



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

Frequency of disturbance mitigates high-severity fire in the Lake Tahoe Basin, California and Nevada

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ABSTRACT. Because of past land use changes and changing climate, forests are moving outside of their historical range of variation. As fires become more severe, forest managers are searching for strategies that can restore forest health and reduce fire risk. However, management activities are only one part of a suite of disturbance vectors that shape forest conditions. To account for the range of disturbance intensities and disturbance types (wildfire, bark beetles, and management), we developed a disturbance return interval (DRI) that represents the average return period for any disturbance, human or natural. We applied the DRI to examine forest change in the Lake Tahoe Basin of California and Nevada. We specifically investigated the consequences of DRI on the proportion of high-severity fire and the net sequestration of carbon. In order to test the management component of the DRI, we developed management scenarios with forest managers and stakeholders in the region; these scenarios were integrated into a mechanistic forest landscape model that also accounted for climate change, as well as natural disturbances of wildfire and insect outbreaks. Our results suggest increasing the frequency of disturbances (a lower DRI) would reduce the percentage of high-severity fire on landscape but not the total amount of wildfire in general. However, a higher DRI reduced carbon storage and sequestration, particularly in management strategies that emphasized prescribed fire over hand or mechanical fuel treatments.

Key Words: *carbon sequestration; disturbance return interval; forest management; high-severity fire*

INTRODUCTION

Land managers recognize the limitations of current forest and fire policy in maintaining forests under climate change; because of past land use patterns, forests in the western United States are becoming denser and experiencing larger disturbances (Hessburg and Agee 2003, Beaty and Taylor 2007). In addition, climate change is creating larger, more severe fires (Westerling and Bryant 2008). Looking forward, forest restoration should accommodate the changing disturbance regime rather than remain fixed on historical regimes. One challenge is that current vegetation reflects the historical land use and disturbance regime. In the Lake Tahoe Basin (LTB) of California and Nevada, for example, wildfires were substantially more frequent before Euro-American colonization, with some watersheds burned annually until widespread fire exclusion (Taylor and Beaty 2005). The swing toward fire suppression resulted in shade-tolerant white fir (*Abies concolor*) encroachment into fire-tolerant and fire-maintained pine dominated stands. Although there is interest in increasing the amount of fire on the landscape, fire management in the Basin is constrained by residential development on account of the risk to structures and the importance of recreation to the local economy. The Angora fire, in 2007, was one of America's most expensive fires up to that time because of the number of structures lost in the fire (Safford et al. 2009). Contemporary forest management activities focus on fuel reduction: reducing the probability of fire spread and high fire intensity, while also suppressing active fires (Safford et al. 2009, Safford et al. 2012). However, the long-term effectiveness of such a strategy may be limited; fires are expected to increase in size under climate change (Westerling and Bryant 2008) and the backlog of areas needing treatment further threatens forest resilience.

Fire is only one part of a larger suite of disturbances affecting forested landscapes. Insects cause significant forest mortality worldwide and are often triggered by the same climatic conditions that magnify fire effects (Kurz et al. 2008, Hicke et al. 2016, Kolb

et al. 2016). Moreover, insect outbreaks can cause mortality over large areas and on par with wildfire (Hicke et al. 2016), and for this landscape, bark beetles have caused significant mortality across large portions of the Sierra Nevada (Scheller et al. 2018). Often as important as natural disturbances, management activities—timber harvesting, fuel reduction treatments, prescribed fires—also shape the composition and density of forests through selective mortality through targeting specific combinations of species and ages. The forest's demography and composition was radically changed with the institution of fire suppression resulting from Euro-American colonization and the harvesting of old-growth wood during the Comstock era (Barbour et al. 2002).

The challenge for management is understanding how to restore historical disturbance processes under a non-stationary climate, given that higher temperatures and increasing aridity can increase the frequency of widespread mortality events (Goulden and Bales 2019). On the other hand, because multiple, interacting disturbances can have a negative feedback on future disturbances (Lucash et al. 2018), we hypothesize that decreasing the disturbance return interval (DRI—the frequency at which an area is impacted by a disturbance), which would lead to more disturbance, would reduce the severity of future disturbances in the long term, which would in turn move the landscape back toward a lower severity fire regime. A potential liability of a high-frequency disturbance regime, however, is that it may reduce carbon sequestration potential, possibly resulting in the forest becoming a carbon source. Our goals were to understand the following: (1) Will shortening the disturbance return interval (DRI) restore a lower severity fire regime to the landscape? (2) Will shortening the DRI reduce landscape-scale carbon sequestration? We used a simulation modeling framework to forecast future forest conditions under natural disturbances and a range of plausible management forcings to address these two questions.

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METHODS

Study area

The Lake Tahoe basin is a mostly forested montane landscape approximately 70,000 ha in size, primarily (~70%) under the management of the USDA Forest Service, in the middle of the Sierra Nevada Mountain range straddling the border of California and Nevada, USA. The climate is seasonally dry—most precipitation falls as snow in the winter—with cold winters and warm to hot summers. Forests are mostly mixed conifer, a mix of white fir (*Abies concolor*) and Jeffrey pine (*Pinus jeffreyi*) among others at lower elevations, trending to red fir (*Abies magnifica*) and western white pine (*Pinus monticola*) at higher elevations. Disturbance return intervals range from infrequent in the subalpine areas to frequent for aspen (*Populus tremuloides*) components. Prior to colonization, wildfires were frequent in pine-dominated areas, with return intervals ranging from two to 20 years (Taylor and Beatty 2005). Fire suppression has resulted in an increase of shade tolerant white fir at the expense of Jeffrey pine, as well as a widespread decline of aspen, which is dependent on disturbance. Insect outbreaks, and subsequent forest mortality, are natural occurrences in the pine forests of the Sierras; however, their frequency and severity have increased compared to historic conditions (Raffa et al. 2008).

Forest and disturbance modeling

We simulated forest change using the LANDIS-II framework because it represents forest succession, integrates climate change, and captures a wide variety of disturbances across wide spatial extents (Scheller et al. 2007). Trees and shrubs are modeled as species-age cohorts, with each species having its own life history attributes (e.g., shade tolerance, dispersal ability, fire tolerance, susceptibility to beetles). Multiple cohorts can occupy the same space and compete intra- and inter-specifically, which allows emergent behavior in response to external drivers (Scheller et al. 2007). There were ten tree species and four shrub groups modeled and their respective parameters are located in Appendix 1 (Table A1.2). The succession extension (NECN v. 6.1) handles growth and non-disturbance mortality, and tracks carbon across these cohorts and aboveground and belowground pools. Additionally, within the framework, the net losses of carbon from the disturbance extensions (below) are tracked, allowing for the calculation of the forest's net ecosystem exchange (NEEC), which is whether the system as a whole is absorbing or releasing carbon.

Wild and prescribed fires were modeled using the Social-Climate Related Pyrogenic Processes (SCRPPLE v. 2.1) extension (Scheller et al. 2019). This extension models the spread and intensity of those kinds of fire, while being sensitive to climate conditions and fuel loads. Fire intensity for a given cell is based on conditions within the cell and in neighboring cells, where high intensity fire is possible when two of the following three conditions are met: (1) crossing the fuel loading threshold for fine fuels within the cell, (2) crossing a fuel loading threshold for ladder fuels within the cell, or (3) presence of high intensity fire in a neighboring cell. Five fire experts working the LTB provided a translation from intensity to severity by providing a breakdown of intensity versus mortality for all the modeled species and age classes. Prescribed fire severity was constrained to low severity: the model selected the burn days based on weather constraints to minimize severity (Appendix 1: Table A1.2) because it was assumed that fire managers would limit fire effects anyway.

Three beetle species (Jeffrey pine beetle [*Dendroctonus jeffreyi* Hopkins], mountain pine beetle [*Dendroctonus ponderosae*], and fir engraver beetle [*Scolytus ventralis*]) were modeled using a modified version of the Biological Disturbance Agent (BDA v.2.0.1) extension (Sturtevant et al. 2004), where an outbreak is triggered by the exceedance of climatic water deficit and minimum winter temperature thresholds. The parameters for insect spread and mortality follow Kretchun et al. (2016) and are based on field studies and expert opinion (Egan et al. 2010, 2016).

Initial aboveground biomass estimates were derived from Forest Inventory and Analysis data and validated against Wilson et al. (2013). Recent wildfires (2000–2016) from California FRAP were used to parameterize fire spread and size. Mean annual fire area for observed data was 117 ha/yr (sd = 309), and for modeled data the mean value was 182 ha/yr (sd = 210). Insect and Disease Detection Surveys (1993–2017) were used to validate insect outbreaks under historical climate conditions. Observed mean area impacted annually by fir engraver beetles was ~1120 ha, Jeffrey pine beetle ~295 ha, and mountain pine beetle ~147 ha. Modeled impacts were ~857 ha, ~711 ha, and ~82 ha respectively.

Forest management

We used management scenarios to capture a range of plausible management activities, each representing a combination of activities, locations, and area treated per year. Five management scenarios were co-developed with managers representing multiple agencies within LTB along with input from stakeholder groups operating in the region (see Table 1). Scenario 1 represented a minimalist scenario that features no fuels management but high-effort fire suppression. Scenario 2 focused on fuel treatments within the wildland–urban interface (WUI) area with treatment type (hand versus mechanical) dependent on accessibility. Like Scenario 1, there was high-effort fire suppression and no prescribed burning. Scenario 3 built off of Scenario 2, increasing both the intensity and extent of fuel treatments, while expanding treatments into the general forest and wilderness areas. Scenario 4 combined the hand and mechanical thinning from Scenario 2 with prescribed fires and managed natural ignitions. Scenario 5 was similar to Scenario 4, but with even higher levels of prescribed burning. Stand re-treatment frequency was set at 20 years for Scenario 2. The re-treatment frequency for Scenarios 3, 4, and 5 was 11 years. Fire suppression effort levels were explicitly set, and for Scenarios 1–3, suppression was at maximum effort. For Scenarios 4 and 5, suppression was at maximum effort for accidental ignitions in all areas and lightning ignitions in the WUI, but minimum effort for lightning ignitions in wildernesses and general forest.

Climate modeling

Following the precedence set by the 4th California Climate Assessment, four global change models (GCM; CanESM2, CNRM5, HADGEM2, and MIROC5) under two different relative concentration pathways (RCP) were chosen because they represented a range of possible future conditions (e.g., warmer and wetter, hotter and drier). The RCPs chosen (4.5 and 8.5) represent an optimistic scenario where future emissions are controlled and an uncontrolled emissions scenario, respectively. Climate downscaling used the localized constructed analogs method developed by Pierce et al. (2014), as available on the USGS GeoData Portal (<https://cida.usgs.gov/gdp/>). We averaged the climate projections across EPA level II climate regions for

Table 1. Management scenario broken down by intent and treatment type, by hectares, annually (approximate, rounded)

Scenario	Management specifications	Mechanical	Hand	Prescribed fire	Total	Percent of landscape treated annually	Stand minimum re-treatment time	Natural ignitions as managed fires
1	The only management activity was to suppress fires.	0	0	0	0	0%	0	No
2	Management activities were focused on forest thinning in the wildland–urban interface (WUI). This management strategy was designed to provide a buffer of defensible space around human-built structures and property. It treated ~2% of the vegetated area each year, all in the WUI. This scenario most closely resembled current management activities in the Lake Tahoe basin. Fire suppression efforts remain the same as Scenario 1.	350	950	0	1300	2%	20	No
3	This scenario builds upon Scenario 2 by expanding management activities into the remaining forested landscape beyond the WUI and used predominantly mechanical and some manual methods to thin the forest and reduce biomass. It treats approximately 6.7% of the vegetated area each year. Fire suppression efforts remain the same as Scenario 1.	1200	3800	0	5000	7%	11	No
4	This scenario builds upon Scenario 2 by expanding management activities into the remaining forested landscape. Scenario 4 uses primarily prescribed fire and managed wildfire. This scenario treats approximately 4% of the vegetated area each year. Fire suppression efforts were the same as Scenario 1 in WUI areas but natural ignitions were allowed to burn for resource objectives in the wilderness areas.	250	1000	1800	3050	4%	20	Yes, in wilderness
5	This scenario builds upon Scenario 4 by greatly expanding the use of prescribed fire. This scenario treats approximately 7.2% of the vegetated area each year, slightly more than Scenario 3, but with the majority of treatments (75%) being prescribed fire. Fire suppression efforts were the same as Scenario 1 in WUI areas but natural ignitions were allowed to burn for resource objectives in the wilderness areas.	250	1000	6600	7850	11%	20	Yes, in wilderness

integration within the model. The climate futures for this region ranged substantially, and although temperatures increased under all projections, precipitation increased, decreased, or changed seasonality.

Analysis methods

We calculated DRI by management area, a zone identified to receive a similar suite of treatments, for each year. This calculation was done by dividing the total management area by the sum of the area affected by management activities, insects, and low and moderate severity fire for one year. The DRI is the amount of time it takes a disturbance to affect an area an equivalent size to the relevant management area for that particular annual timestep averaged across multiple replicates. This was done in order to track changes in DRI through time in order to separate the climate signal and track the cumulative effect of disturbance on the landscape. Multiple regression was used to evaluate the relationships that DRI had with fire severity and net ecosystem exchange. All analyses were performed with R (v 3.5.3).

RESULTS

Disturbance return interval

When considering the suite of all forest disturbances, these management strategies have vastly different footprints on the ground. Management actions were the main driver of DRI on the

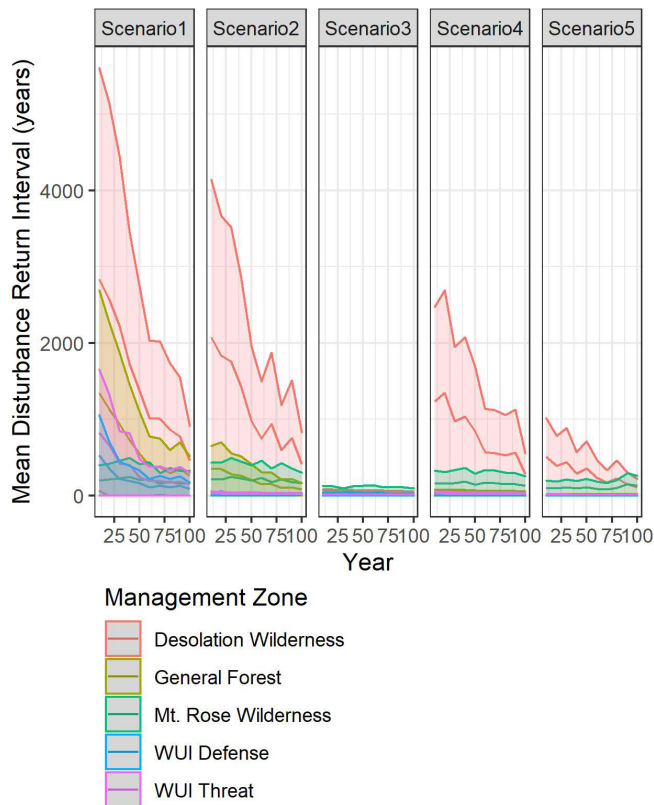
landscape, which is reflected by the large differences in DRI between Scenario 1 (the no action scenario) and the other scenarios that utilized management activity, as well as the DRI in wilderness areas outside of Scenario 3 (Fig. 1). The actions that each scenario implemented had different results on the ground: the scenario that utilized the most prescribed fire (Scenario 5) resulted in the highest amount of low severity fire (Fig. 2). The scenario that had the most fuel treatments (Scenario 3) had the most moderate severity fire of the scenarios. The no-management scenario resulted in the highest percent of high-severity fire (Fig. 2). Increasing the DRI did not result in a reduction in the amount of total area burned but it did reduce the proportion of the landscape that burned at high severity (Fig. 2B; Table 2).

Management and carbon sequestration

Climate change is moving the landscape toward becoming a carbon source (Fig. 3, left). This can be moderated or accelerated by the type of management actions taken on the landscape, which is reflected in the different management areas present (see Table 3). Higher removals of biomass (whether from combustion of litter/downed woody material or from higher mortality than other forms of treatment) by prescribed fires in Scenarios 4 and 5 on the landscape affected the carbon balance (Fig. 3, right), where both live and dead C pools decreased through time. A more direct comparison of Scenario 2 and 4, in spite of similar areas treated,

indicated higher mortality from prescribed fires resulting in lower levels of live C but a higher ratio of low severity fire. Scenario 3, the intensive harvest scenario, maintained the highest levels of sequestration despite the highest levels of removals.

Fig. 1. Mean disturbance return interval by management zone for the entire Lake Tahoe Basin. Averaged across all climate projections and replicates. Ribbons represent +/- 1 standard deviation. WUI, wildland–urban interface.



DISCUSSION

Our analysis suggests that, with the management approaches tested, there was a trade-off between C storage and fire severity. Although a lower DRI reduced high-severity fire, the net effect was reduced C storage. Managers must therefore decide whether reduced fire risk (and subsequent avoidance of attendant human health risks, from emissions, and hydrologic risks, from erosion, represented as reduced high-severity fire) justify the costs (both C storage and the additional resources expended to implement these strategies), which are issues addressed in other articles in this special issue. Prescribed fire can have longer lasting reductions in future fire severity over thinning actions because of the greater reduction of plant material and down dead materials, though duration can be limited on highly productive sites (Casals et al. 2016). Nevertheless, prescribed fire can have additional widespread restorative outcomes for wildlife and fire-dependent plant species (Alcasena et al. 2018) that are not in the realm of this study.

Table 2. Results of generalized linear model of percentage of low and moderate severity fire burned each year.

Dependent variable:	
Percentage of Low and Moderate Severity Fire per Year	
logDRI	-0.066*** (0.004)
Period Late	-0.190*** (0.007)
Constant	1.122*** (0.013)
Observations	500
Log Likelihood	556.268
Akaike Inf. Crit.	-1,106.536

* = p < 0.1, ** = p < 0.05, *** = p < 0.01

Table 3. Results of generalized linear model of net ecosystem exchange and disturbance return interval (DRI) by year and management zone. NEEC, net ecosystem exchange; WUI, wildland–urban interface.

Dependent variable:	
NEEC	
logDRI	-2.170*** (0.052)
Period Late	17.127*** (0.128)
General Forest	-31.264*** (0.214)
Mt. Rose Wilderness	5.868*** (0.206)
WUI Defense	-37.833*** (0.230)
WUI Threat	-25.453*** (0.223)
Constant	-6.493*** (0.319)
Observations	59,880
Log Likelihood	-249,136.500
Akaike Inf. Crit.	498,287.100

* = p < 0.1, ** = p < 0.05, *** = p < 0.01

An alternative approach to landscape C management could be through the promotion or protection of C hotspots. In our simulations, C dense hotspots on the landscape persisted through time regardless of management scenario but increasing the DRI reduced C heterogeneity across the landscape—reducing the hotspots while increasing the mean elsewhere through the release of the remaining trees (Fig. 4). Large trees store and sequester higher levels of C than smaller trees, and reducing the risk of high-severity fire in the C-dense stands could maintain landscape C in the medium (< 30 years) term (Harris et al. 2019).

To the degree that managers can control DRI, a DRI that is too high may result in the decline of the resilience of landscape C sequestration. Because of climate change, doing nothing also incurs a cost, and so management decisions need to consider the whole suite of inputs and potential outcomes of implementing any given strategy, the goal of this special issue and the

Fig. 2. (A) Cumulative area burned, in hectares, by severity and total. Averaged across all replicates and climate projections. Ribbon represents ± 1 standard deviation. (B) Disturbance return interval (DRI) against the percentage of area burned at low and moderate severity each year by scenario. Early period indicates years before 2060, late indicates after 2060.

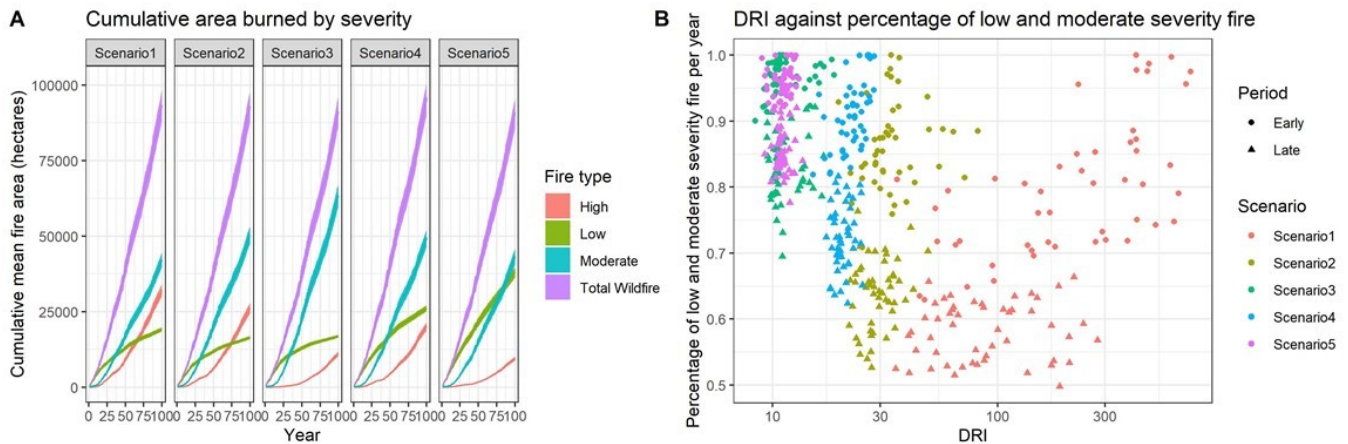
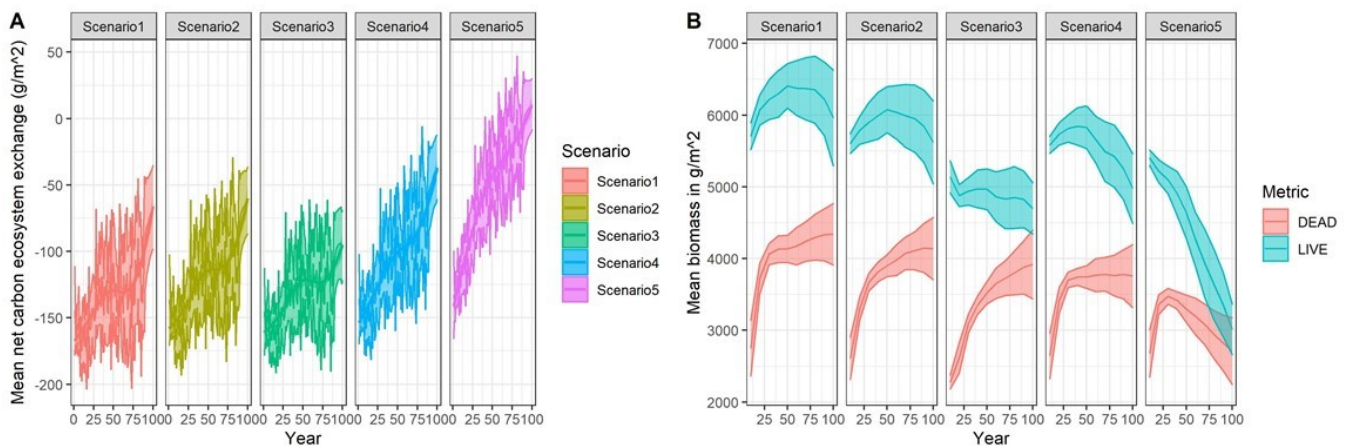


Fig. 3. (A) Net ecosystem exchange in $\text{g C m}^{-2} \text{yr}^{-1}$, averaged across all climate projections and replicates. Line of best fit calculated as GAM. (B) Carbon by dead and live pools in $\text{g C m}^{-2} \text{yr}^{-1}$, averaged across all climate projections and replicates with ribbon representing ± 1 standard deviation.

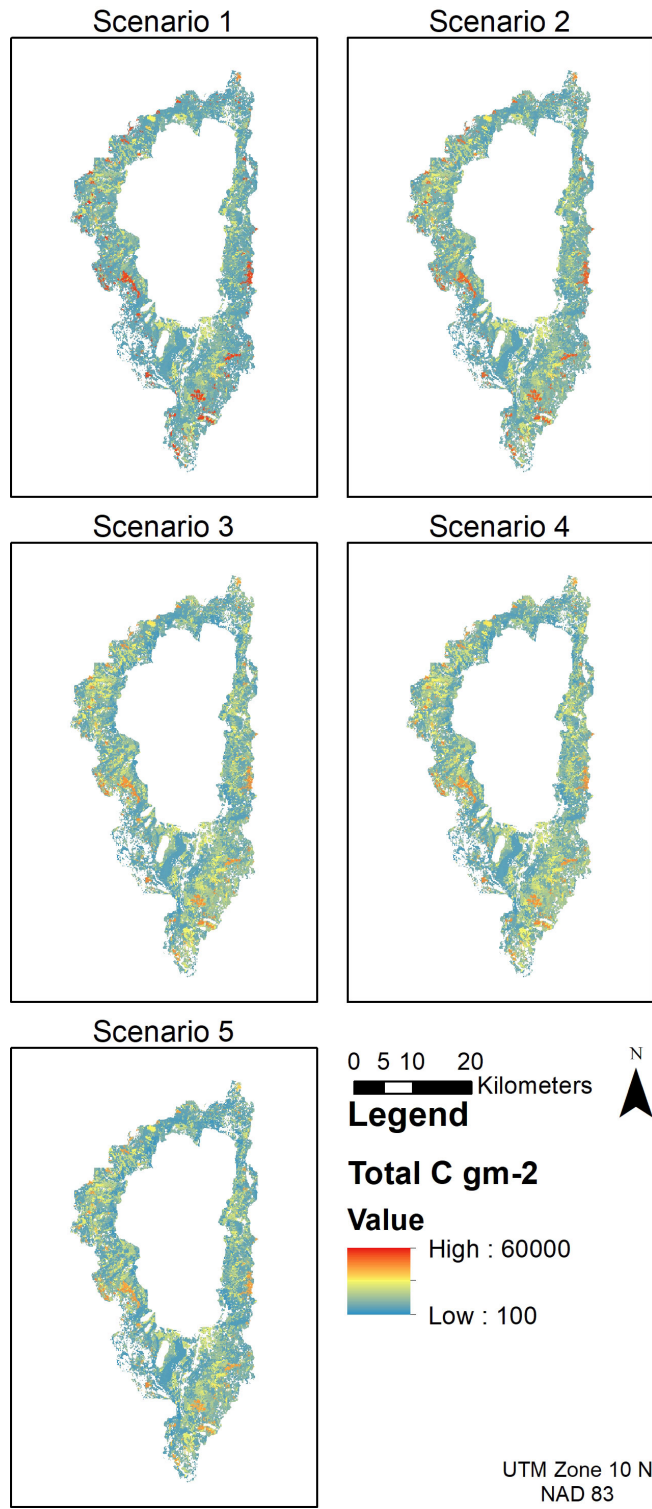


implementation of the Environmental Management Decision Support (EMDS) tool (Reynolds et al. 2014). Within the LTB, recent management is largely focused on the WUI (Loudermilk et al. 2014) and has the potential to increase C sequestration over many decades (Loudermilk et al. 2017). These studies assumed, however, that management would be restricted to the WUI. Our scenarios were designed to elucidate trade-offs for management actions occurring across the entire landscape. Scenario 1, the no-management scenario, had the highest levels of live carbon but also the highest rate of high-severity fire. Although Scenario 3 had the lowest DRI, enforcing a lower DRI (high disturbance rate) in the high-elevation forests and wilderness areas—areas that experience limited disturbance otherwise—did not confer any substantial C benefits and would presumably also have the highest cost. Harvesting can enhance growth in remaining trees while also reducing unpredictable high-severity fire. Thus, Scenario 3 might have additional C benefits based on how the harvested forest products are used.

Estimating the DRI provided necessary information for estimating the carbon carrying capacity (Liang et al. 2017) for the Lake Tahoe basin. We found that for a given DRI there was an upper limit for landscape carbon storage. Liang et al. (2017) found that forests in the Sierra Nevada could take hundreds of years to equilibrate to a new carbon carrying capacity under climate change and that climate mediated wildfire. Similarly, our results suggest that by the end of this century, this landscape will likely be above its carry capacity for C given the downward trend in live C and decreasing net ecosystem exchange and will not be approaching any sort of equilibrium within this time frame. This latter point is exemplified by the upturn in simulated high-severity fire occurring in the latter half of the century (Fig. 2).

Although maintaining a forest in its “safe operating space,” where the underlying disturbance regime aligns with the biological traits of the forest species, promotes ecological resilience (Johnstone et al. 2016), the complicating factor is climate change. While the

Fig. 4. Mean total C by scenario at model year 90 (2100), averaged across all model replicates and climate projections.



long-term stability of the forests prior to Euro-American colonization and climate change is viewed as that safe-operating space, climate change alters disturbance regimes and forest conditions directly (Johnstone et al. 2016), and such climate mediated disturbances such as fire and insects will substantially limit growth in landscape C and alter patterns of species dominance as we observed in the LTB (Scheller et al. 2018).

There are uncertainties with any modeling study, particularly when trying to account for novel climatic conditions. Although temperatures are unequivocally projected to increase, there is substantial variation in expected precipitation and extreme events that may not be captured by these GCMs. The drought conditions in California in 2021 are part of a larger megadrought made worse by climate change (Williams et al. 2020) that are unprecedented in modern history. Although mechanistic models like LANDIS are generally more robust to novel conditions, they can be limited by an incomplete understanding of mechanism in question (e.g., direct drought mortality) or a resultant new process not previously documented (mass fire due to unprecedented fuel build-up from insect and drought mortality).

Responses to this article can be read online at:

<https://www.ecologyandsociety.org/issues/responses.php/12954>

Acknowledgments:

Funders included the following: National Forest Foundation, California Tahoe Conservancy, USDA Lake Tahoe Basin Management Unit, Southern Nevada Public Lands Management Act Public Law 105-263, California Climate Investments, USDA Pacific Southwest Research Station

Data Availability:

The model parameters and code used in this analysis that support the findings of this study are openly available in: <https://github.com/LANDIS-II-Foundation/Project-Lake-Tahoe-2017/> This code has been archived on zenodo.org at: <https://doi.org/10.5281/zenodo.4644579>

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Appendix 1

- 1 **This file includes:**
- 2 Supplementary methods
- 3 Tables A1.1 to A1.6
- 4 Figures A1.1 to A1.9
- 5 Supplementary references

6 **Supplemental Methods:**

7 *Climate projections*

8 A combination of 8 projections were used from 4 different global change models (GCMs) at two
9 relative concentration pathways (RCPs). The RCPs chosen were 4.5 and 8.5, the former
10 representing an emissions-controlled future, while the latter represents an uncontrolled emissions
11 future. The particular combination is based on recommendations from Pierce et al. 2016. The
12 LANDIS model utilizes the following climatological variables: daily precipitation (Figure A1.1
13 and A1.2), daily maximum temperature (Figure A1.3), daily minimum temperature, daily
14 average windspeed, and daily average wind direction that are averaged across the Level II EPA
15 ecoregions in the study area.

16 *Forest succession*

17 NECN (v6.5) simulates both above and belowground processes, tracking C and N through
18 multiple live and dead pools, as well as tree growth (as net primary productivity--a function of
19 age, competition, climate, and available water and N). Soil moisture, as well as movement
20 across the dead pools: wood and litter deposition and decomposition, soil accretion and
21 decomposition are based on the CENTURY soil model (Parton et al. 1983, Scheller et al. 2011).
22 Carbon estimates by pool were validated against Wilson et al. (2013) at the ecoregion level,
23 where the model overestimated total C for only one region but was within one standard deviation
24 for all others (see supplemental Figure A1.4). Forest growth estimates using the climate data for
25 year 2010-2015 for the region were calibrated against the MODIS 17a3 product annual mean for
26 2000 – 2015 (Figure A1.5). Mean landscape value for MODIS was 393 g C/m² (sd 134),
27 while for LANDIS the mean value was 320 g C/m² (sd 312). Reproductive success is
28 dependent on temperature and water.

29 *Fire modeling*

30 The SCRPPLE extension (v2.1) models ignitions by drawing the number of ignitions from a
31 zero-inflated Poisson distribution and allocates them across the landscape with a weighted
32 ignition surface for each type of fire modeled (Scheller et al. 2019). The weather influence on
33 fire is based on the Fire Weather Index (FWI) measures created by the Canadian Fire Prediction
34 System (1992). There are three categories of fires that can be modeled: lightning, accidental
35 (i.e., human started), and prescribed fire. The extension also includes the ability to explicitly set
36 fire suppression effort levels across the landscape as well as by ignition type, where the
37 suppression parameter reduces the probability of fire spread from one cell to another. Effort
38 levels can range from 0 to 3, where 0 is no suppression attempted, to 3 which represents high
39 effort and was designed to mimic current suppression efforts in the Basin (Figure A1.6).
40 However, suppression effectiveness can be limited by weather as well, a maximum wind speed
41 parameter can limit suppression to days only when resources can be deployed safely. That
42 parameter was set at wind speeds of 11 meters per second (~25 miles per hour) in consultation
43 with regional fire personnel. Prescribed fires follow a set of weather prescriptions for when fires
44 can occur (Table A1.2).

45 Contemporary wildfires (2000-2016, from CalFIRE FRAP) were used to parameterize fire
46 spread and size from the Central Sierra Nevada in order to increase the sample size of fires.
47 Mean annual fire area (in ha) for observed data was 117 hectares per year (SD = 309), for

48 modeled data, the mean value was 122 hectares per year (SD = 210). In order to move from fire
49 intensity to fire severity (to encompass the mortality associated with fire), five fire experts
50 working in the LTB provided their estimates of mortality for varying species, age, and intensity
51 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 $\sim 1100\text{g/m}^2$ 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. In order to try to validate fire intensity for the Basin, the targeted
66 fire intensity value for any of the larger multi-day fires was 40% high, 40% mid, and a 20% low
67 intensity, with high intensity less than 60% of the total fire area. These percentage targets were
68 based on the thematic burn severity values present within the Basin from Monitoring Trends in
69 Burn Severity website.

70 *Insect modeling*

71 A modified version of the Biological Disturbance Agent extension (Biomass BDA v.2.0)
72 (Sturtevant et al. 2009) was used to simulate insect outbreaks for three species of insects: Jeffrey
73 pine beetle (*Dendroctonus jeffrey*), mountain pine beetle (*Dendroctonus ponderosae*), and fir
74 engraver beetle (*Scolytus ventralis*). The extension requires insect-specific resource
75 requirements and assigns a species-specific vulnerability that varies by age. Cells are
76 probabilistically selected for disturbance based upon the species host density at a given site and
77 the presence of non-hosts reduce disturbance probability. The parameters for spread and
78 mortality are outlined in Kretchun et al. (2016), see Table A1.5 and Table A1.6 below. Mortality at
79 an outbreak site is subsequently determined by species' age and host susceptibility probabilities
80 based from empirical field studies (Egan et al. 2010, 2016) and expert opinion, see Table A1.2
81 below. The insects had differing rates of spread per year from previous outbreaks. Mountain
82 Pine Beetle had positive neighbor effects, where pheromones promoted more rapid spread when
83 there were neighboring populations. All insects were able to exploit recently burned stands up to
84 10 years after a fire. Following mortality, dead biomass remains on site and moves to the
85 downed woody debris C pool and the fine woody debris C pool.

86 However, unlike Kretchun et al. (2016), the trigger for an outbreak was changed to be responsive
87 to climate signals. This is because for many beetle species climate influences outbreaks in three
88 ways: low winter temperatures cause beetle mortality; year-round temperatures influence
89 development and mass attack; and drought stress reduces host resistance. Here, we modeled
90 climate influences as a function of drought and mean minimum winter temperature, recognizing
91 that the full suite of climatic influences is necessary for a fully mechanistic model. So long as

92 annual climatic water deficit exceeded a set threshold, in conjunction with mean winter
93 minimum temperatures exceeded a certain threshold, outbreaks could occur. A comparison
94 between the modeled and observed outbreak dataset (USFS Aerial Detection Survey:
95 <https://www.fs.fed.us/foresthealth/applied-sciences/mapping-reporting/index.shtml>) found an
96 overestimation of frequency of occurrence but an underestimation of area impacted by
97 insects (Figure A1.7).

98

99 **Supplemental Tables:**

100 Table A1.1. Suppression effort levels and effectiveness on fire spread

probability.	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

102 Table A1.2. 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)

103

104 Table A1.3. 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
<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

105

106

107 Table A1.4. 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%					

109 Table A1.5. Insect disturbance inputs by insect

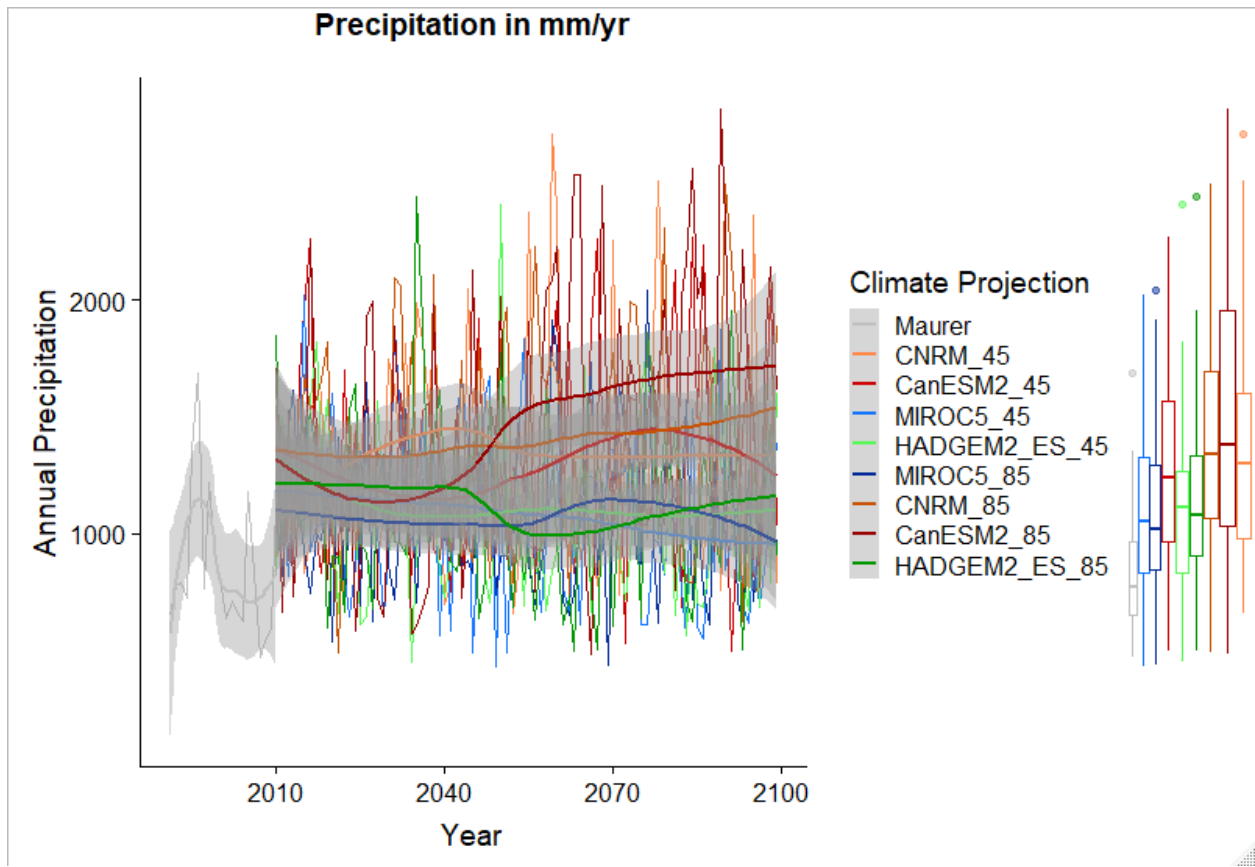
	Fir Engraver		Jeffrey Pine Beetle		Mountain Pine Beetle	
	Parameter	Source	Parameter	Source	Parameter	Source
Dispersal Rate	1000 m/year	Jactel (1991)	600 m/year	Egan (personal comm.)	400 m/ year	Safranik (2006)
Neighborhood Effect	N/A	USFS Fir Engraver Facts (2017)	N/A	N/A	Yes, 2x	Safranik (2006)
Disturbance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

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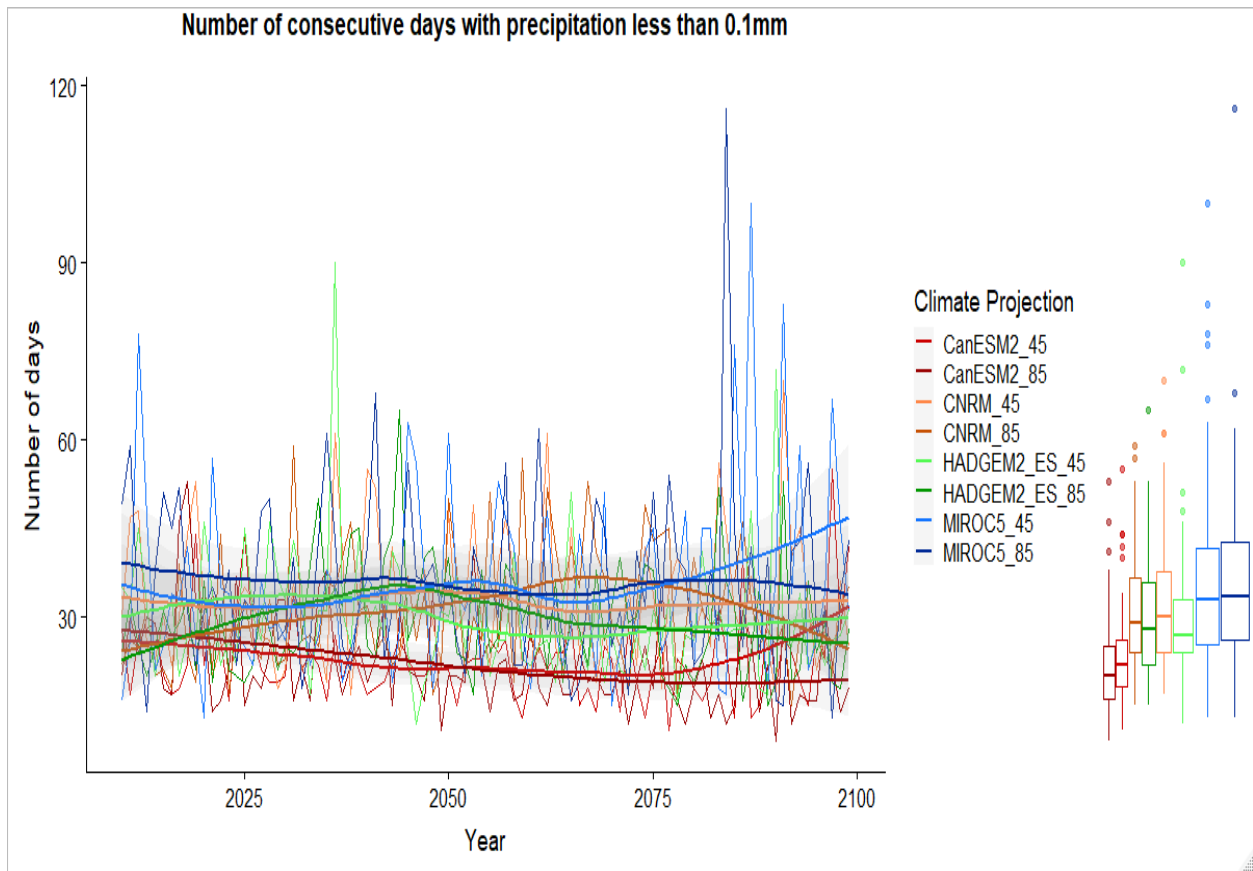
112 Table A1.6: Insect disturbance parameters by insect by host species

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



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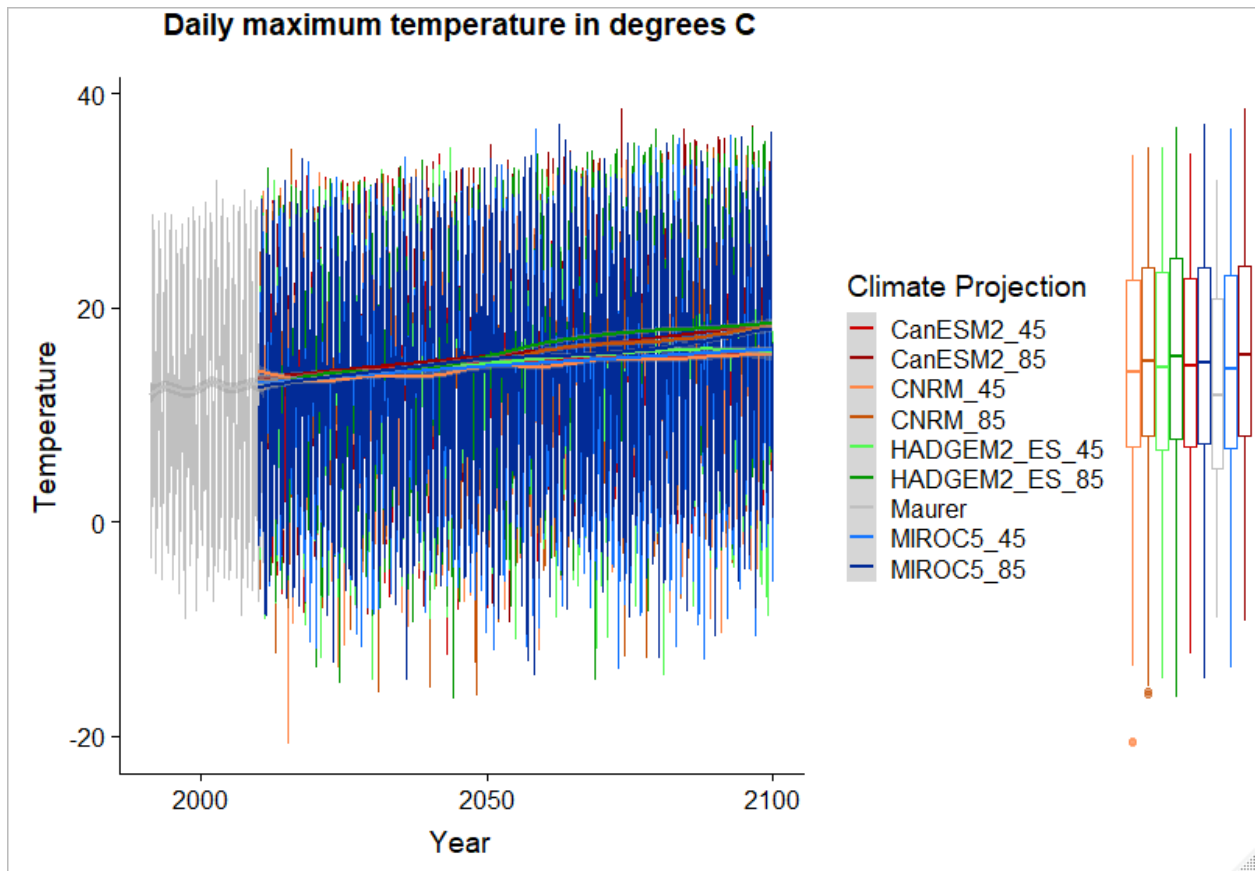
116 Figure A1.1. Projected precipitation in mm yr^{-1} , lines of best fit are GAM estimated, and
117 boxplots represent distribution of annual precipitation for the years 2090-2100.



118

119 Figure A1.2. Projected number of consecutive days with no precipitation, lines of best fit are GAM
 120 estimated, and boxplots represent distribution of consecutive days per year for the years 2090-
 121 2100.

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124 Figure A1.3. Projected daily maximum temperature in degrees C, lines of best fit are GAM
 125 estimated, and boxplots represent distribution of daily temperatures for the years 2090-2100 for
 126 the future climate projections.

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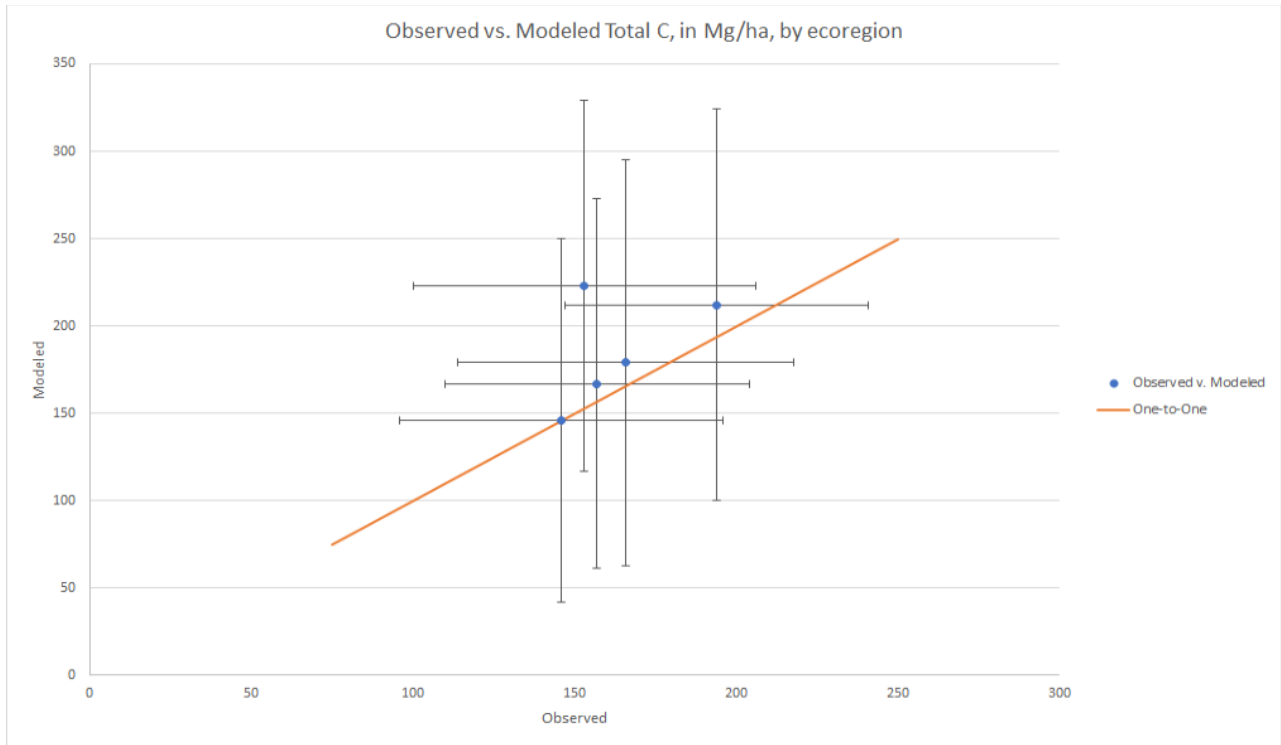
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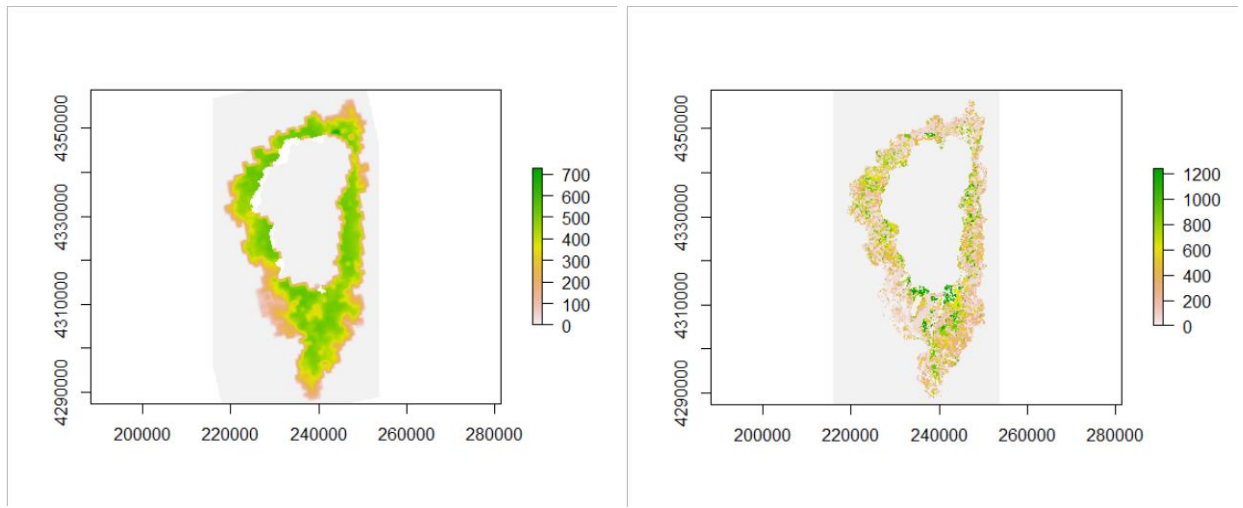


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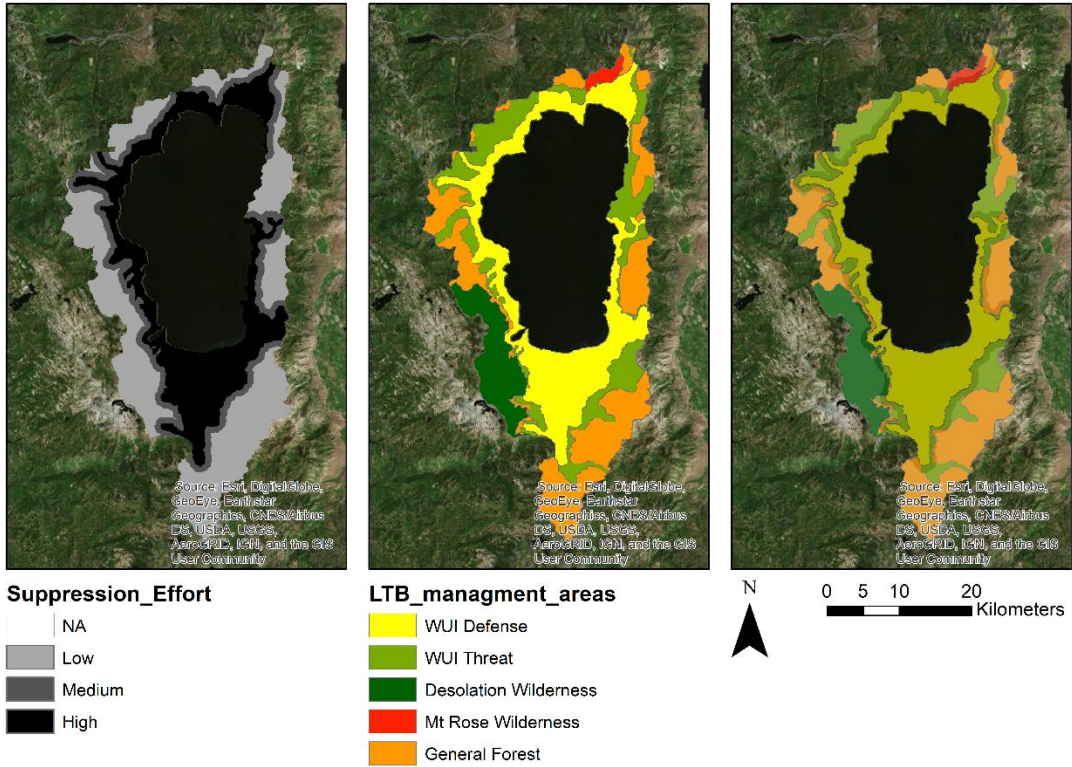
139 Figure A1.4. Observed versus modeled total C, in egagrams C per hectare, by ecoregion, error
 140 m bars represent +/- 1 standard deviation.

141

142 Figure A1.5. Comparison of MODIS (left) and LANDIS (right) estimates of Net Primary
143 Productivity in $g\ C/m^2$. Mean landscape value for MODIS was $393\ g\ C/m^2$ (sd 134), while
144 for LANDIS the mean value was $320\ g\ C/m^2$ (sd 312).

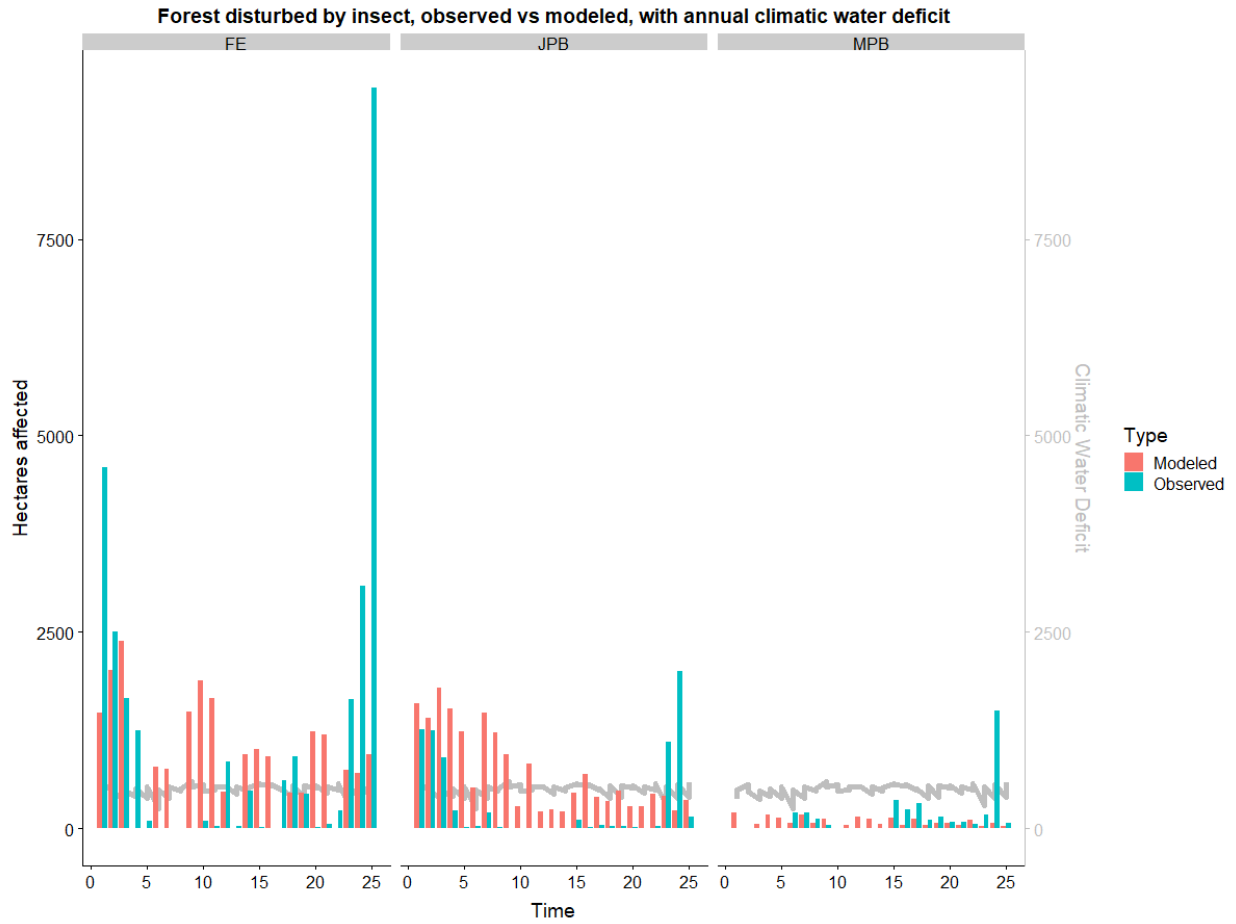


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147 Figure A1.6. Map of suppression (left), management zone (middle), and the overlay of the
 148 effort two (right).

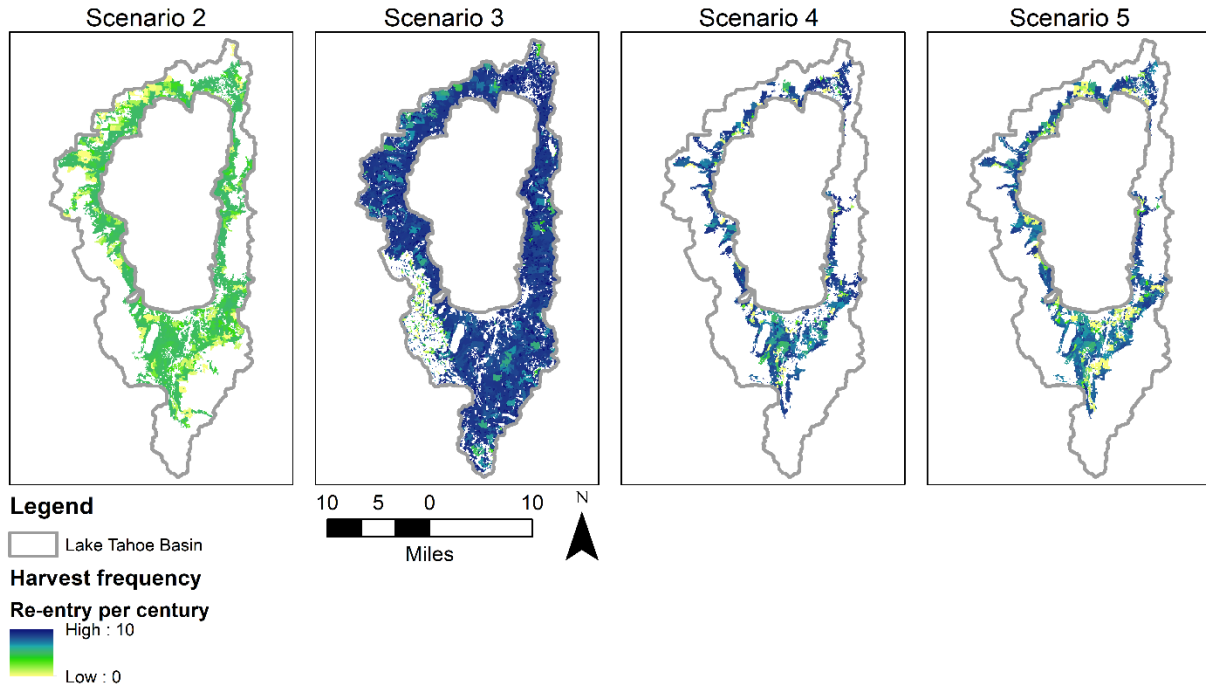


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150 Figure A1.7. Observed versus modeled number of hectares affected by insect/mortality agent.
 151 Time 0 is equal to 1990, with Time 22-25 corresponding to the 2012-2015 California drought.
 152 FE is fir engraver beetle (*Scolytus ventralis*), JPB is Jeffrey pine beetle (*Dendroctonus jeffreyi*),
 153 and MPB is mountain pine beetle (*Dendroctonus ponderosae*).

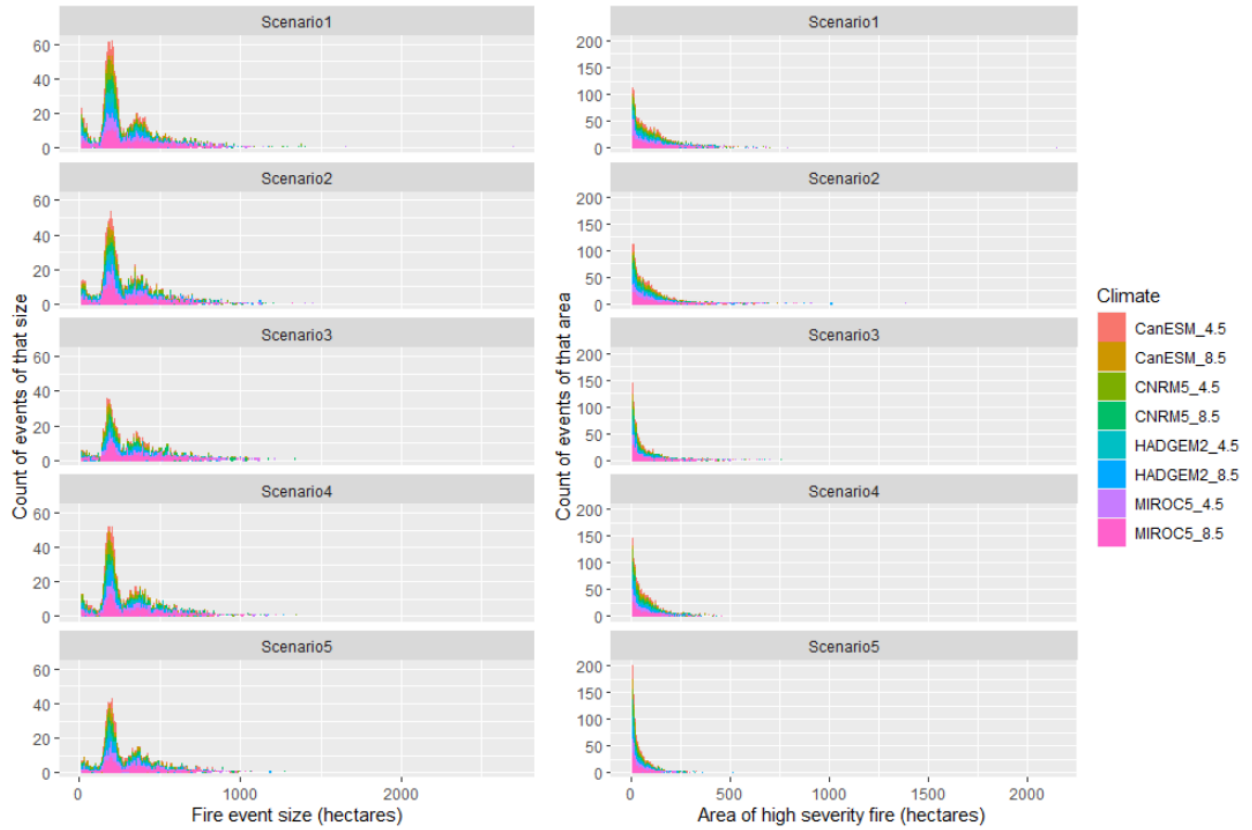
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157 Figure A1.8. Harvest return frequency by management scenario. Treatments were
 158 expanded beyond the WUI area in Scenario 3. Scenarios 3 through 5 had a higher
 159 intended treatment frequency.



160

161 Figure A1.9. Histogram of fire sizes (left) and
 162 high severity fire area (right) by scenario and by

high severity fire area (right) by scenario and by

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