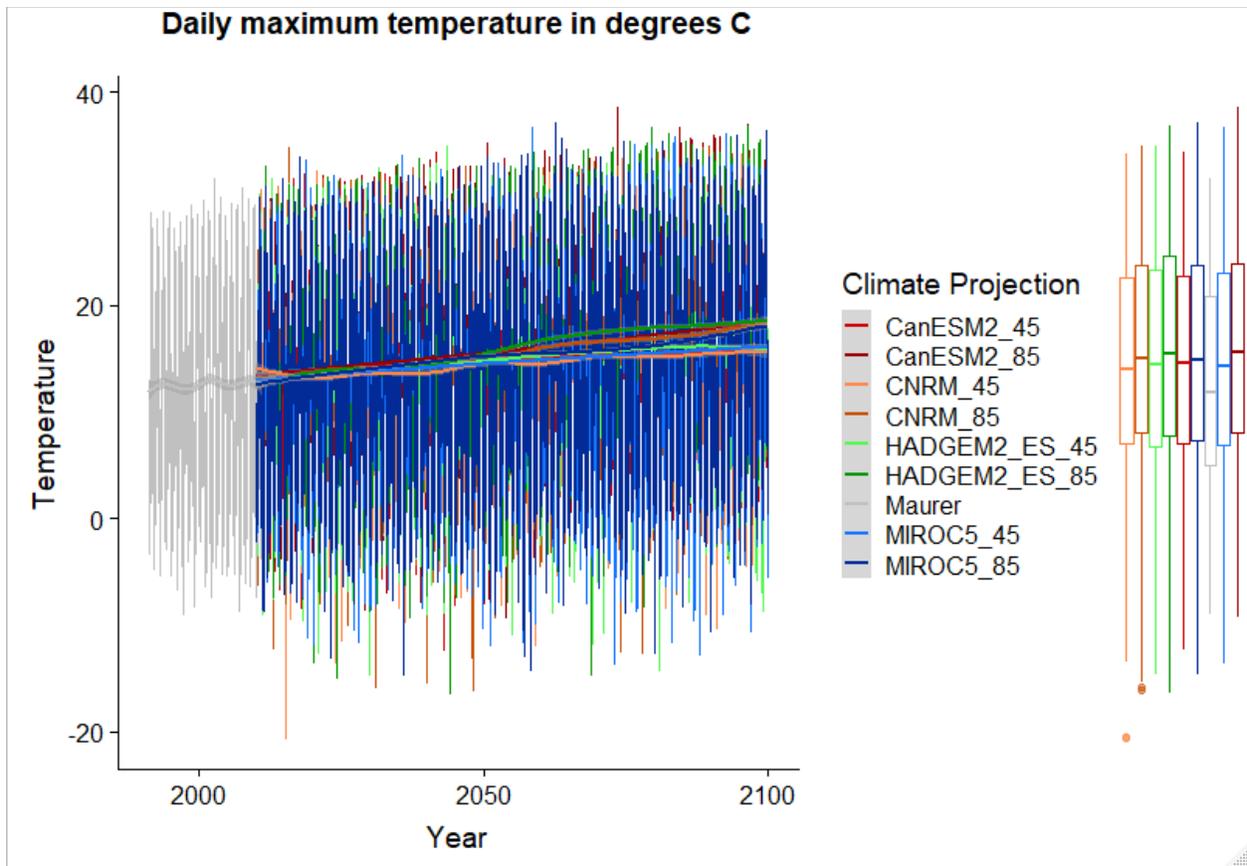
Figure S3. Projected daily maximum temperature in degrees C, lines of best fit are GAM
estimated, and boxplots represent distribution of daily temperatures for the years 2090-2100 for
the future climate projections.
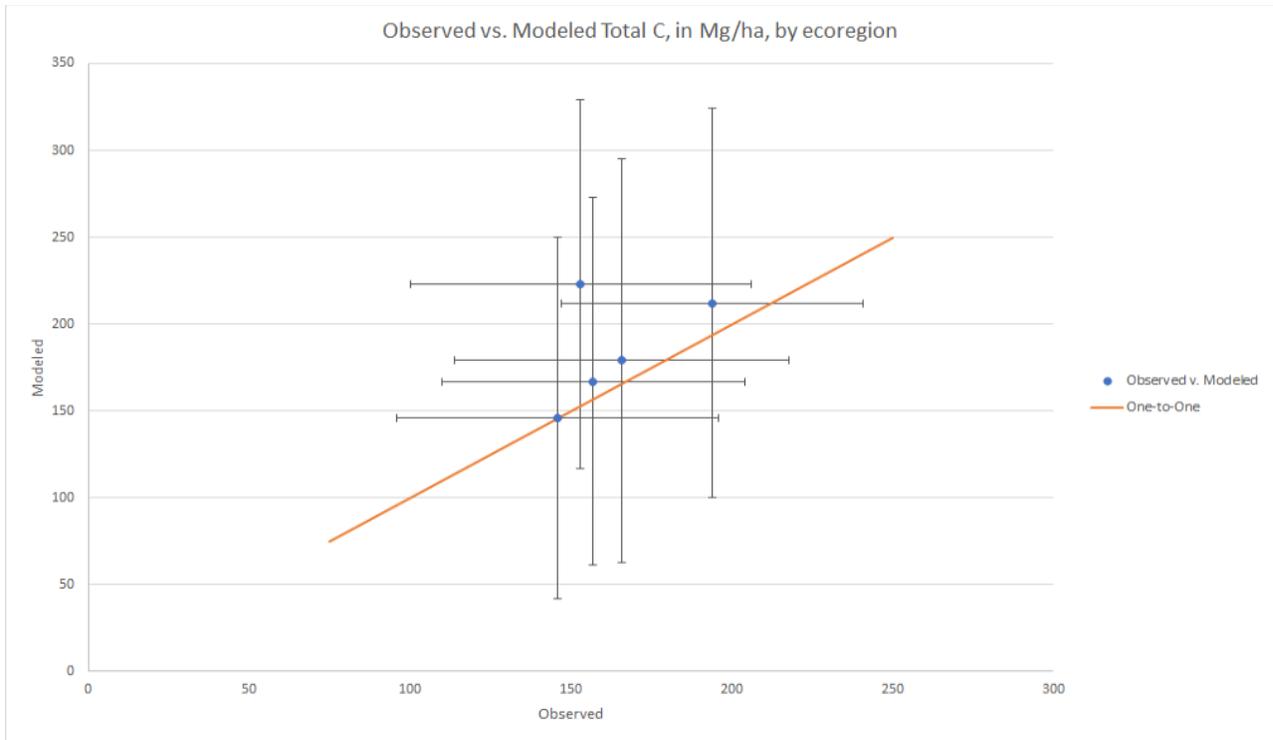
Figure S4. Observed versus modeled total C, in megagrams C per hectare, by ecoregion, error
bars represent +/- 1 standard deviation.

181   Figure S5. Comparison of MODIS (left) and LANDIS (right) estimates of Net Primary
182   Productivity in g C/m ^2. Mean landscape value for MODIS was 393 g C/m ^2 (sd 134), while
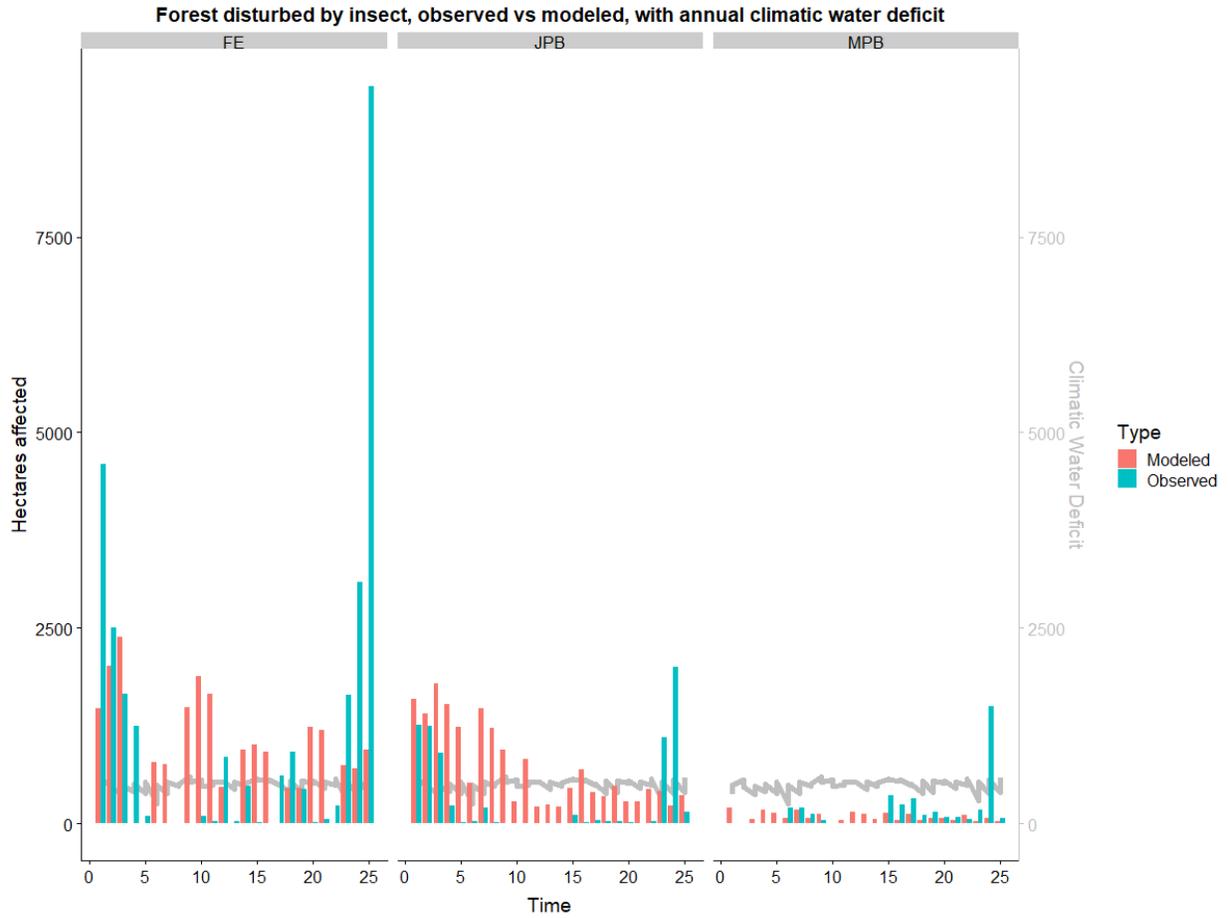183   for LANDIS the mean value was 320 g C/m^2 (sd 312).


184

Suppression_Effort
- NA
- Low
- Medium
- High

LTB_managment_areas
- WUI Defense
- WUI Threat
- Desolation Wilderness
- Mt Rose Wilderness
- General Forest
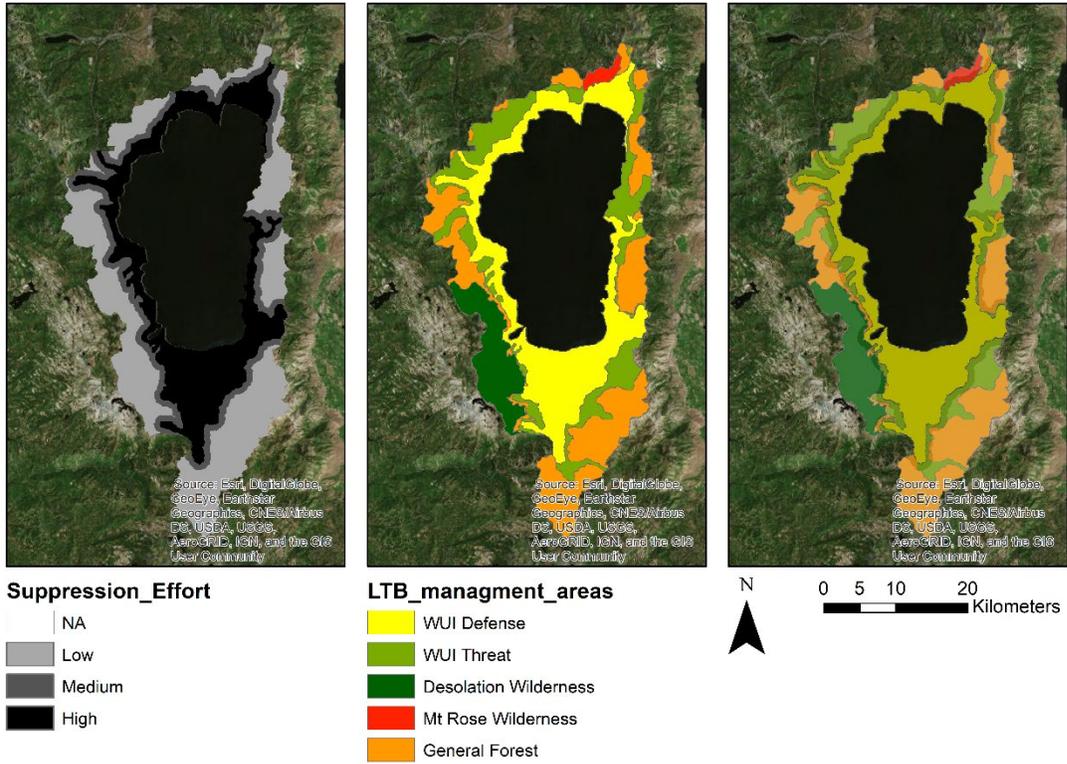
185
186   Figure S6. Map of suppression effort (left), management zone (middle), and the overlay of the
187   two (right).

Figure S7. Observed versus modeled number of hectares affected by insect/mortality agent. Time 0 is equal to 1990, with Time 22-25 corresponding to the 2012-2015 California drought. FE is fir engraver beetle (*Scolytus ventralis*), JPB is Jeffrey pine beetle (*Dendroctonus jeffrey*), and MPB is mountain pine beetle (*Dendroctonus ponderosae*).
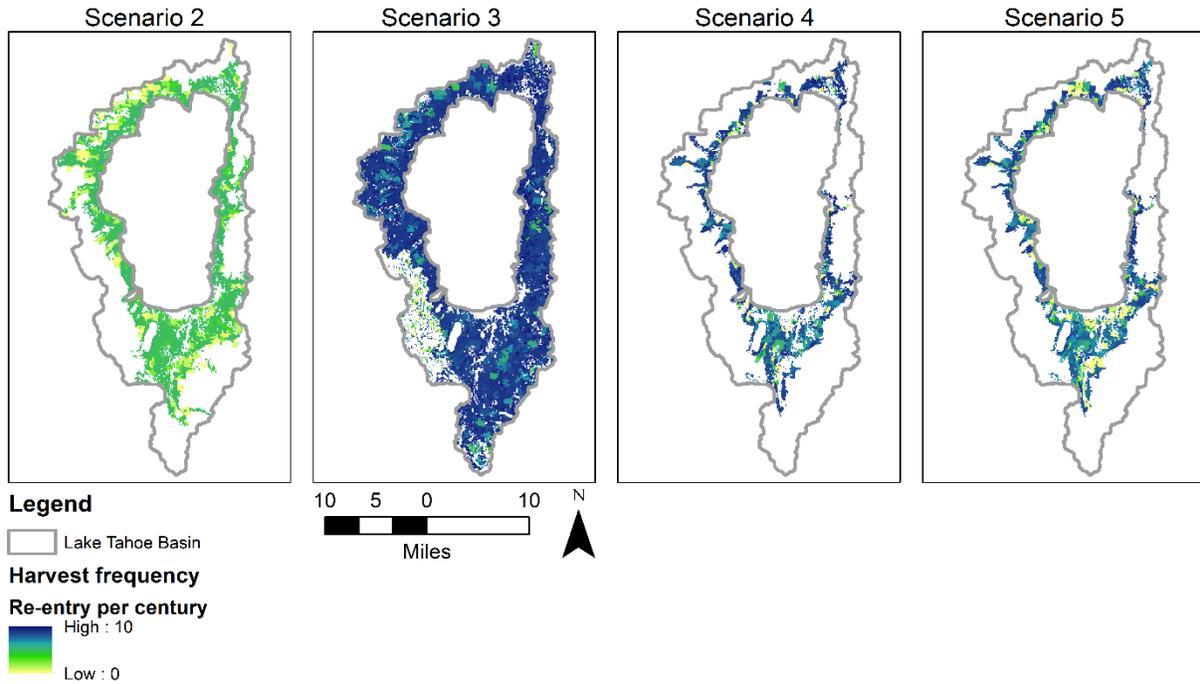
195
196 Figure S8. Harvest return frequency by management scenario. Treatments were expanded
197 beyond the WUI area in Scenario 3. Scenarios 3 through 5 had a higher intended treatment
198 frequency.
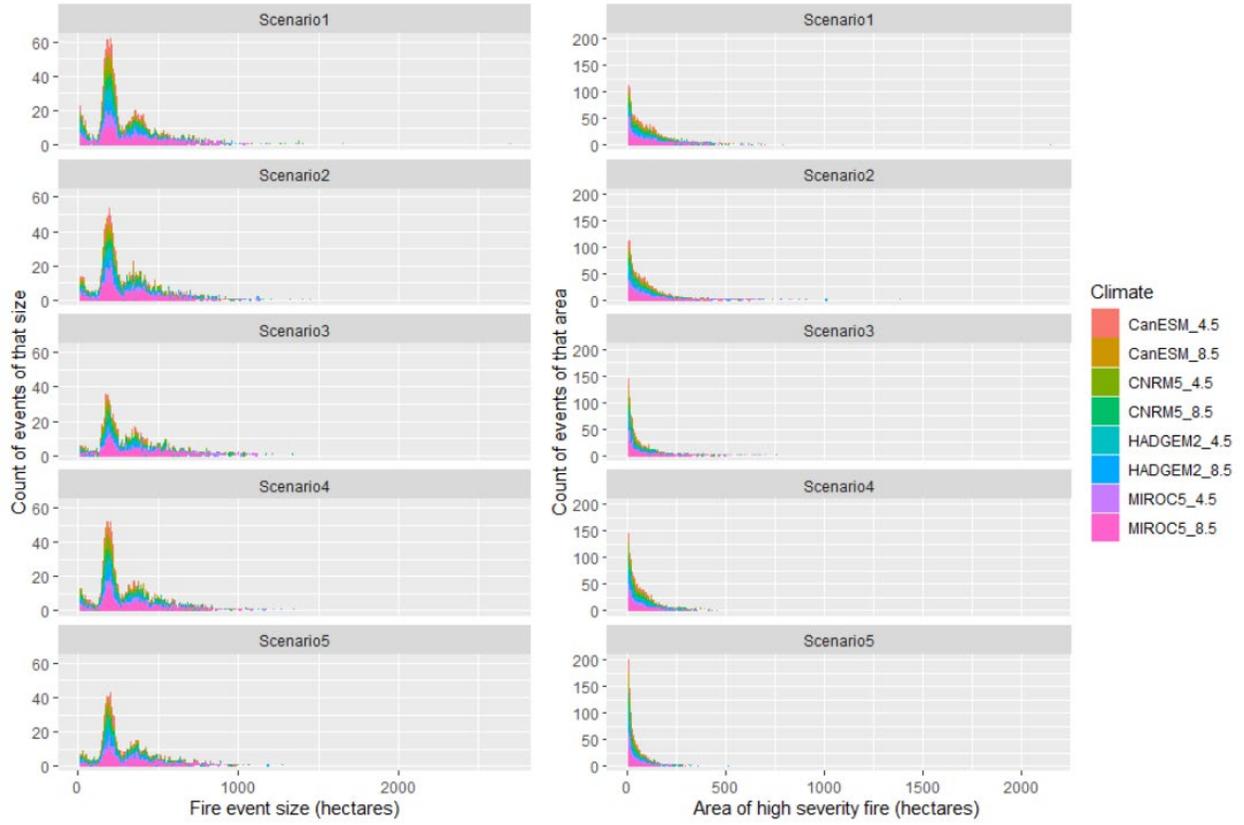
199
200 Figure S9. Histogram of fire sizes (left) and high severity fire area (right) by scenario and by
201 climate

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