



Research, part of a Special Feature on [The Many Facets of Forest Resilience in the Lake Tahoe Basin](#)

Water quality and forest restoration in the Lake Tahoe basin: impacts of future management options

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ABSTRACT. Land managers in the Lake Tahoe basin are considering increasing the use of prescribed fire and forest thinning to restore conditions that will be more resilient to wildfires. However, such restorative treatments also constitute disturbances that could increase sediment and nutrient loads. We examined whether the water-quality impacts from future treatments are likely to be lower compared to the potential impacts from future wildfires under various climate change scenarios. We applied an online interface for the Water Erosion Prediction Project (WEPP) model in combination with a landscape change model (LANDIS-II) to evaluate the effects of different combinations of thinning and prescribed burning on fine sediment (< 2 mm), very fine sediment (< 16 µm), and phosphorus over time. First, we generated results based on historic weather data for soil disturbance conditions, including: an undisturbed baseline, a uniform thinning treatment; a uniform prescribed fire treatment; and uniform low, moderate, and high wildfire burn severity. Residual ground cover declined in that order, and expected loads of sediment and phosphorus increased. We then combined the estimated loads from hillslopes with projected management-disturbance regimes across each decade of the next century. We found that expected sediment and phosphorus loads were lower under the scenario that emphasized thinning, whereas scenarios that increased prescribed burning resulted in loads that were comparable to scenarios that involved less treatment. These results reflect the finding from the WEPP analysis that prescribed burning is expected to reduce ground cover more than is thinning. Our analysis supports efforts to increase fuel reduction treatments to mitigate future wildfires, but it also suggests that preventative treatments may not avoid a long-term decline in water quality as wildfires increase with climate change.

Key Words: *forest management; Lake Tahoe basin; landscape modeling; nutrients; soil erosion; water quality*

INTRODUCTION

During the 1900s, fire suppression became the dominant management strategy in forested watersheds throughout the western United States (Fiedler et al. 2010). This activity reduced the prevalence of low-severity, patchy wildfires resulting from lightning and burning by Native Americans (Lindström et al. 2000). Increased air temperatures in recent decades coupled with a century of fuel buildup from fire suppression have increased the severity and frequency of large wildfires (Westerling et al. 2006). Large, high-severity wildfires often lead to increased soil erosion and associated downstream flooding and degradation of water quality.

Soil erosion is a natural process; however, runoff from forested watersheds that have not recently been disturbed carries very little sediment (Elliot 2013). Forested watersheds with such low sediment loads have minimal concentrations of nutrients adsorbed to that sediment and few heavy metals that may be part of the soil chemistry (e.g., phosphorus and arsenic, respectively). By removing soil ground cover, disturbances (through either forest treatments or wildfire) can cause an increase in soil erosion, which can impair water quality in several ways. Sediments deposited in upland streams can adversely affect habitat for aquatic organisms (McCormick et al. 2010). Suspended fine sediments reduce water clarity. Fine inorganic soil particles (1–16 µm) are associated with a decrease in water clarity (Swift et al. 2006) and are of particular concern for managers in areas where water clarity is important, such as Lake Tahoe, which has been designated as an “Outstanding Natural Resource Water.” Unlike sand and coarse particles, which have rapid settling velocities, silt and clay particles can remain in suspension for extended periods of time and can reduce a water body’s clarity through light scattering (Sahoo et

al. 2010, Davies-Colley et al. 2014). In addition, suspended fine sediments transport adsorbed nutrients such as phosphorus, which in turn stimulates algal blooms with detrimental consequences for water quality and clarity.

Wildfire, especially high-severity fire, tends to have major and long-lasting effects on water quality (Murphy et al. 2006). Given the current high risk of wildfire in many forests in the western United States, land managers are trying to reduce the available fuel loads from dead or dying trees, downed woody debris, and overly dense understories through treatments such as thinning or prescribed fires. Managers in the U.S. Forest Service design treatments while considering a range of objectives, including enhancing wildlife habitat and recreation, sustaining water quality, and using biomass for wood products or energy. In particular, forest managers face the challenge of managing the water-quality risk trade-offs between fuel management activities and potential wildfire (Elliot et al. 2008). Associated road networks and fire lines can be additional sources of sediment, and they increase peak runoff events, causing higher channel erosion and sediment delivery (Gucinski et al. 2001, Elliot et al. 2019, Cao et al. 2020). In addition to causing erosion, biomass reduction may decrease evapotranspiration, increasing runoff, channel erosion, and sediment transport from watersheds (Srivastava et al. 2018). In most cases, however, these activities are likely to cause much less erosion than would occur following a high-severity wildfire (Elliot 2013).

Estimating water quality trade-offs between wildfire and fuel management is not simple. Forest landscape and disturbance models have been developed that can estimate fire frequency and severity (Buckley et al. 2014, Scheller et al. 2018). Several recent

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studies (Elliot et al. 2016) have used the Water Erosion Prediction Project (WEPP) model (Laflen et al. 1997) to estimate upland erosion and sediment yield. Such an approach has been applied to forested hillslopes (Buckley et al. 2014), but rarely at a watershed scale, which involves considering channel processes such as sediment transport, deposition, and entrainment. Another important watershed process, phosphorus delivery, has not been evaluated in previous analyses. Elliot et al. (2015) demonstrated a method for using WEPP model outputs to estimate phosphorus delivery, but the method has not been applied at a landscape scale or validated for either hillslopes or watersheds. Further integrating fire spread or burn severity models with soil erosion models can provide an estimation of these trade-offs on soil erosion and sediment delivery to downstream water bodies.

Our objectives were: (1) to link a model of landscape change and disturbance (LANDIS-II; Scheller et al. 2007) to the WEPP watershed model to evaluate the effects of forest management on the delivery of sediment and phosphorus from disturbed forest hillslopes, and (2) to compare estimated sediment and phosphorus following forest management activities and following wildfires.

METHODS

Our study focuses on watersheds on the west side of the Lake Tahoe basin, a high-elevation lake in the Sierra Nevada mountains along the California-Nevada border in the western United States. The lake is renowned for its exceptional water clarity and has been afforded special environmental protections as an outstanding water body, with land managers and regulators implementing programs to reduce pollutant loads, especially those associated with urbanization (Riverson et al. 2008, Sahoo et al. 2010). Managers are also working to reduce the threat of wildfires that threaten life and property, air quality, forests, and water quality, primarily through thinning and prescribed fire treatments. Lake Tahoe was placed on the Section 303(d) list of water bodies requiring total maximum daily loads in 1988 because of ongoing loss of the lake's historic deep water transparency, and it has been designated as an Outstanding Natural Resource waterbody, which affords it the highest level of protection under the antidegradation policy of the *Clean Water Act*. The bi-state Tahoe Regional Planning Agency has formulated strict policies and regulations to protect and restore water quality throughout the basin (Cobourn 2006). As such, the Lake Tahoe basin provides an ideal test case for understanding the water quality impacts of alternative management strategies.

The elevation on the west side of Lake Tahoe ranges from 1900 m along the shore to 3040 m at Dick's Peak, on the crest of the Sierra Nevada mountain range. Watersheds within this area include a mixture of different land covers, soils, and slopes. Vegetation consists mainly of mixed coniferous forests of Jeffrey pine (*Pinus jeffreyi*), white fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*), red fir (*Abies magnifica*), and western white pine (*Pinus monticola*), and shrubs and grasses, with patches of bare ground and rock outcrops. Climate is characterized by dry summers and wet winters, with most precipitation falling as snow between December and March. A decade-scale trend analysis of temperature and precipitation data from long-term weather stations in the basin revealed that the basin could be warming faster than the surrounding regions (Coats 2010), which

has major implications for forest management and wildfires in the basin (Trotochaud 2015). In the Lake Tahoe West study area, soils are derived from volcanic rocks in the north and granitic rocks in the south, with alluvial wash deposits along the shore of Lake Tahoe and major streams.

The United States Department of Agriculture, Forest Service manages approximately 78% of the forested area within the Lake Tahoe basin (Scheller et al. 2018). These forests have been managed over the past few decades with restoration as the primary objective, specifically focused to eliminate livestock grazing and to harvest trees for fuel reduction rather than timber production. Managers intend to reduce fuels by "thinning from below", which means to harvest and remove understory trees using hand crews or mechanical equipment, and by applying prescribed fire (United States Department of Agriculture, Forest Service, Forest operations equipment catalog: <https://www.fs.fed.us/forestmanagement/equipment-catalog>). Pile burning of the harvested materials on site has been a customary treatment because biomass removal has often been economically infeasible (LTBMU 2014). Fuel management activities have focused on the wildland-urban interface to reduce the risk of wildfire to homes and other structures, and that is likely to continue to be a management priority. However, stakeholders within the Tahoe basin want to evaluate the potential benefits or impacts of expanding fuel management into the more remote forested areas.

Management scenarios and LANDIS-II landscape dynamics modeling

The LANDIS-II model was used to evaluate how the landscape would respond to five different management scenarios over a full century (Scheller et al. 2007). This model was originally developed to aid in managing forests for optimal timber harvest but has evolved to consider forest health, fuel management, and wildfire risk over large landscapes and long periods (Scheller et al. 2018). The LANDIS-II modeling framework, including the fire module, is a process-based simulation model that integrates multiple disturbances (human and natural) and climate change and is described more extensively in previous works (Scheller et al. 2019, Maxwell et al. 2022).

Within the LANDIS-II framework, the Net Ecosystem Carbon and Nitrogen (v.6.5) forest succession extension was used to track carbon and nitrogen through multiple live and dead aboveground and belowground pools. This extension also tracks forest growth and species dynamics, which are both dependent on temperature and water. Wildfire processes in LANDIS-II are stochastic (ignitions are constrained between start of spring and end of fall but are otherwise random through time), with ignition locations based on a probability surface derived from previous wildfire events. Treatment locations were randomly placed within a management zone, which followed the scenario intent, i.e., scenario 2 had treatments confined to the wildland-urban interface management zones.

Forest growth was calibrated against the MODIS 17A3 annual Net Primary Productivity product (Running and Zhao 2015). The SCRPPLE extension (v.2.1) modeled fire and was calibrated against Monitoring Trends in Burn Severity and CalFire Fire and Resource Assessment Program data sets (Scheller et al. 2019). A modified version of the Biological Disturbance Agent extension (Biomass BDA v.2.0) was used to simulate insect outbreaks and

Table 1. Management scenarios as defined by the Lake Tahoe West Restoration Partnership.

Scenario number	Scenario name	Scenario description
1	Suppression only	No treatment other than continued fire suppression
2	Wildland-urban interface (WUI) focused	A WUI-focused strategy similar to recent management: assumes no prescribed understory burning; includes hand and mechanical treatments in the WUI; thinning treatments could recur after 20 years
3	Increased thinning	A strategy of increasing pace and scale of vegetation thinning treatments: includes hand and mechanical treatments in the WUI and the general forest, with some hand treatments occurring in the wilderness; thinning treatments could recur after 11 years following thinning or burning
4	Fire focused	A fire-focused strategy combining modest WUI thinning with prescribed burning in all zones; limited suppression of lightning-ignited wildfires managed for resource objectives in the general forest and wilderness; thinning treatments projected to recur after 11 years without thinning or burning; prescribed burns do not have a set re-treatment interval; this scenario proposes 220 ha/yr of prescribed burning
5	Fire focused, expanded	A fire-focused strategy combining the modest WUI thinning under scenario 4 with much greater use of prescribed burning in all zones, averaging 1050 ha/yr within the Lake Tahoe western watersheds

was calibrated against the U.S. Forest Service Aerial Detection Survey data. More details about the calibration process are available in Appendix 1. Carbon estimates by pool were validated against Wilson et al. (2013) at the ecoregion level, where the model overestimated total carbon for only one region but was within one standard deviation for all others (Fig. S1 in Appendix 1). Forest growth estimates using the climate data for 2010–2015 for the region were calibrated against the MODIS 17A3 product annual mean for 2000–2015 (Fig. S2 in Appendix 1). Mean landscape value for MODIS was 393 g/cm² (standard deviation [SD] = 134), whereas for LANDIS-II, the mean value was 320 g/cm² (SD = 312). Contemporary wildfires (2000–2016, from CalFire Fire and Resource Assessment Program) were used to parameterize fire spread and size from the Central Sierra Nevada to increase the sample size of fires. Mean annual fire area for observed data was 117 ha/yr (SD = 309) and for modeled data was 122 ha/yr (SD = 210).

The five management scenarios were developed through a collaborative process led by an interagency team that articulated goals and targets with input from a committee of stakeholders (Table 1). The scenarios were intended to represent strongly contrasting management approaches (i.e., to “pin the corners”), rather than to precisely emulate a specific alternative. Thinning treatments were constrained to wildland-urban interface zones under scenarios 2, 4, and 5; under scenario 3, those treatments could also fall in the general forest zone. However, thinning occurred only in forested areas. Prescribed burns were ignited randomly and could occur in any area with sufficient fuels to carry a fire. In addition, under the two scenarios with prescribed burning (scenarios 4 and 5), an average of 40 ha/yr was burned by wildfires that were managed for resource objectives in remote areas, rather than targeted for full suppression.

Climate scenarios

Based on the findings of California’s fourth climate change assessment (Pierce et al. 2018), four global circulation models were the most representative of California’s hydrology and served as the basis for the future climate projections used here. The global circulation models were: Hadley Center Global Environment Model (HadGEM2), Canadian Earth System Model (CanESM), Centre National de Recherches Meteorologiques (CNRM5), and Model for Interdisciplinary Research on Climate (MIROC5). The climate projections included these global circulation models run

under two representative concentration pathways, 4.5 and 8.5, which represent a controlled and an uncontrolled emissions future, respectively.

The LANDIS-II model uses daily climatological variables with the data downscaled using the localized constructed analogs methodology (Pierce et al. 2018), averaged across the Level-IV U. S. Environmental Protection Agency ecoregions, and obtained from the U.S. Geological Survey geodata portal. Three LANDIS-II replicates were run for each combination of eight climate projections and five management scenarios (Table 1), resulting in 120 runs in total, and the erosion outputs were generated for each replicate and then averaged.

The future climate data were projected for the period 2010–2110. Recent historical average precipitation was 840 mm/yr for 1990–2010, with a coefficient of variation of 35% (minimum = 472 mm, maximum = 1688 mm). Future climate projections of precipitation are higher, with CanESM 8.5 having an increase in total precipitation as well as summertime precipitation. End of century (2080–2099) average annual precipitation was projected to be anywhere from 14% (MIROC5 4.5) to 107% (CanESM 8.5) higher than the 1990–2010 baseline. Daily maximum temperature averages are projected to increase by 5.5°C on average over recent historical by the end of century for representative concentration pathway 8.5, and by 2.6°C on average for representative concentration pathway 4.5.

The Water Erosion Prediction Project model and the WEPPcloud interface

The WEPP model is a process-based hydrology and erosion model that was initially developed to evaluate the effects of various management operations on surface runoff and soil erosion from small agricultural, rangeland, and forested hillslopes (Flanagan and Livingston 1995, Flanagan and Nearing 1995, Laflen et al. 1997). Since then, scientists from the U.S. Department of Agriculture’s Agricultural Research Service and Forest Service, and from elsewhere, have developed multiple tools, online interfaces (Elliot 2004, Robichaud et al. 2007, Frankenberger et al. 2011, Flanagan et al. 2013, Elliot et al. 2015), and GIS platforms (Flanagan et al. 2013, Miller et al. 2022) specifically designed to help users with the input data preparation and model results interpretation. These efforts have increased WEPP’s popularity among land and water managers, and the model

continues to be an important asset for managers seeking to understand the effects of various management treatments on water quality.

Within the last decade, major improvements to the model have made it applicable to larger forested watersheds (Covert et al. 2005, Dun et al. 2009, Zhang et al. 2009, Wang et al. 2010, Srivastava et al. 2013, 2017, Brooks et al. 2016), which further extended its applicability to forest management applications (Srivastava et al. 2018, 2020) and wildfire (Miller et al. 2011, 2022). The model can provide daily output of three major components of the streamflow hydrograph (surface runoff, lateral flow, baseflow), and sediment, fine sediment, and phosphorus yields (Elliot et al. 2015, Brooks et al. 2016, Dobre et al. 2022, Lew et al. 2022). Model results can be summarized for each hillslope and channel and as integrated output at the watershed outlet (Flanagan and Nearing 1995).

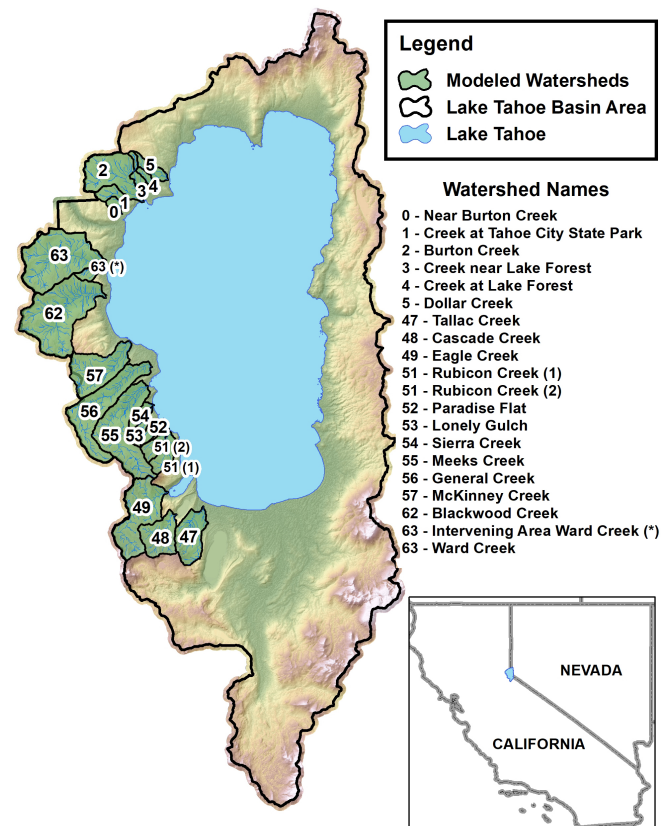
Brooks et al. (2016) previously validated the WEPP model in the Lake Tahoe basin at five watersheds and found the relative magnitude, timing, and distribution of sediments were comparable to observed sediment. However, the authors did not model the instream processes, so a direct comparison between observed and simulated sediments at watershed outlets was not possible. Recently, Dobre et al. (2022) updated the WEPP model runs in the Lake Tahoe basin to include baseflow processes and channel routing algorithms. Additionally, the authors calibrated the model for streamflow and sediment and phosphorus yields at 17 watersheds across the Lake Tahoe basin, including the five watersheds previously modeled by Brooks et al. (2016). Model calibration was minimal and involved alterations of the baseflow coefficient, critical shear, and phosphorus concentrations in runoff, lateral flow, and baseflow, which were obtained from observed water quality data at the outlet of several watersheds in the Lake Tahoe basin (Dobre et al. 2022). Model performance assessment based on daily streamflow and annual sediment and phosphorus indicated satisfactory agreement between modeled and observed values.

Using calibrating parameter values from Dobre et al. (2022), we applied the WEPP model to 20 watersheds on the west side of Lake Tahoe (Fig. 1) to estimate conditions resulting from the following management and wildfire events:

1. No event: baseline or undisturbed conditions (based on recent vegetation cover) associated with 100% ground cover in forested areas and 90% in shrub-dominated areas;
2. Forest thinning: 96, 93, and 85% ground cover in forested areas (the equivalent of hand, cable, and skidder thinning, respectively), with no treatment in other vegetation types;
3. Prescribed burning: 85% ground cover in forested areas and 75% cover in shrub-dominated areas, with no change in other vegetation types;
4. Low-severity wildfire: 80% ground cover in forested areas and 70% in shrub-dominated areas, with no treatment in other vegetation types;
5. Moderate-severity wildfire: 60% ground cover in forested areas and 50% in shrub-dominated areas, with no change in other vegetation types; and

6. High-severity wildfire: 30% ground cover in forested areas and 30% in shrub-dominated areas, with no change in other vegetation types.

Fig. 1. Map of the modeled watersheds in the western Lake Tahoe basin, California, USA. Names and numbers are based on established nomenclature in the Lake Tahoe basin. The Truckee River outlet to the lake is located between watersheds 0 and 63.



The purpose of simulating undisturbed conditions was to establish a baseline for sediment and phosphorus that managers could use to compare the effects of alternative management strategies with current conditions. For watersheds that were gauged, the undisturbed conditions also provided an opportunity to finely calibrate the model. Thinning and burning scenarios were simulated assuming the entire watershed was exposed to the same condition at once, although it is improbable that a fire would burn an entire watershed uniformly or that a thinning would occur on all hillslopes within a short period. This uniform application of a scenario tends to increase the overall sediment yield at the outlet of a watershed, but it allowed us to directly compare simulated runoff, sediment, and phosphorus for each hillslope and watershed from all management conditions. All model simulations were performed on a daily time step between 1990

and 2019. Although there are several WEPP model outputs important for management, we only focused on fine sediment (particles < 2 mm), very fine sediment (particles < 16 μ m), and total phosphorus loading. The latter two parameters, along with nitrogen, have been the primary pollutants targeted in load reduction efforts for Lake Tahoe (Sahoo et al. 2010).

All hydrological simulations were performed using wepppy (Lew et al. 2021; <https://github.com/rogerlewe/wepppy>) and are publicly available on the WEPPcloud interface (<https://wepp.cloud>), a newly developed, online, decision-support tool for the WEPP model, designed to facilitate input data preparation and model runs and to provide model outputs in both tabulated and spatial formats that are easily interpretable by land and water managers. Within the WEPPcloud interface, we created a site-specific interface for the Lake Tahoe basin. This interface contains enhanced soil and vegetation parameterizations based on Brooks et al. (2016) and from other published and unpublished data to address current management needs in the basin.

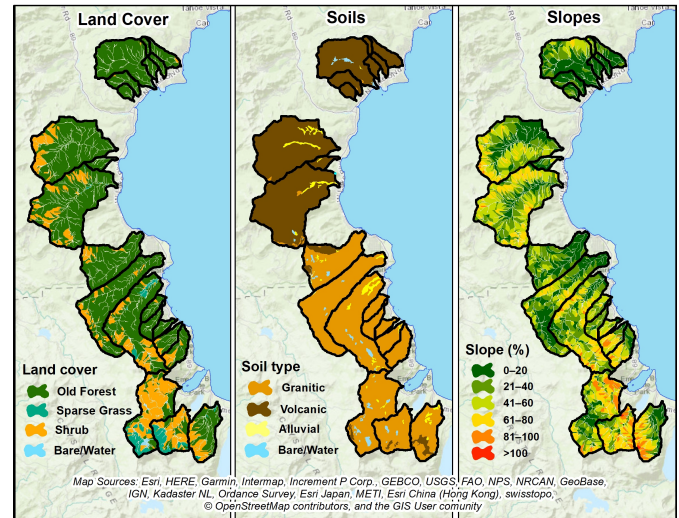
Watershed selection and modeling approach

We modeled all major watersheds ($N = 19$ of 22 watersheds) in the Lake Tahoe West landscape. We only excluded areas where the WEPP model would not be applicable, specifically, urban areas, watersheds with ski runs, and other associated impervious areas occurring in small “frontal” watersheds that are concentrated in the wildland-urban interfaces. Treatments in such developed areas differ from those in the general forest and would require more complex calibration and customization of input parameters. Furthermore, these developed areas are already included in pollutant load reduction plans in the basin, and they have previously been examined in modeling of sediment load reduction (Riverson et al. 2008, Grismer 2014).

Soils, land cover, and management conditions

All soil properties required by the model were automatically extracted from the U.S. Department of Agriculture Natural Resources Conservation Service’s Soil Survey Geographic (SSURGO) database (web soil survey: <https://websoilsurvey.nrcs.usda.gov/>; Keybold and TeSelle 1989). Similarly, the land-cover distribution within the watershed was based on the 2016 National Land Cover Database map (e.g., deciduous forest, evergreen forest, shrubland, etc.; Homer et al. 2015). The vegetation characteristics required within a WEPP management file were adopted from Brooks et al. (2016); however, initial canopy cover, ground cover, and leaf area index values were set based on the type of disturbance (Lew et al. 2021). Fig. 2 shows the distribution of soils, land-cover types, and slope steepness within the simulated watersheds. Although WEPP requires several soil and vegetative parameters, the most sensitive for runoff and soil erosion, especially among those that could be changed through treatment, are rill and interrill erodibility, canopy cover, rill and interrill ground cover, and leaf area index. The current vegetation algorithms we specified in WEPP do not simulate dynamic changes in vegetation within a single year. Average erosion rates assigned to a hillslope for these conditions were simulated by WEPP using 30 years of weather data. Vegetative recovery following disturbance was represented with the LANDIS-II model. Srivastava et al. (2020) successfully modified the WEPP model codes to include revegetation post-treatment; however, these changes are not yet implemented in the WEPPcloud interface.

Fig. 2. Land cover, soil, and slope distributions within the modeled Lake Tahoe watersheds.



Soil properties assigned in the model for each hillslope vary with soil type (which is strongly influenced by parent materials, e.g., granitic, volcanic, alluvial) and land cover (e.g., forest, shrubs, grass) and are affected by management and wildfire disturbances. To reflect a change in condition due to thinning, prescribed fire, or wildfire, key soils and vegetation parameters were altered based on default parameters similar to the Disturbed WEPP model (Elliot and Hall 2010, Elliot 2013, Miller et al. 2016, Dobre et al. 2022).

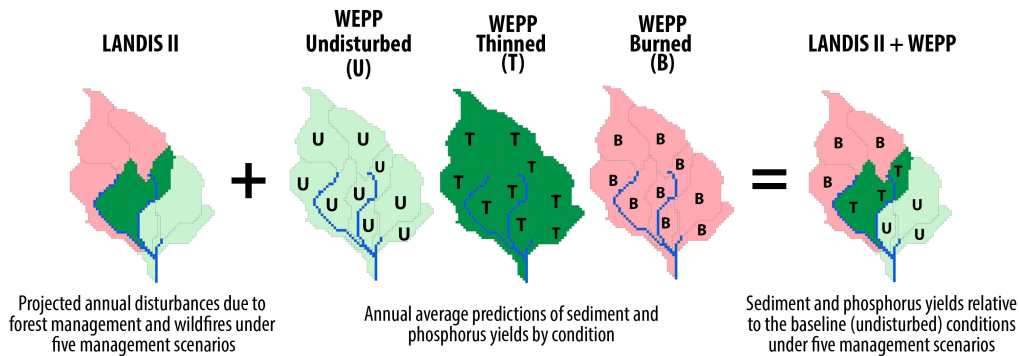
Weather data

In the Lake Tahoe model runs, we used the historic gridded Daymet (Thornton et al. 2016) database to acquire daily precipitation, maximum temperature, and minimum temperature for each hillslope within the modeled watersheds between 1990 and 2019. The rest of the weather parameters (storm duration, time to peak intensity, peak intensity, solar radiation, average wind speed and duration, and dew point temperature) were generated stochastically based on the nearby Tahoe, California station using the CLIGEN weather generator (Nicks and Lane 1989, Srivastava et al. 2019). The average precipitation at the Tahoe City weather station for the period 1990–2019 was 987 mm with a coefficient of variation of 38% (minimum = 228 mm, maximum = 1680 mm). Based on the probability distribution of the total annual precipitation, we classified eight years as dry (< 25th percentile) and eight years as wet (> 75th percentile).

Total phosphorus and very fine sediment calculations

The current version of the WEPP model does not include a full process-based soil phosphorus model. However, given that the model can predict the proportion of total streamflow delivered by runoff, lateral flow, and baseflow, dissolved phosphorus loads were calculated similar to Dobre et al. (2022) by multiplying the portion of total stream discharge in each of the three flow paths by a static phosphorus concentration obtained from long-term observed data from U.S. Geological Survey gauging streams in the basin. In addition to dissolved phosphorus, phosphorus can be attached to

Fig. 3. Schematic representation of the overlay of LANDIS-II and Water Erosion Prediction Project (WEPP) model outputs.



sediment particles or to organic matter embedded in eroded soil aggregates. Particulate phosphorus is included in most phosphorus budgets, but it may not necessarily be biologically active, and hence, it may not directly contribute to a decline in water quality (Ellison and Brett 2006). Particulate phosphorus was calculated similarly to dissolved phosphorus by multiplying sediment delivery for each hillslope by a static concentration obtained from observed data at the U.S. Geological Survey gauging stations (Dobre et al. 2022). Dissolved phosphorus and particulate phosphorus are summed to give total phosphorus.

Water quality regulators in the Lake Tahoe basin are especially concerned with the effects of very fine sediment particles ($< 16 \mu\text{m}$) on water quality (Sahoo et al. 2010). The WEPP model provides an estimate of the particle size distribution of delivered sediment as clay particles, silt particles, small soil aggregates containing silt, clay, and organic matter, sand particles, and large aggregates made up of clay, silt, sand and organic matter, with mean diameters of 0.002, 0.01, 0.03, 0.30, and 0.2 mm, respectively (Flanagan and Nearing 1995). The proportion of fine sediment in the aggregates was determined using a linear interpolation based on mean particle size. We estimated the total fine sediments delivered from each hillslope by multiplying the fine sediment fraction by the total delivered sediment from that hillslope.

We calculated both the annual average delivery rate ($\text{kg ha}^{-1} \text{yr}^{-1}$) and annual average yield (Mg/yr) for both sediment and phosphorus for each hillslope and watershed in the study area. While annual delivery rates from specific hillslopes can serve as guidance for land managers when selecting areas for treatments, total watershed loads are more relevant for the overall sediment and phosphorus delivery to Lake Tahoe. Therefore, both metrics are important to consider when analyzing forest treatments in the context of protecting water quality resources. In addition to calculating the overall load from all types of vegetation, we also calculated sediment and phosphorus yield from the forested hillslopes alone because most treatments in the Lake Tahoe basin are focused particularly on forested hillslopes.

We assessed the treatment effect on sediment and phosphorus yield using the Kruskal-Wallis nonparametric test followed by a multiple pairwise Wilcoxon test to determine differences in sediment and phosphorus among treatments. All analyses were performed in the statistical program R version 4.0.3 (R Core Team 2020).

Overlay with LANDIS-II outputs of disturbance

To evaluate how management scenarios would affect water quality over time, we overlaid simulated results from the WEPP analysis under different types of disturbed conditions with LANDIS-II estimates of future treatments and wildland fires. We used the combined models to forecast the overall effects of each management scenario on sediment yield, very fine sediment yield, and total phosphorus over the next 100 years (Fig. 3). Specifically, we overlaid WEPP annual average results of sediment and phosphorus yields for every hillslope with LANDIS-II annual projections of vegetation change under future climate scenarios. For each watershed, we first calculated the average annual hillslope soil and phosphorus loads under various management conditions (e.g., undisturbed, thinned, burned) for the 1990–2019 time period. We then identified hillslopes that experienced treatment or wildfire in LANDIS-II (2010–2110) under the five scenarios and added the difference in erosion or phosphorus loads resulting from the treatments and fires to the annual averages resulting from the undisturbed conditions. From this overlay, we projected total sediment and phosphorus loads for each year and a 20-year average period that resulted from the combination of treatments and wildfire. These projections did not account for the effects of climate change directly on the erosion and phosphorus through changes in precipitation type (e.g., snow vs. rain), amount, and intensity. An important distinction is that the processes in the WEPP model account for soil erosion, transport, and deposition from hillslopes to channels, within the channel profiles, and to the watershed outlet. In this analysis, we only used the spatially distributed sediment load delivered from the hillslopes that are mainly the target for the thinning and prescribed fire management operations. Additional channel and outlet output results, as well as results for particulate and soluble reactive phosphorus, in both tabulated and spatial formats, are available on the WEPPcloud interface (<https://weppcloud.lt/>).

We quantified the effects of various management scenarios based on the simulated fine sediment and phosphorus hillslope loading and delivery rates as well as percent increase above undisturbed conditions. Those percentages were then applied to the baseline load values to estimate loads resulting from disturbance (Fig. 3). This approach allowed us to compare the effects of management strategies on sediment and phosphorus yield over time. We used both the Mann-Kendal (Mann 1945, Kendall 1948) and Cox-

Stuart (Cox and Stuart 1955) tests at an alpha of 0.05 to identify monotonic trends in the daily sediment and phosphorus yield for the five management scenarios (Table 1). The null hypothesis for the Mann-Kendall test is the absence of a trend in the data, whereas the null hypothesis for the Cox-Stuart test is a decreasing trend in the data.

We linked the simulated WEPP outputs for different burn severities to the LANDIS-II estimates of burn severity. However, burn severity derived from the SCRPPLE module within LANDIS-II relates to expected flame lengths and tree mortality (Scheller et al. 2019), whereas the WEPP model is associated with soil burn severity. Using the LANDIS-II representation of vegetation burn severity as a proxy of soil burn severity might not be accurate. Vegetation burn severity refers to tree mortality, whereas burn severity refers to fire effects on the soils. The two metrics can overlap spatially; however, the soil burn severity maps tend to underestimate the extent of vegetation stand-replacing fires (Safford et al. 2008). Additionally, although vegetation high-severity (stand-replacing) fires can greatly reduce soil ground cover, it does not necessarily result in high soil burn severity (Safford et al. 2008, Morgan et al. 2014).

We averaged the results from the WEPP-LANDIS-II overlay across all management scenarios and also by each of the two climate scenarios. This process allowed us to consider the effects of the future climate scenarios (moderate greenhouse gas emissions vs. high emissions) on management scenarios and the anticipated sediment and phosphorus loads in the coming century.

RESULTS

Both WEPP and LANDIS-II models are complex process-based models that can generate a suite of outputs that are useful for numerous management applications (Elliot 2013, Creutzburg et al. 2017, Krofcheck et al. 2018, Scheller et al. 2018). Here, we focused on the sediment and phosphorus loads generated from hillslopes and their future projections for each of the five management scenarios (Table 1).

Water Erosion Prediction Project model results for undisturbed conditions

All hydrological simulations were performed using the WEPPcloud interface. Daily model outputs for all watersheds and conditions, as well as tables and shapefiles with summaries of all the results can be found at <https://wepp.cloud/weppcloud/it/>. These spatially distributed results were used to identify sensitive areas within the landscape that are prone to soil erosion, as well as to identify land-use classes or specific soils and slopes that should be avoided when planning fuel management actions to minimize soil erosion.

Under undisturbed conditions, the shrub and sparse grass areas were the main sources of sediment and total phosphorus, followed by areas covered with old forest (Table 2). Shrubs and sparse grasses were predominantly found in two watersheds (Cascade Creek and Eagle Creek) in the southern part of the study area, which have the greatest upland erosion rates on a unit area basis, followed by watersheds that were traditionally known to land managers as the main contributors of sediment to Lake Tahoe (Blackwood Creek and Ward Creek). Watersheds located north of the Truckee River (watersheds 0–5 in Fig. 1) generated no or

minimal fine sediment and total phosphorus. The limited erosion and phosphorus from these watersheds was likely due to deeper soils and gentler slopes. These watersheds have, on average, soils with depths of 1.7 m and slopes of 15% compared to watersheds located south of Truckee River, which have, on average, soil depths of 1.17 m and slopes of 28%.

Table 2. Water Erosion Prediction Project modeling results for sediment and phosphorus loads in undisturbed conditions by land-cover type.

Land cover	Sediment yield (kg ha ⁻¹ yr ⁻¹)	Very fine sediment (< 16 µm) yield (kg ha ⁻¹ yr ⁻¹)	Total phosphorus (kg ha ⁻¹ yr ⁻¹)
Old forest	6.6	0.9	0.038
Shrub	145.7	28.8	0.212
Sparse grass	1925.2	375.7	2.536

Very fine sediment load followed the same trend as the overall sediment yield and represented approximately 19% of all sediments delivered from all land uses and 14% of sediments delivered from forested hillslopes. Similarly, total phosphorus yield followed the trends of sediment yield, with the highest eroding watersheds generating the largest amounts of total phosphorus.

The forest slopes with the greater erosion were those that had soils with a high proportion of rock outcrops (Table 3). Nearly 81% of all sediments, 78% of very fine sediments, and 40% of total phosphorus were generated from only 26% of the forested areas. Sediment and phosphorus yield increased with slope length and steepness for all land covers, although exploratory data analyses suggested that slope length had a greater influence on soil erosion than slope steepness (data not presented). These high-eroding areas were mainly associated with high elevation and, besides forests, they also extended to sparse areas of shrubs and grasses. These associations are important for considering management strategies because thinning treatments would not occur in these areas, but prescribed burning might be applied.

Effects of forest treatments and wildfire on sediment and phosphorus yield

We simulated hillslope sediment and phosphorus delivery from 20 watersheds for three thinning conditions (96%, 93%, and 85% ground cover), one prescribed fire condition, and three wildfire conditions (low, moderate, and high). WEPP model simulations indicated that, on average across all watersheds, there was only a moderate increase in sediment and phosphorus delivery rates from both thinning and prescribed fire compared to undisturbed conditions (Fig. 4). However, in comparison, uniform high-severity wildfires increased erosion rates up to 6 Mg ha⁻¹ yr⁻¹ for sediment yield and 7 kg ha⁻¹ yr⁻¹ for total phosphorus. We observed a similar increase when we examined only the forested hillslopes, which are the target of thinning treatments (Fig. 4).

The Kruskal-Wallis test was statistically significant when considering the average sediment and phosphorus yield calculated for all land covers (sediment yield: Kruskal-Wallis chi-squared = 2696, df = 7, $P < 0.001$; fine sediment yield: Kruskal-Wallis chi-squared = 2736, df = 7, $P < 0.001$; total phosphorus: Kruskal-Wallis chi-squared = 1691, df = 7, $P < 0.001$) and for the hillslopes

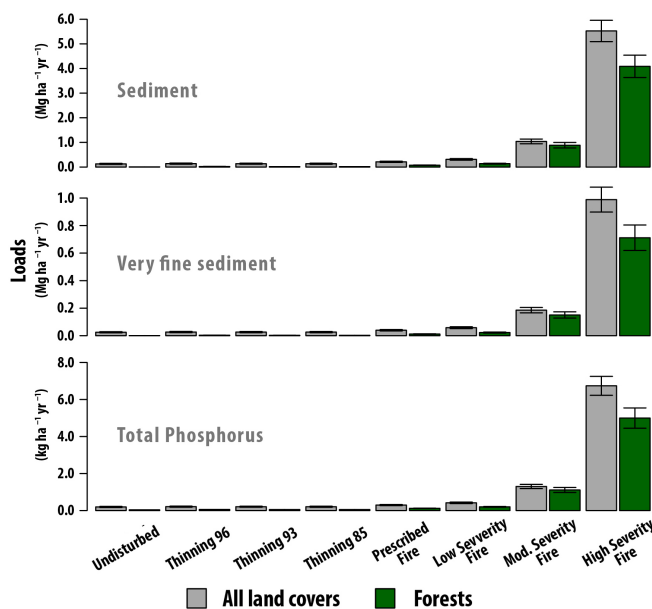
Table 3. Sediment and phosphorus yields (%) for each of the dominant soil types based on model outputs for forested hillslopes.

Soil name or complex [†]	Sediment yield (%)	Very fine sediment (< 16 µm) yield (%)	Total phosphorus (%)	Total area (%)
Melody-Rock outcrop complex	31	46	10	2
Temo-Witefels complex	26	6	9	3
Ellispeak-Rock outcrop complex	15	15	5	2
Meeks gravelly loamy coarse sand	5	3	10	14
Paige medial sandy loam	5	8	5	5
Waca very gravelly medial coarse sandy loam	4	6	12	11
Ellispeak-Waca complex	3	4	2	1
Rubble land-Glenalpine complex	2	1	1	0
Tallac gravelly coarse sandy loam	2	3	5	8
Whittell-Jobsis-Rock outcrop complex	2	1	1	1
Sky gravelly sandy loam	1	2	9	7
Kneeridge gravelly sandy loam	1	1	2	2
Sky-Melody complex	1	2	4	4
Rock outcrop-Rockbound complex	1	0	4	6
Dagget very gravelly loamy coarse sand	0	0	6	8
Rock outcrop	0	0	1	1
Tahoma-Jorge complex	0	0	0	3
Tahoma very cobbly sandy loam	0	0	1	3
Cassenai gravelly loamy coarse sand	0	0	1	3
Cassenai cobbly loamy coarse sand	0	0	2	2
Jorge very cobbly fine sandy loam	0	0	6	8
Jorge-Tahoma complex	0	0	2	2
Total (all soils) [‡]	98	98	97	96
Total (top five eroding soils)	81	78	40	26

[†]Soils sorted based on percent sediment yield.

[‡]Only includes soils with sediment or phosphorus yield ≥ 1% of total yield.

Fig. 4. Annual average sediment and phosphorus loads from all land covers and from forests under various management conditions for the time period 1990–2019. Error bars represent the standard error.



with forest covers only (sediment yield: Kruskal-Wallis chi-squared = 2606, df = 7, $P < 0.001$; fine sediment yield: Kruskal-

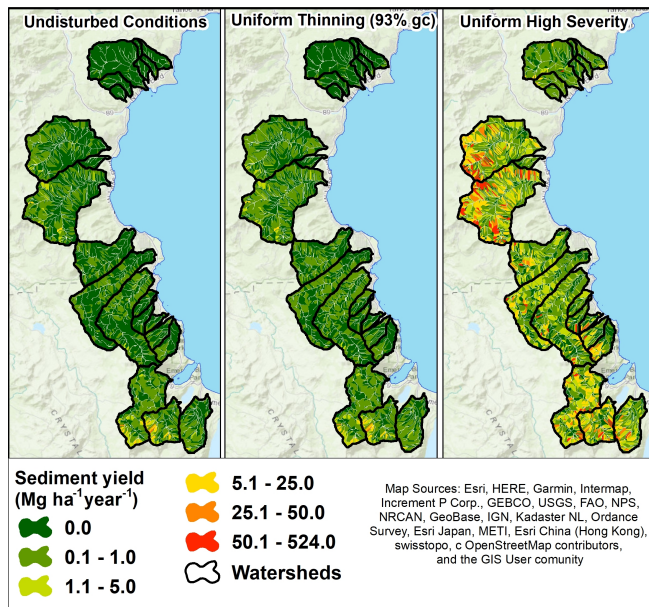
Wallis chi-squared = 2659, df = 7, $P < 0.001$; total phosphorus: Kruskal-Wallis chi-squared = 1464, df = 7, $P < 0.001$), suggesting that the means of sediment and phosphorus yield for at least one treatment are different than the means of the other treatments. The multiple pairwise Wilcoxon test further revealed statistically significant differences between all treatments, with a few exceptions. There was no statistically significant difference ($P > 0.05$) between the means of the three thinning treatments for sediment or phosphorus when averaging across all land covers or forested areas only. Additionally, there was no statistically significant difference ($P > 0.05$) between the means of prescribed fire and low severity fire when averaging across all land covers. When averaging across the hillslopes with forested land covers only, there was no statistically significant difference between thinning (85%) and low-severity fire for sediment yield or between prescribed fire and low-severity fire for total phosphorus.

Spatially, the distribution of soil erosion rates followed similar patterns to the undisturbed conditions; however, wildfire had the capacity to exacerbate erosion across all watersheds and land uses (Fig. 5). Similar to the undisturbed conditions, higher erosion rates after wildfire were found on high-elevation steep slopes covered by sparse vegetation, specifically on slopes > 50% with soils from the Melody-Rock outcrop and Ellispeak-Rock outcrop complexes. Among the predominantly forested watersheds, Blackwood Creek and Ward Creek (Fig. 1) were the top eroding watersheds per unit area under all treatment conditions.

Effects of alternative management regimes under different future climate scenarios on sediment and phosphorus

The effects of five alternative management scenarios were evaluated by combining the proposed fuel treatment scenarios in time and space with LANDIS-II projections for thinning and fire

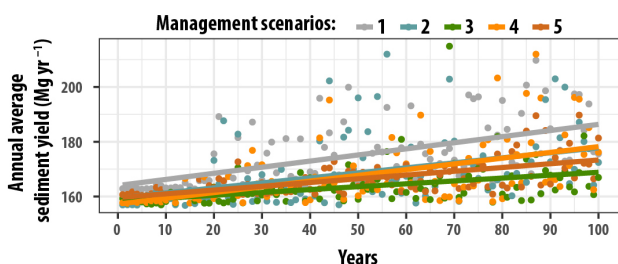
Fig. 5. Spatial distribution of erosion across all modeled watersheds in the Lake Tahoe basin under undisturbed, uniform thinning with 93% ground cover (gc), and uniform high-severity wildfire.



disturbances and the WEPP estimates of sediment and phosphorus delivery from hillslopes (Fig. 3). Fine sediment and phosphorus yields varied from year to year and decade to decade, although the yields generally increased over time as wildfire activity increased with climate change, particularly in the second half of the century. The Mann-Kendall test of the annual average sediment and phosphorus yields based on the five scenarios indicated a statistically significant trend in the data, and the Cox-Stuart test indicated significant increasing trends for all scenarios. Fig. 6 shows such trends for sediment yield; similar trends were observed for both very fine sediment and total phosphorus yield.

When comparing across management scenarios (Fig. 7), the scenario with the most area treated through thinning, scenario 3, resulted in modestly lower average load compared to all other

Fig. 6. Increase in annual average sediment yield due to treatments for all five management scenarios averaged across all future climate scenarios and models.



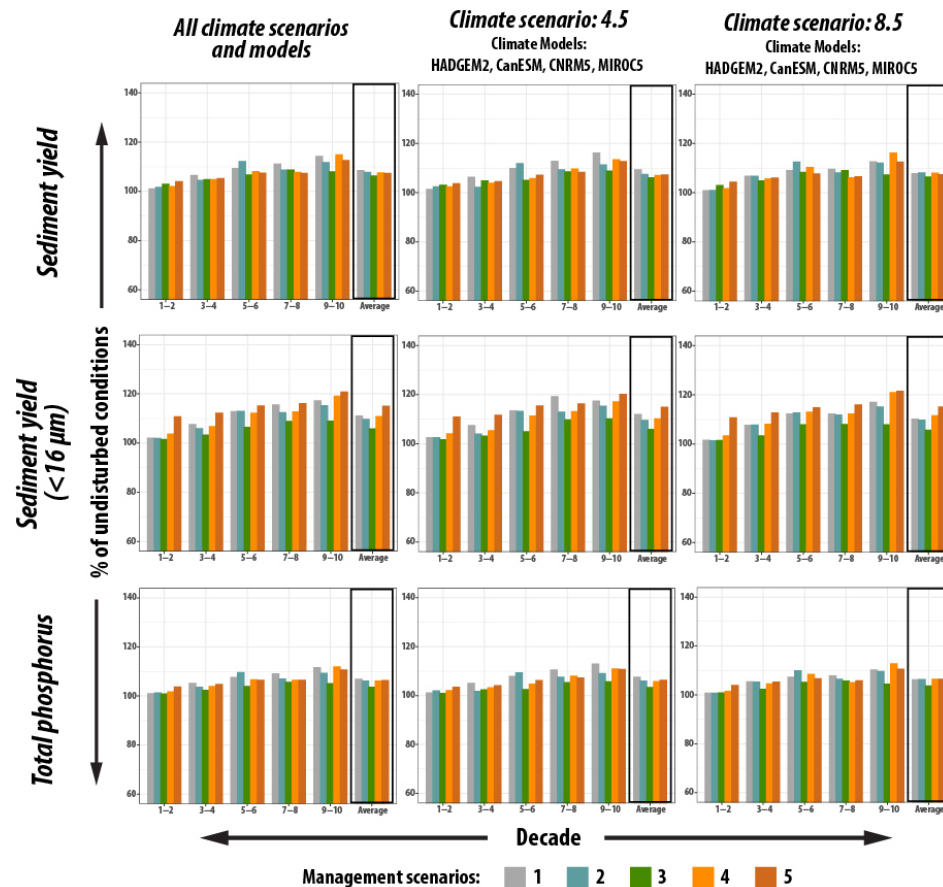
scenarios, including the suppression-only scenario 1. This trend became more apparent in the last two decades of the century and was consistent for both sediment and phosphorus load. In the near term, more treatment increased the sediment load compared to the suppression-only scenario, but the load under the suppression-only scenario generally increased so that overall performances became more similar with time. The fire-focused scenarios were projected to increase load more than thinning because prescribed burning is expected to result in greater reductions of ground cover and increased disturbance within shrub and grass areas. The simulated very fine sediment yield was more sensitive to management treatment than were total sediment and phosphorus; specifically, the fire-focused management scenarios (scenarios 4 and 5) generated consistently higher load than thinning-focused scenarios (2 and 3) in each decade. Projections of sediment and phosphorus load based on the low-emission vs. high-emission climate scenarios did not seem to differ. Lastly, there was greater variability in yield due to management scenarios than due to climate scenarios.

DISCUSSION

Protecting and restoring the clarity of Lake Tahoe poses a significant challenge for restoring the terrestrial ecosystems of the lake's basin given projections of increased wildfire activity. Any forest management activity has potential to increase erosion, but the risks of failing to actively manage forests poses a greater risk in the form of large and severe wildfires. In 2020, California experienced five of the six largest fires in state history, and the projected increases in fuel aridity and fire seasons indicate increasing wildfire risk (Higuera and Abatzoglou 2021). Landscape modeling in the basin (Maxwell et al. 2022) and elsewhere suggests that large wildfires are increasingly likely (Westerling et al. 2006). When large high-severity fires occur, erosion can be greatly elevated and may be difficult to mitigate. Increasing forest treatments reduce the risk of very high loads from future wildfires that may otherwise be difficult to mitigate. However, present water quality frameworks in the basin, such as the total maximum daily load, do not factor in this substantial risk of increased future loading from wildfires (Tetra Tech 2007, Elliot et al. 2008).

Traditionally, pollution control efforts have focused on reducing loads from existing sources, but the projections of increased fire and storm activity requires thinking ahead toward avoiding expected increases in pollutant loading. Specifically, land managers and regulatory agencies have to balance the increasing long-term risks of wildfire against the short-term effects of treatments that reduce wildfire risks. By integrating the results of hydrological and landscape vegetation models, our results help land managers to evaluate trade-offs associated with these management choices on water quality in the coming decades. Our results indicate that sediment and phosphorus yield will likely increase in the future in the Lake Tahoe basin, but that increased active management, particularly thinning, can help to mitigate those expected load increases. The detailed hillslope-scale analysis identifies watersheds and soil types within the basin that can be examined in greater detail to evaluate which management approach, including avoidance, thinning, or prescribed burning, may help to reduce projected increases in erosion associated with wildfire.

Fig. 7. Future projections of sediment and phosphorus yields in the modeled Lake Tahoe watersheds averaged across all climate scenarios and models and across all models for each climate scenario.



Spatial variability in sediment and phosphorus yields across watersheds

Spatially, we identified specific soil types and slopes that are more prone to erosion. For example, the Melody-Rock outcrop and Ellispark-Rock outcrop complexes contain up to 25% and 40% rock outcrops, respectively (USDA-NRCS 2007) and are characterized by high-elevation shrublands with scattered trees, including red fir, white fir, and Jeffrey pine. These low-productivity, highly erodible areas may have been adapted to less-frequent, stand-replacing wildfires and, therefore, may be low priorities for treatment. However, given their substantial contributions to pollutant loads, they may warrant further consideration for potential treatments such as prescribed burning or mastication to mitigate potential loads from wildfires.

Effects of increased treatment

Thinning and prescribed fire treatments may increase fine sediment and phosphorus loads in the short term by reducing ground cover, but our results indicate that such increases are likely to be small relative to baseline loads. An earlier modeling analysis for the Madden Creek watershed within the Lake Tahoe West study area concluded that > 30% of forested areas would have to be treated to result in detectable increases in fine sediment (Grismer 2014). A key reason for such outcomes is that the

conservative practices used in the Lake Tahoe basin are expected to retain high levels of ground cover. A field study of thinning and prescribed burning in the Lake Tahoe basin found that erosion was generally deterred when there was at least 25% residual ground cover (in the form of surface fuels and duff) following treatment (Harrison et al. 2016). That study found that most treatments in the basin left much higher residual ground cover, consistent with the assumptions applied in our WEPP modeling. Elsewhere in northwestern USA, Elliot and Glaza (2008) and Elliot et al. (*unpublished manuscript*) measured minimal to zero erosion associated with thinning, biomass removal, and prescribed fire operations.

Furthermore, landscape modeling suggest that treatments would lead to less severe future wildfires (Maxwell et al. 2022). Consequently, our results suggest that increased thinning treatments are likely to reduce the long-term fine sediment and phosphorous loads in the study area. A previous similar analysis in the nearby Mokelumne watershed also suggests that the potential loading associated with forest treatment would be offset by avoided future impacts from wildfires (Buckley et al. 2014).

Our results indicate that scenarios that rely more heavily on prescribed burning for fuel treatments are more likely to increase sediment and phosphorus loads relative to mechanical thinning

because such burns are expected to reduce residual ground cover and treat shrub-dominated areas that are more erodible. However, the projected differences in loads are small (only a few percentage points relative to the baseline) and would be difficult to detect through monitoring, given the wide natural variation in loading. Managers in the basin indicate that prescribed burning rarely results in patches that are burned intensely enough to consume mature trees, and that such patches would each be < 1 ha. It is also likely that undisturbed buffers would be incorporated into burn plans, further reducing the risk of off-site delivery of sediment and phosphorus.

Large increases in pollutant delivery to Lake Tahoe following wildfires are not necessarily assured. Studies following both the Angora wildfire of 2007 (Oliver et al. 2012) and the Emerald wildfire of 2016 (Cao et al. 2021) found that pollutant loads may have been retained within roadside ditches, detention basins, meadows, and marshes. Because wetlands have the potential to trap sediments, restoration of incised floodplains is one strategy that may help to reduce future loads (Stubblefield et al. 2006).

An additional potential source of sediment associated with fuel management activities is from increased traffic on existing roads or new roads. Here, we incorporated the effects of skid trails with the reduced ground cover in the thinning scenarios. There were no plans to construct new roads; however, increasing traffic on the current road network is likely to increase road erosion (Foltz et al. 2009). In a separate study, as part of the overall Lake Tahoe West research effort, Elliot et al. (2019) found that increasing logging traffic on unpaved roads would increase sediment delivery during their active use. In contrast, a related study following the small Emerald wildfire on the southern edge of the project area determined that the presence of a road network after wildfire likely decreased offsite sediment delivery (Cao et al. 2021); however, site-specific attributes of road location, fire severity, topography, and road design make it difficult to generalize the impacts of roads following wildfire (Sosa-Pérez and MacDonald 2017, Cao et al. 2021).

Assumptions regarding burn severity

The assumption that the low, moderate, and high soil burn severities modeled with WEPP are equivalent to the low, moderate, and high vegetation mortality in the LANDIS-II burn severity model is a potential source of error. Burn severity, or the effects of a fire, can either be applied to the vegetation or to the soil (Parsons et al. 2010). Wildfires reduce ground cover, and more severe fires result in lower levels of residual ground cover and greater soil burn severity. Erosion rates are more directly related to soil burn severity than to vegetation burn severity. Analyses of recent wildfires within and near the Lake Tahoe basin found that soil burn severity variability within a landscape was often driven more by inherent landscape factors (i.e., slope, soil type, and climate) rather than by pre-fire vegetation biomass. Vegetation burn severity may often appear greater than soil burn severity (Pannkuk and Robichaud 2003, Safford et al. 2008, Morgan et al. 2014). One reason is that some fires that burn intensely enough to kill trees may still leave residual ground cover in the form of needles and woody biomass; however, in other areas of high vegetation burn severity, needle cast is rare because tree crowns are fully consumed (Robichaud et al. 2013). Although tools have been developed to predict vegetation burn severity, there has been

less research on predicting soil burn severity (Buckley et al. 2014). Previous work has demonstrated the complexity of evaluating soil burn severity using attributes such as overstory vegetation cover (Robichaud et al. 2007, Morgan et al. 2014) and topography (Dobre et al. 2014), which also tend to be the focus of landscape modeling as opposed to surface conditions. Because the LANDIS-II model focuses on vegetation, relying on its projections of high vegetation burn severity as a proxy for high soil burn severity might overestimate loadings from wildfires.

Effects of changing climate on storm intensity and future pollutant loading

Our projections of future sediment and phosphorus yield (Figs. 6 and 7) are mainly due to the projected changes in disturbance regimes and vegetation under various climate scenarios with LANDIS-II, but not to increased storm intensity. Soil erosion is highly sensitive to storm amount, duration, and intensity (Nearing et al. 1990, Miller et al. 2011), and changing climate will likely increase storm intensity and frequency and shift precipitation from snow to rain (Bayley et al. 2010, Coats 2010). Data from 30 global climate models for the representative concentration pathway 8.5 scenario suggest that, for California, two-thirds of the models project wetter winters with a large increase in extreme precipitation frequency (Polade et al. 2017). Similarly, precipitation intensity will likely increase (Pierce et al. 2013, Polade et al. 2017), with a significant increase in events > 60 mm/d (Pierce et al. 2013). For soil erosion, the projected increase in precipitation intensity is significant and will likely result in an increase in future sediment yield in some areas. A study in the Lake Tahoe basin that evaluated the effects of projected climate change on sediments did not find significant changes in fine sediments with climate change when data were averaged across the basin, in part because lower precipitation volume may have offset shifts from snow to rain (Riverson et al. 2013). However, when analyzed by zones, the authors found an increase in fine sediments at higher elevations and a decrease in the flatter meadow regions. Variable effects of climate change on water quality within the landscape might further inform management strategies.

Where increases in sediment loading due to increased storm activity are likely, it may be appropriate to discount somewhat the impact of treatments in the near term. A recent field study found that the effects of thinning on reduced fuels last for at least 10 years (Low et al. 2021). Factoring in this temporal dynamic suggests that there could be an additional benefit from conducting wildfire risk reduction treatments in the near term because such treatments could help reduce higher loads from wildfires in subsequent years as storms become more intense.

Strategies for treating highly erodible areas

Our results identified four watersheds that are prone to excessive soil erosion. Two of these watersheds, Cascade Creek and Eagle Creek, are characterized by steep and rocky slopes with sparse vegetation (Fig. 2) and are managed largely as wilderness. Such areas are unlikely to be selected for forest thinning treatments; however, they may be targeted for limited fire suppression or prescribed fire treatments to reduce fire hazard and restore fire regimes. The other two main contributing watersheds, Blackwood Creek and Ward Creek, are mainly forested, with high-elevation areas covered by sparse patches of shrubs and some highly erodible badlands (Stubblefield et al. 2009). The Blackwood watershed has

a long history of soil erosion caused by both natural characteristics and anthropogenic disturbances (historical excessive grazing, road construction, forest harvest) and has been the target of several stream channel restoration projects (Oehrli 2013, Norman et al. 2014). Other studies, including those used to develop a total maximum daily load program, also identified Blackwood Creek and Ward Creek as the greatest sources of sediment and phosphorus pollutants in the Lake Tahoe basin (Tetra Tech 2007, Sahoo et al. 2013, Coats et al. 2016), along with Upper Truckee River and Trout Creek watersheds on the south side of the basin, which are outside the study area that we examined.

Because many of the more highly erodible areas tend to be steep and dominated by shrubs, they have often not been considered for mechanical treatments, but they may be important areas for prescribed burning or mastication. A previous field study found that erosion was low following mastication and burning on areas with slopes < 30% (Harrison et al. 2016). However, landscape prescribed burning in steeper areas has not been widely conducted nor studied, so there is more uncertainty regarding its effects.

Recent research at the nearby King Fire in 2014 suggests that steep shrub-dominated slopes are important areas for treatment (Coen et al. 2018). Because our results suggest that such areas tend to have high erosion rates, long-term sediment and phosphorus pollution may be reduced by prioritizing treatment either within or around these areas to reduce the potential for severe wildfires. However, further analysis is needed to evaluate the net benefits of directly treating those areas either with mechanical fuel reduction, prescribed fire, and managed natural ignitions. Additionally, given that high-elevation shrub and grass areas also generate high erosion rates under undisturbed conditions, management should focus on hillslopes prone to burn at moderate and high severity.

One of the reasons for the widespread burning of residual harvest material piles in the Tahoe basin is that there have been inadequate markets for harvested trees (LTBMU 2014). Alternatives to burning include grinding the trees for mulch (Robichaud et al. 2013) or feeding them into a biochar generator to make biochar (Dumroese et al. 2020); such products might have value for erosion control. Already, needles and branches from around homes in the Tahoe basin are collected and often spread on areas of high foot traffic and erosion risk on ski resorts (Tahoe-Douglas Fire Protection District, yard waste removal options: <https://tahoe-fire.org/news/entry/spring-yard-clean-up>), so the concept of moving biomass around within the basin to reduce fire risk and erosion is not new, despite the costs.

Uncertainty associated with burning large areas

Prescribed fire is considered highly effective at reducing wildfire (Kolden 2019) despite setbacks related to weather, air quality and smoke management, and institutional capacity (Melvin 2018). However, an increase in wildfires within the last several years has resulted in an increase in the adoption of prescribed fire by governmental agencies, especially in the western United States (i.e., 268% increase from 2011 to 2019; Melvin 2020). There is uncertainty about the extent to which large prescribed fires would result in changes in ground cover and sediment and nutrient loads. Previous research suggests that prescribed burns

would be unlikely to increase such loads because they tend to leave high levels of ground cover, and even patchy residual cover (> 25% of plot area) would be sufficient to deter such erosion (Stephens et al. 2004, Harrison et al. 2016). When prescribed burning occurs across larger landscape blocks or watersheds, it may traverse steeper slopes and include shrub-dominated areas with less ground cover. Consequently, the resulting impacts on water quality could be more comparable to those from low-intensity wildfires. Very large prescribed burns have been relatively uncommon in the region, particularly in the Lake Tahoe basin, but the increasing use of fire as a management tool will provide greater opportunities to document effects of prescribed fire strategies in the basin. To meet the challenge of increasing the pace and scale of treatments, managers may also consider ramping up the intensity of prescribed burns (Striplin et al. 2020). Such shifts might promote many ecological restoration objectives yet might also lead to greater risks of increased erosion. Adaptive management of such operations could help managers increase the benefits of fire while minimizing potential downsides. It would be useful to monitor residual ground cover, hillslope erosion, sediment yield, and phosphorus delivery following large-scale prescribed burns and timber harvest treatments.

Other mitigation strategies to minimize impacts of treatments on sediment and water quality, which were not directly accounted for in our modeling analysis include the following:

- Encouraging very patchy treatments (Harrison et al. 2016);
- Staggering treatments in time and space to minimize cumulative impacts at the watershed outlet;
- Designing topographically based buffers to reduce the connectivity of potential source areas to stream networks. These buffers could be strips of undisturbed soils on long slopes and at the bottom of steep slopes. This approach would be distinct from standard stream zone buffers because full restoration goals may include thinning and burning within riparian areas (Elliot et al. 2009, Van de Water and North 2011);
- Planning upland treatments to follow meadow restoration projects that are designed to help capture eroded sediments and burned debris on floodplains. Such effects have been suggested for meadow restoration projects to mitigate channel incision, such as at Trout Creek (Stubblefield et al. 2006);
- Using care when reopening roads to access areas for thinning to minimize erosion risk (Elliot et al. 2019).

CONCLUSION

Wildfires in many forests of the western United States, including in the Lake Tahoe basin, have evolved with frequent, relatively low-severity and patchy fire regimes. More than a century of fire suppression and climate change have increased the risk of large and severe wildfires and associated effects on water quality. Land managers and regulatory agencies need to consider multiple landscape management objectives. A large body of research suggests that forest treatments will help to decrease risks of wildfire, with important social benefits. Our study adds to this body of knowledge by linking complex hydrological and vegetation models to evaluate potential future management

scenarios, and by quantifying their effects on key water-quality parameters. Our results indicate that sediment and phosphorus yields would increase under all management scenarios as climate change increases wildfire; this result suggests that efforts to restore the clarity of Lake Tahoe will be increasingly challenged. Overall, we observed relatively small differences in sediment and phosphorus yields among the five management scenarios, although the scenario that involved more thinning (scenario 3) appeared to be most effective in mitigating pollutant loads. Increased use of prescribed fire entails greater uncertainty, particularly because we expect it to increase soil disturbance more than thinning will; however, areas being treated using frequent and large prescribed burns are rare enough that we lack information about their water-quality effects. Adaptive management experiments using prescribed fires and thinning would help to test our assumptions and findings and to refine strategies for highly erodible areas.

Responses to this article can be read online at:
<https://www.ecologyandsociety.org/issues/responses.php/13133>

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Data Availability:

All hydrological simulations were performed using wepppy (<https://github.com/rogerlew/wepppy>). Model runs, including all the data inputs and outputs, are available on the WEPPcloud interface at <https://wepp.cloud/weppcloud/ltl>. The WEPPcloud documentation (<https://doc.wepp.cloud/>) contains additional information on the publicly available data resources used to parameterize the hydrological simulations. Inputs and outputs from the LANDIS-II model and the LANDIS-II + WEPP analysis are openly available at <https://github.com/LANDIS-II-Foundation/Project-Lake-Tahoe-2017>. The code has been archived at <https://doi.org/10.5281/zenodo.4644579>.

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This file includes:

Supplementary text

Tables S1-S3

Figures S1 to S7

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). 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 et al. (2019). Suppression effort and fire spread are calibrated at the same time in order to try to account for both forces in recreating the contemporary fire regime.

Insect modeling

A modified version of the Biological Disturbance Agent extension (Biomass BDA v.2.0) was used to simulate insect outbreaks. Outbreak locations are based upon the species host density at a given site and the presence of non-hosts reduce disturbance probability. However, unlike Kretchun et al. (2016), the trigger for an outbreak was changed to be responsive to climate signals. This is because for many beetle species climate influences outbreaks in three ways: low winter temperatures cause beetle mortality; year-round temperatures influence development and mass attack; and drought stress reduces host resistance. Here, we modeled climate influences as a function of drought and mean minimum winter temperature, recognizing that the full suite of climatic influences is necessary for a fully mechanistic model. So long as annual climatic water deficit exceeded a set threshold, in conjunction with mean winter minimum temperatures exceeded a certain threshold, outbreaks could occur. A comparison between the modeled and observed outbreak dataset (USFS Aerial Detection Survey: <https://www.fs.fed.us/foresthealth/applied-sciences/mapping-reporting/index.shtml>) found an overestimation of frequency of occurrence but an underestimation of area impacted by insects (Figure S7).

Supplemental Tables:

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

Table S2. Prescribed fire parameters used for Scenario 5

Prescribed Fire Parameters	
MaximumRxWindSpeed	6.6 (m/s)
MaximumRxFireWeatherIndex	55 (unitless)
MinimumRxFireWeatherIndex	10 (unitless)
MaximumRxFireIntensity	1 (low)
NumberRxAnnualFires	364 (days of year allowable, subject to climate constraints)
FirstDayRxFires	1 (first julian day for allowable fire, subject to climate constraints)
TargetRxSize	72 (hectares)

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
<i>Pinus jeffreyi</i>	500	25	2	5	50	300	0	0	0	none
<i>Pinus lambertiana</i>	550	20	3	5	30	400	0	0	0	none
<i>Calocedrus decurrens</i>	500	30	3	5	30	1000	0	0	0	none
<i>Abies concolor</i>	450	35	4	3	30	500	0	0	0	none
<i>Abies magnifica</i>	500	40	3	4	30	500	0	0	0	none
<i>Pinus contorta</i>	250	7	1	2	30	300	0	0	0	none
<i>Pinus monticola</i>	550	18	3	4	30	800	0	0	0	none
<i>Tsuga mertensiana</i>	800	20	5	1	30	800	0.0005	100	800	none
<i>Pinus albicaulis</i>	900	30	3	2	30	2500	0.0001	100	900	none
<i>Populus tremuloides</i>	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

Table S3. Species parameters used in modeling.

Supplemental Figures:

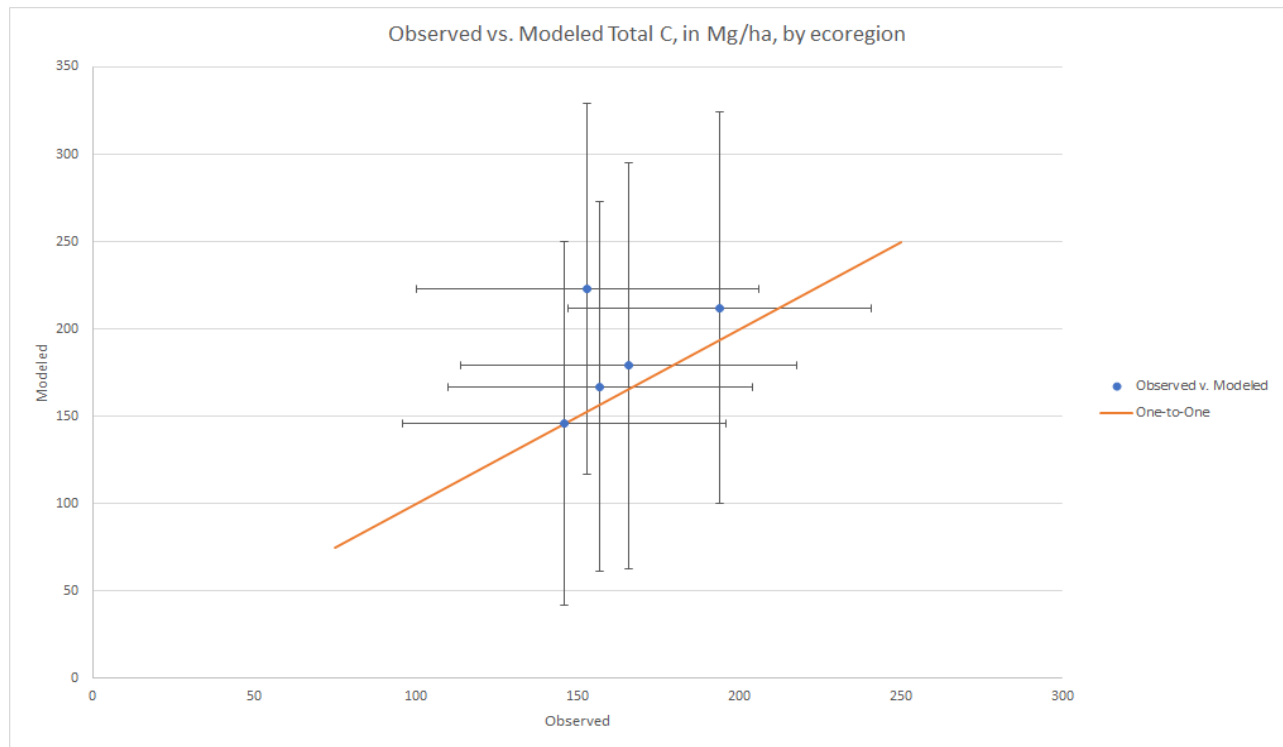


Figure S1. Observed versus modeled total C, in megagrams C per hectare, by ecoregion, error bars represent ± 1 standard deviation.

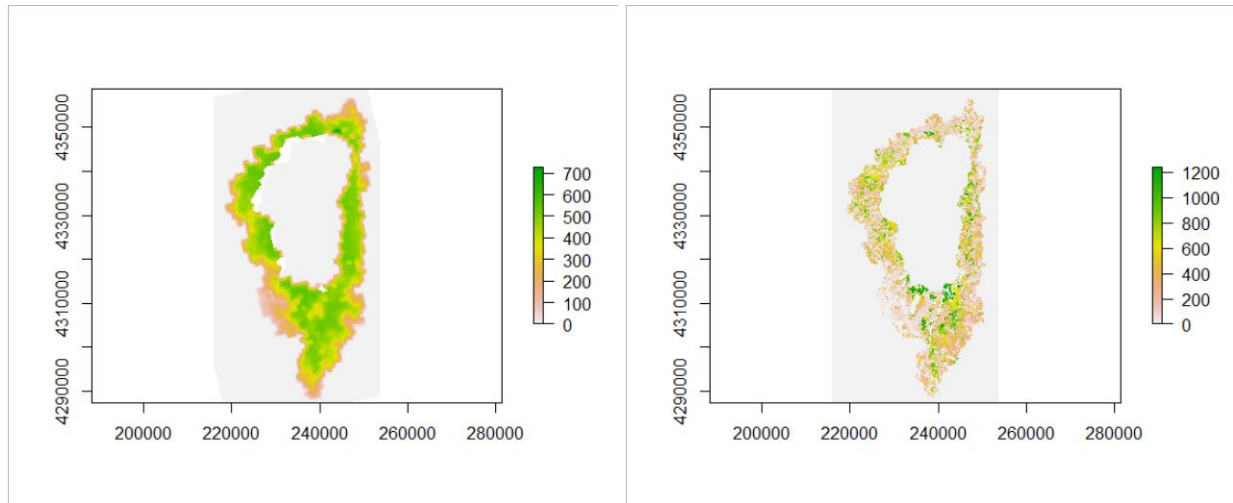


Figure S2. Comparison of MODIS (left) and LANDIS (right) estimates of Net Primary Productivity in g C/m². Mean landscape value for MODIS was 393 g C/m² (sd 134), while for LANDIS the mean value was 320 g C/m² (sd 312).

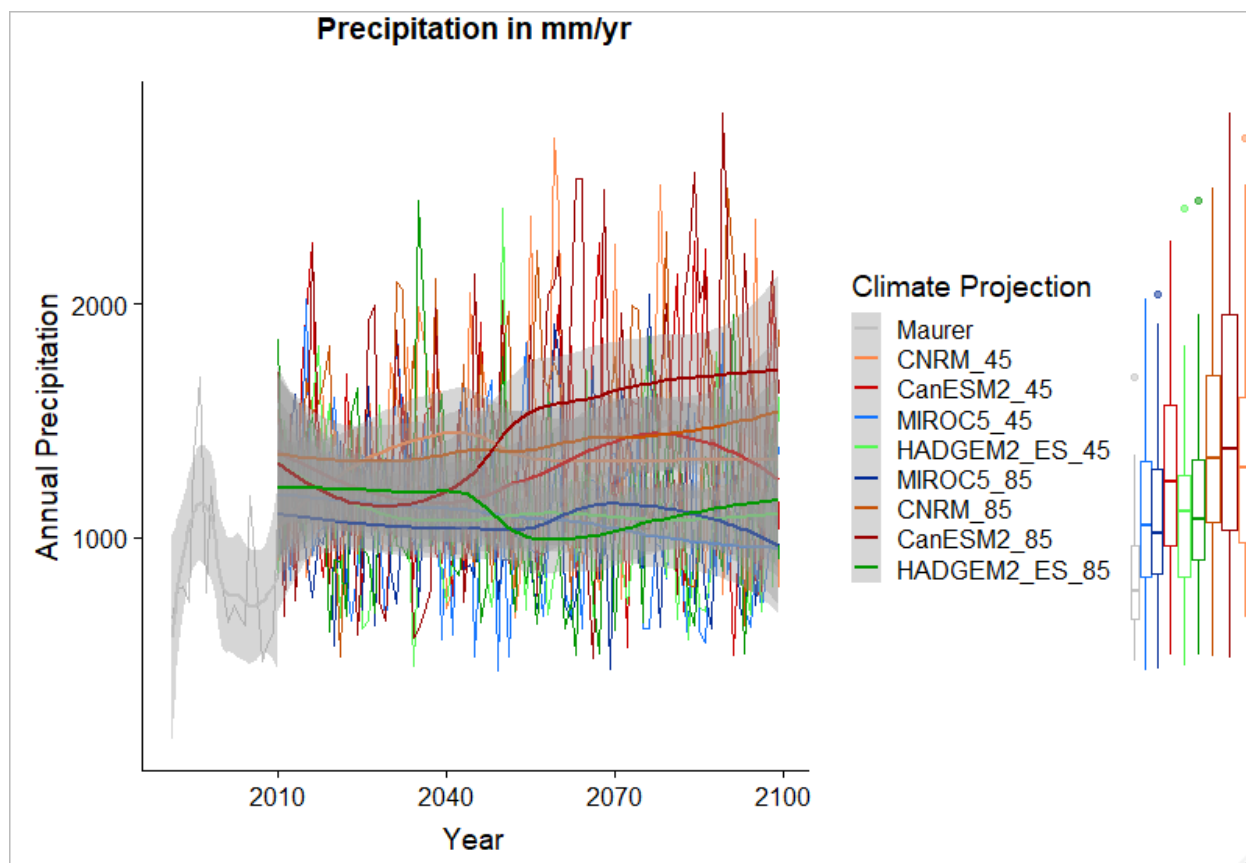


Figure S3. Projected precipitation in mm yr^{-1} , lines of best fit are GAM estimated, and boxplots represent distribution of annual precipitation for the years 2090-2100.

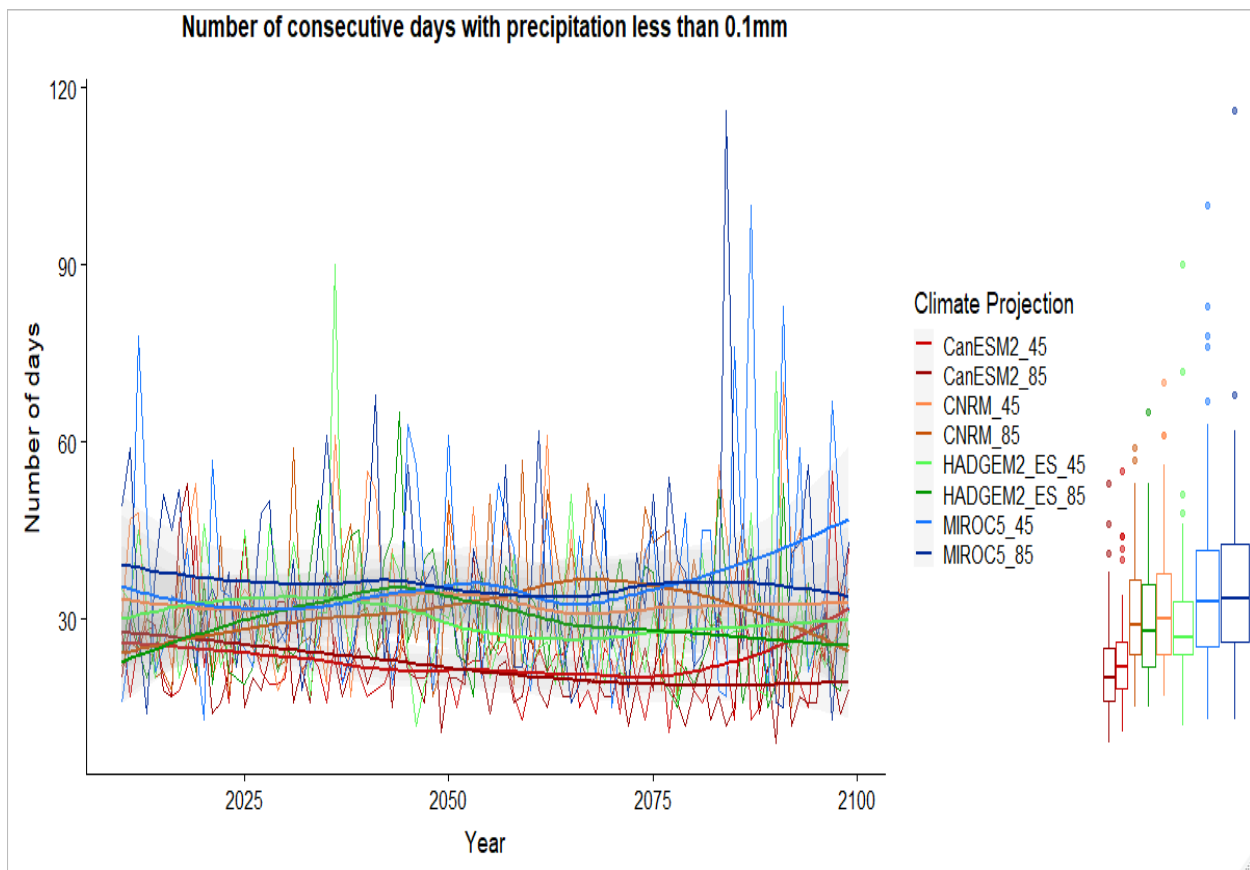


Figure S4. Projected number of consecutive days with no precipitation, lines of best fit are GAM estimated, and boxplots represent distribution of consecutive days per year for the years 2090-2100.

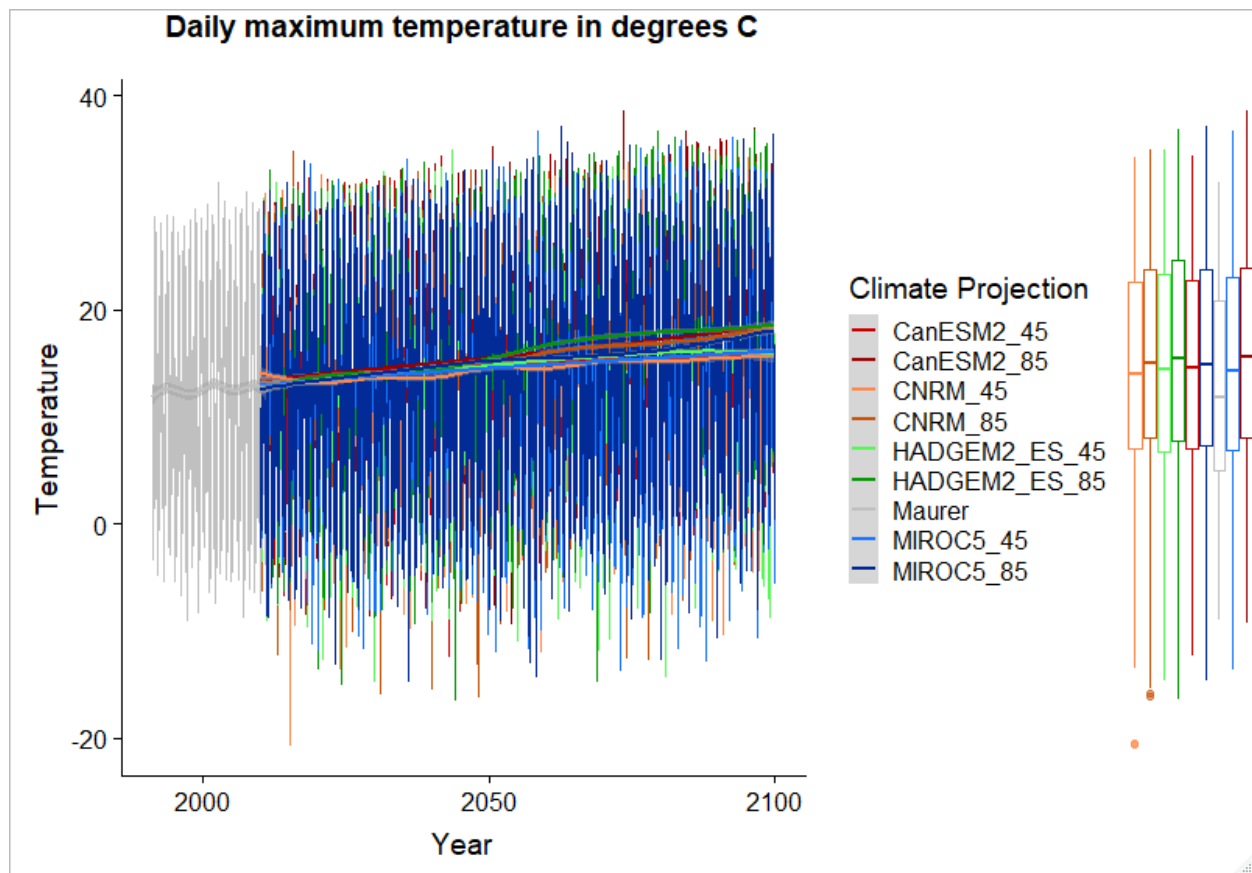


Figure S5. Projected daily maximum temperature in degrees C, lines of best fit are GAM estimated, and boxplots represent distribution of daily temperatures for the years 2090-2100 for the future climate projections.

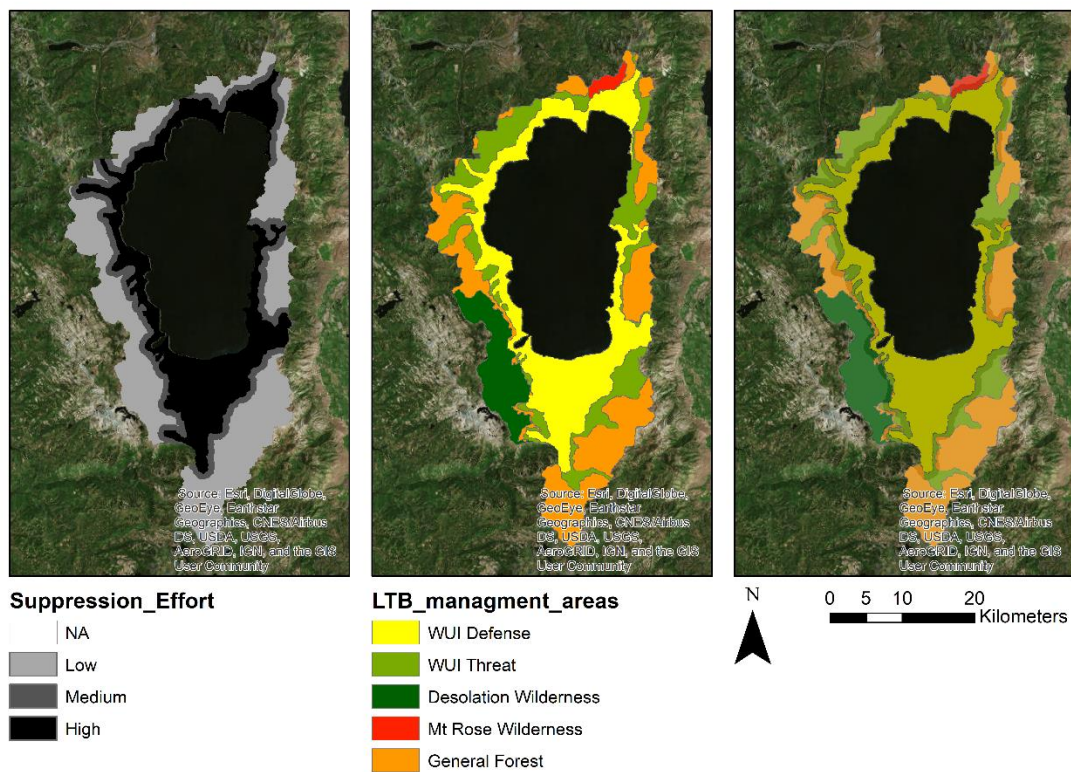


Figure S6. Map of suppression effort and management zone.

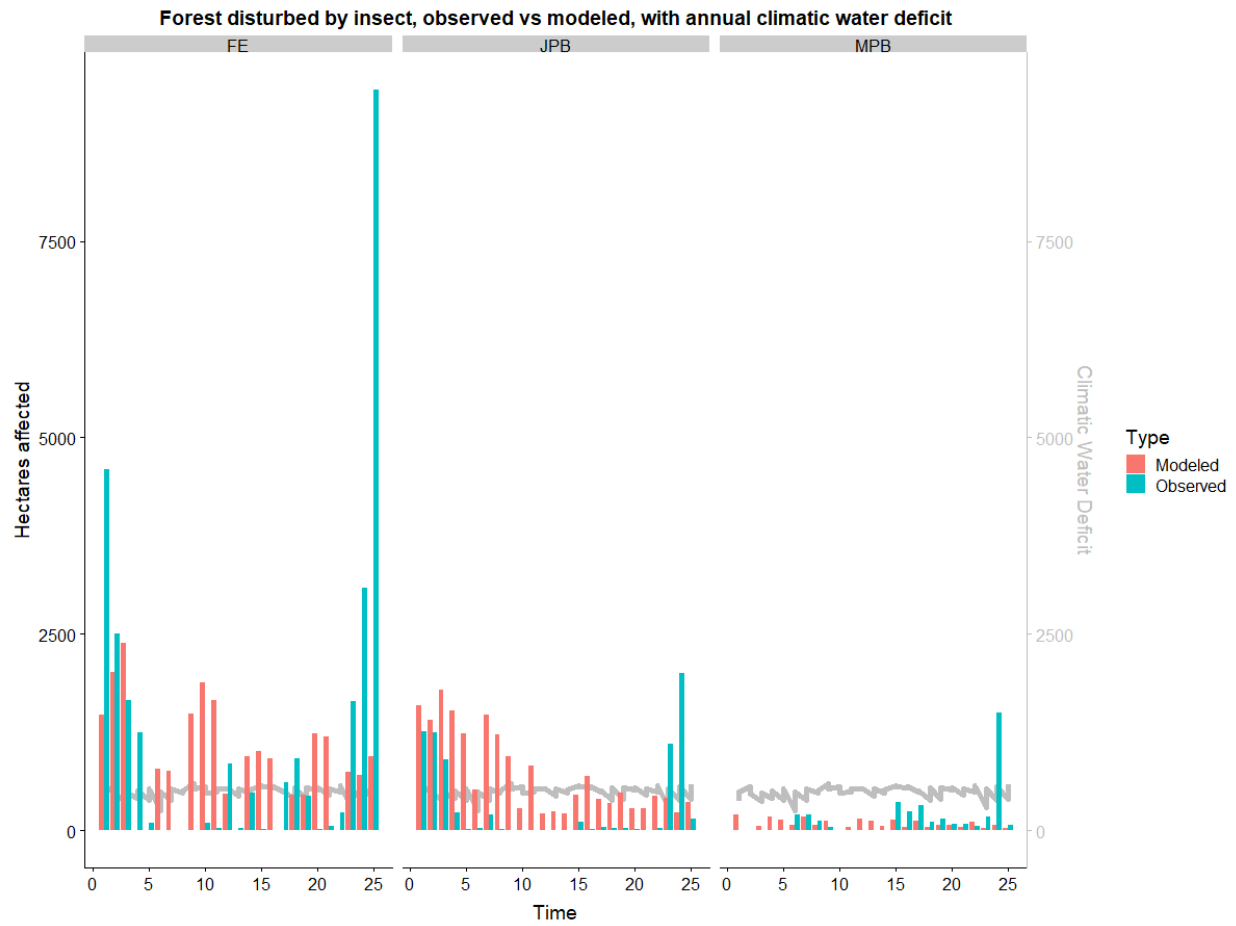


Figure S7. Observed versus modeled number of hectares affected by insect/mortality agent.

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