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

Modeling the Risk Reduction Benefit of Forest Management Using a Case Study in the Lake Tahoe Basin

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ABSTRACT. Across the United States, wildfire severity and frequency are increasing, placing many properties at risk of harm or destruction. We quantify and compare how different forest management strategies designed to increase forest resilience and health reduce the number of properties at risk from wildfire, focusing on the Lake Tahoe Basin of California and Nevada. We combine landscape change simulations (including climate change, wildfire, and management effects) with scenarios of current and plausible fuel treatment activities and parcel-scale fire risk analysis. Results suggest that more aggressive fuel treatment activities that treat more area on the landscape, whether through mechanical and hand thinning or prescribed fire, dramatically lower the fire probability in the region and lead to a corresponding lower risk of property loss. We estimate that relative to recent practices of focusing management in the wildland–urban interface, more active forest management can reduce property loss risk by 45%–76%, or approximately 2600–4900 properties. The majority of this risk reduction is for single family residences, which constitute most structures in the region. Further, we find that the highest risk reduction is obtained through strategies that treat a substantially greater area than is currently treated in the region and allows for selective wildfires to burn for resource objectives outside of the wildland–urban interface. These results highlight the importance of more active forest management as an effective tool in reducing the wildfire risk to capital assets in the region.

Key Words: *forest management; Lake Tahoe; prescribed fire; property risk; wildfire*

INTRODUCTION

Across the western United States, wildfire severity and frequency are increasing (Dennison et al. 2014, Abatzoglou and Williams 2016, Parks and Abatzoglou 2020). California has experienced some of the worst fires in its history over the past few years, with the Camp Fire in 2018 destroying roughly 19,000 structures and killing 85 people: the deadliest fire in California history (CAL FIRE 2018). Development, fire suppression policy, and climate change have all been shown to increase fire risk to property and infrastructure (Westerling and Bryant 2008, Syphard et al. 2019). The risk extends well beyond California given that one-third of all homes in the United States are built in or near wildland vegetation, commonly termed the wildland–urban interface (WUI; Schoennagel et al. 2017, Radeloff et al. 2018). These homes are some of the most at risk to wildfires, with 69% of buildings destroyed by wildfire across the United States having been located in the WUI, and 75% in California (Kramer et al. 2018). Despite these risks, development in the WUI is growing (Radeloff et al. 2018), increasing future wildfire risk to property.

Although wildfires are natural, beneficial, and even necessary for many ecosystems (Perry et al. 2011, McLauchlan et al. 2020), the public and policy makers call on resource managers to mitigate fire risk. Over the past century, fire suppression was the primary strategy to lower fire risks, but the cumulative recent effect of this strategy has been an increase in destructive crown fires (Fulé et al. 2004, Ohlson et al. 2006, Steel et al. 2015) and suppression costs exceeding several billion dollars in recent years (NIFC 2020, CAL FIRE 2021).

Recently, active forest management, including thinning and prescribed burning to reduce forest fuel loads, has emerged as a promising management tool to mitigate this risk in a more ecologically sound manner (Stephens and Ruth 2005, North et al. 2021). Forest thinning and prescribed burns reduce the severity and frequency of fires (Pollet and Omi 2002, Ritchie et al. 2007, Safford et al. 2009, Prichard et al. 2010, Wu et al. 2013, Stevens et al. 2016), but some studies have also found that these benefits may be short lived, lasting around five years (Price and Bradstock 2012). In the focal area of our study, the Lake Tahoe Basin, Safford et al. (2009) showed that fuel treatments dramatically reduced the severity of wildfires, with crown fires generally turning to surface fires within 50 meters of treated areas. Despite obvious benefits, the costs of ongoing active forest management can be high and are often higher in areas that overlap with property and human infrastructure (Loomis et al. 2019). In addition, federal and state agencies historically have not been provided with sufficient resources to treat current fuel loads (North et al. 2015).

Beyond localized fuel loads, the severity of wildfires and the risk they pose to property has been shown to be highly connected to landscape ownership and governance. Starrs et al. (2018) show how federal land ownership and firefighting responsibility were both associated with higher fire probability in the Sierra Nevada. Other studies indicate that human presence increases the frequency of ignition and loss of human infrastructure and property (Syphard et al. 2008) and that certain patterns of development can increase property risk to wildfires (Syphard et al. 2013). These retrospective analyses describe how management and landscape makeup influenced fire regimes and risk in the past, but little has been done to model future wildfire risk to property and the effects of mitigation efforts (see Westerling and Bryant 2008 as an exception).

In this study, we estimate the property at risk from simulated wildfires under various forest management scenarios in the Lake Tahoe Basin (LTB) in California and Nevada. Stakeholders in the

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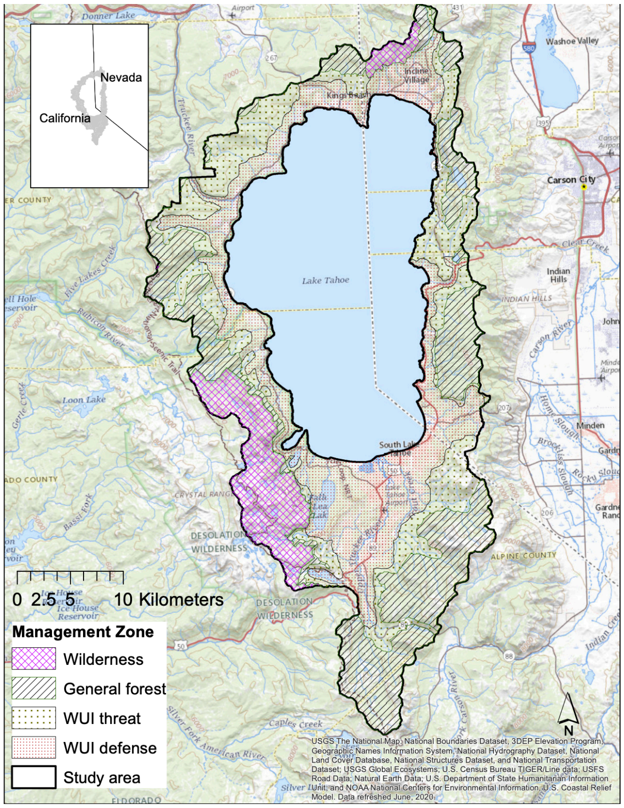
LTB wanted to evaluate the potential effects of forest management under future climates on a range of social and ecological indicators, and this analysis is a component of this broader effort. Our focus is on forest management, particularly fuel treatments, and a predictive, landscape approach to the number and intensity of fires, as well as fire risk to properties under these models. Through this analysis, we provide insight into the tradeoffs associated with forest management and property value and give local land use planners and forest managers critically needed information on projected risks of fire to property.

METHODS

Study area

The study area for this analysis is the 88,000-hectare Lake Tahoe Basin in California and Nevada (Fig. 1), over 70% of which is composed of National Forest System Lands managed as part of the Lake Tahoe Basin Management Unit (LTBMU). California and Nevada state authorities manage an additional 8100 hectares, and just over 11,000 hectares are managed by tribal authorities or are private property. The LTBMU has a very large area characterized as wildland–urban interface, with almost half of the Basin's land area adjacent to general forest and wilderness. The area has a relatively high number of homes in the wildland–urban interface and is located in a region that is at risk of high tree mortality and high-intensity wildfire (Restaino et al. 2019), making considerations of fire risk and management paramount to residents in the LTBMU.

Fig. 1. Lake Tahoe Basin study area, California and Nevada.



USGS The National Map: National Boundaries Dataset, 3DEP Elevation Program, Geographic Names Information System, National Hydrography Dataset, National Land Cover Database, National Structures Dataset, and National Transportation Dataset; USGS Global Ecosystems; U.S. Census Bureau TIGER/Line data; USFS Road Data; Natural Earth Data; U.S. Department of State Humanitarian Information Unit; and NOAA National Centers for Environmental Information, U.S. Coastal Relief Model. Data refreshed June, 2020.

Fire regimes in the Basin have changed significantly over time. Prior to European colonization, fire regimes were largely determined by natural climate conditions and prescribed burning practices of the native Washoe Tribe in the region (Taylor and Beaty 2005). Safford and Stevens (2017) describe the pre-settlement natural range of variation for wildfires as frequent (11–16 years) burning at low to moderate severity. Post-settlement fire regimes have shifted to infrequent but higher severity fires (Stephens et al. 2018). This is the result of extensive logging of the region during the Comstock mining era of the mid/late 1800s, followed by over 100 years of fire suppression (Safford et al. 2009). Removing fire, both natural and managed, from the landscape has also increased stand densities across the region and reduced stand heterogeneity (Safford and Stevens 2017). Fire hazard, defined as the potential for wildfires to cause harm to people and property, has increased in the region as population growth pushes development in high hazard landscapes. The combination of high hazard and the potential for larger, more intense wildfire events presents a major risk to capital assets in the region.

Despite this increasing risk, large, destructive wildfires have been rare in the Basin. The 2007 Angora fire in the southwest portion of the Basin is the most notable exception. The Angora fire burned 1250 hectares and destroyed 254 homes, making it one of the most destructive wildfires at the time in the United States. Most other wildfires in the Basin have been small in size and have not caused large amounts of property damage. However, higher fuel loads from a century-long history of fire suppression in the region and the expansion of residential development in the wildland–urban interface have increased the likelihood of potential damages to structural assets in the region (Moody et al. 2009, Stephens and Sugihara 2018). This increasing risk was highlighted in 2021 when two large fires, the Caldor fire and the Tamarack fire, burned in areas just adjacent to the southern LTBMU border. The Caldor fire was nearly 90,000 hectares and destroyed 782 structures. The Tamarack fire was 27,800 hectares and destroyed 23 structures.

Estimating wildfire risk

This analysis integrates two distinct datasets to identify properties at risk of wildfire in the Lake Tahoe Basin under various forest management regimes. First, fire probabilities were derived from the results of the LANDIS-II forest disturbance and change model (Scheller et al. 2007) using the SCRPPLE extension (Scheller et al. 2019). The LANDIS-II model projects landscape change, and incorporates climate projections, management activities, and natural disturbances. For this application, LANDIS-II was calibrated to recent conditions and disturbance regimes in the Lake Tahoe Basin at a resolution of one hectare. A full model description and applications to the study area are documented in Loudermilk et al. (2014), Kretchun et al. (2016), Scheller et al. (2018, 2019). Detailed results from this LANDIS-II modeling exercise are described in two other studies in this special issue (Maxwell et al. 2022a and 2022b).

Fire dynamics were modeled using the Social-Climate Related Pyrogenic Processes (SCRPPLE) extension in LANDIS-II (Scheller et al. 2019). SCRPPLE models the ignition, spread, and intensity of fire activity in a landscape. Within the LTB, a probabilistic ignition surface was derived for the landscape from contemporary ignition information (Short et al. 2016). Each year, a varying number of ignitions are modeled on the landscape based on this probabilistic ignition surface. This was done for each of ten replicates to allow for some probabilistic variation in where fires begin on the landscape. Once a modeled ignition occurs, fire spread in the model is driven by two factors: weather and fuel loadings. Modeled weather conditions were based on climate projections taken from the CanESM2 model results of the relative concentration pathway (RCP) 4.5 scenario. Modeled fuel loadings are determined by the management scenarios described below. The location of the treatments is varied probabilistically in the model in each replicate across the landscape. Modeled fire spread is also spatial in that high-intensity fires in one cell can spread into adjacent cells. Modeled annual area burned was calibrated and validated against contemporary fire events in the CalFire FRAP dataset (observed annual mean = 117 ha, s.d. = 309 ha, max = 1250 ha; modeled multiple replicate mean = 188 ha, s.d. = 223 ha, max = 1055 ha).

The principal measure of fire intensity in SCRPPLE is flame length. Flame lengths correspond to fire intensity metrics commonly used by forest managers (Scheller et al. 2019). Flames can threaten structures through two pathways: radiant exposure from large flames close to a structure or direct flame contact (Caton et al. 2017). Through both pathways, flames must be relatively close to a structure to present an ignition risk (Cohen 2000, Stocks et al. 2004). In the model, low, moderate, and high-intensity fires correspond to flame lengths of less than 4 ft, 4–8 ft, and greater than 8 ft, respectively. Fire intensity in LANDIS-II is a function of fuel loadings, wind speed, and ladder fuels in each grid cell. These fuel loadings are determined by forest growth dynamics, climate, and most importantly for this analysis, management decisions. In the model, more intensive forest management, whether by hand and mechanical treatments or prescribed burning, will reduce the fuel load in the treated cells and thus reduce modeled fire intensity and spread. In reality, this is not always the case, because some fires burn at high intensity on account of extreme weather conditions, regardless of fuel reduction history (Ager et al. 2010, Lyderson et al. 2014, 2017).

Using the spatially explicit wildfire occurrence and intensity data, a probabilistic, parcel-level risk metric was developed for each management scenario described below based on 10 within-scenario replicates. As noted above, replicates represent stochastic variation in the location of the fuel treatments across the landscape and in the ignition location of wildfires. Our risk metric is then constructed as the probability of a fire occurrence in that parcel over a 30-year time horizon, a relevant period of time for management decisions. Risk metrics are specified for multiple different fire intensities. We report findings for the probability of a high-intensity fire (flame lengths > 8 ft) occurring in a parcel as well as a moderate (4–8 ft flame lengths) or high-intensity fire occurring in the parcel. The risk metric is defined in Equation 1.

$$Pr\left(Wildfire\right)_{i,k} = \sum_{r} \frac{FireOccurance_{r,i,k}}{TotalReplicates} \tag{1}$$

Where i indicates parcel, k indicates fire intensity (none, low, moderate, high), and r indicates the replicate. *FireOccurrence* is an indicator variable that is equal to one if a fire of intensity k occurred on parcel i in replicate r over the 30-year analysis period. For example, if LANDIS-II results show that parcel i experienced a moderate-intensity fire in three replicates and a high-intensity fire in one replicate, then the risk of a moderate- or high-intensity wildfire would be 40% (4/10). We do not make adjustments if multiple fires occur over the 30-year time frame in the same pixel. We define a property as “at risk” based on a threshold risk percentage. Results are reported for 25%, 50%, and 75% thresholds. As an example, a home is at risk using the 50% threshold if five or more of the replicates for the parcel containing that property predict a wildfire of a specified intensity.

LANDIS SCRPPLE was designed to represent moderate flame lengths that are associated with isolated crown fires with low canopy-level spread (passive crowning) and high flame lengths associated with spreading crown fires (active crowning). Crown fires, low fuel moisture, and high winds are all associated with ember production, which is a leading factor in predicting property loss (Manzello and Foote 2014, Caton et al. 2017, Syphard and Keeley 2019). High flame lengths also render wildfires difficult for firefighters to directly combat, which in turn signifies greater likelihood of property loss (Syphard and Keeley 2019). One limitation of the metric used in this analysis is that the model does not account for ember transport. If wind-driven fires carry embers across parcel boundaries, our current approach would underestimate the potential property risk.

Property location

Structure locations were identified using Zillow’s Transaction and Assessment Dataset (ZTRAX), which compiles county assessor office records for most counties in the United States. There are five counties in the Lake Tahoe Basin Management Unit: El Dorado and Placer counties in California and Carson City, Douglas, and Washoe counties in Nevada. In total there are approximately 36,547 properties in the LTBMU, after removing properties that had no geographic coordinates in the database. Properties that were registered as vacant land were also removed under the assumption that there were no structures at risk of wildfire on these properties. Of the remaining properties, 92% were residential or multi-family dwellings, 3% were commercial or industrial properties, and the rest were registered under an alternate designation. Figure 2 shows the density per square kilometer of registered properties across the Lake Tahoe Basin. To validate the location information in ZTRAX, we selected a random sample of one hundred properties from the dataset and visually compared (using Google Earth Pro) the property address to the geographic coordinates provided. For the purposes of this modeling exercise, there was sufficient agreement. In the instances where there were discrepancies, they were generally smaller than the modeling units in the LANDIS-II model (one hectare). These small deviations between the physical address and the geographic coordinates used for modeling are unlikely to affect the results presented below.

Management scenarios

To understand the relationship between forest management and the wildfire risk to homes in the region, five forest management scenarios were co-developed with local stakeholders (summarized in Fig. 3). Scenario 1 (S1) assumes no active forest management activities except for wildfire suppression. Scenario 2 (S2) represents a WUI-focused strategy that includes hand and mechanical treatments in the WUI, with a particular emphasis on the defense zone and hand thinning. This WUI-focused scenario, which treats approximately 1300 hectares (or 2% of the landscape), is most similar to recent management practice in the region and can be considered a business-as-usual scenario. The minimum stand retreatment time in S2 is 20 years. Scenario 3 (S3) increases the scale and pace of vegetation thinning treatments, including mechanical and hand thinning treatments in the WUI and the general forest, with some hand treatments occurring in the wilderness as well. Scenario 3 treats approximately 2000 hectares per year (7% of the landscape), with an 11-year retreatment time. Scenarios 4 (S4) and 5 (S5) represent two options for increasing the use of prescribed and managed fire on the landscape. Scenario 4 treats a similar area using hand and mechanical treatments as the WUI-focused scenario (S2) but adds approximately 730 hectares per year of prescribed fire and allows for some managed wildfires from natural ignitions in wildness areas. The total treatment area per year is approximately 4% of the landscape with a 20-year retreatment time. Scenario 5 (S5) is an expanded fire-focused strategy combining modest WUI thinning (similar to S2) with much greater use of prescribed burning (2700 hectares per year) and some managed natural ignitions for resource objectives. The total treatment area per year for S5 is approximately 11% of the landscape with a 20-year retreatment time. Currently, prescribed fire treatments are quite low in the Basin, but are being considered as a lower cost alternative or complement to hand and mechanical treatments.

Fig. 2. Property density in the Lake Tahoe Basin. Densities are reported as the number of properties per square kilometer in each census tract.

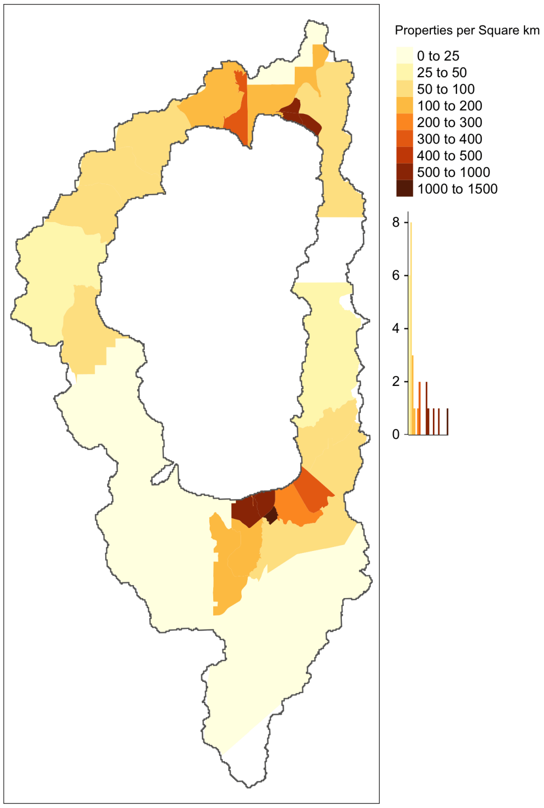
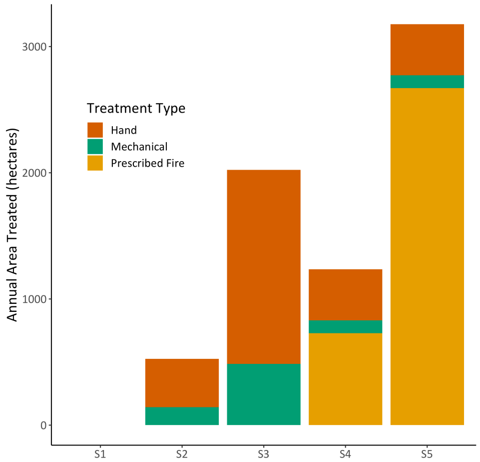


Fig. 3. Forest management scenarios used for evaluation. Scenarios differ primarily by the number of acres treated and the use of hand/mechanical treatments or prescribed fire treatments.



RESULTS

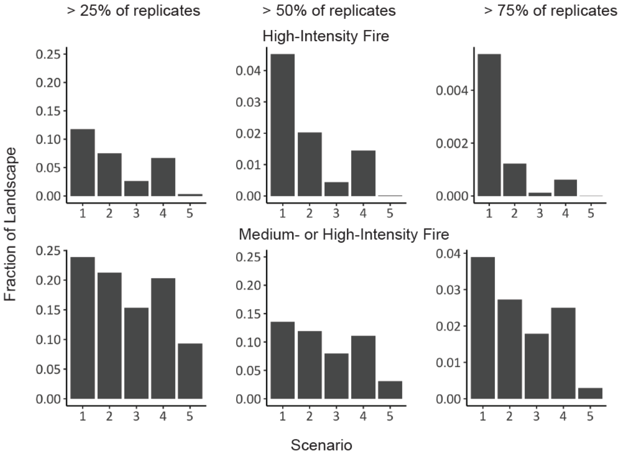
We present the results in two parts. First, we report results on the projected fraction of the landscape encountering fires of various intensities. Second, we report results on how the number of properties at risk vary across scenarios and risk thresholds. We also conduct a back-of-the-envelope cost–benefit calculation to compare the costs of fuel treatments to the benefits to property of wildfire reductions.

Fire occurrence and intensity

The occurrence and intensity of wildfire vary considerably across the five management scenarios (Fig. 4). Each plot shows the percentage of the entire LTB landscape that experiences a specific intensity of fire (reported by row) and probability threshold (reported by column) over the 30-year analysis time period. For example, the top left panel of Figure 4 shows that approximately 7–12% of the landscape has a greater than 25% chance of experiencing a high-intensity fire over 30 years in Scenarios 1, 2, and 4. In Scenario 3, approximately 3% of the landscape has a greater than 25% chance of experiencing a high-intensity fire. In Scenario 5, < 1% of the landscape has a greater than 25% chance of experiencing a high-intensity fire. This shows a clear negative relationship between the treated area and the fraction of the landscape predicted to experience a high-intensity fire.

This general trend is observable for most of the assumed fire intensities and probability thresholds. However, there is a larger reduction in high-intensity fires (top row of Fig. 4) than moderate-intensity fires for the more aggressive treatment scenarios. For example, using a 50% fire probability (the middle column), high-intensity fires in Scenario 2 cover approximately 2% of the landscape, whereas in Scenarios 3 and 5, the probability of high-intensity fires all but disappear from the landscape. This finding suggests that fuel treatments are having the desired effect in the model of reducing high-intensity fires, and to some extent moderate-intensity fires, from the LTB landscape.

Fig. 4. Fraction of the landscape experiencing wildfire by scenario. The y-axis shows the percent of the entire Lake Tahoe Basin where a wildfire occurs. Columns show different probability thresholds for each parcel. Rows break down results by the wildfire intensity category.



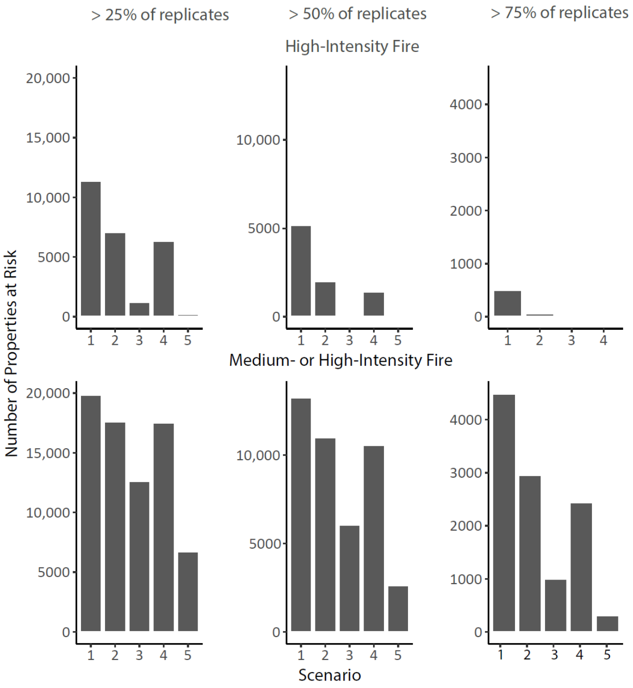
At-risk property

After intersecting the spatial fire probabilities with the known location of existing properties in the Basin, results show that the reduction in high- and moderate-intensity wildfires have the intended effect of reducing the number of properties that were exposed to a wildfire over the next three decades (Fig. 5). Results are presented for both a variety of fire intensity outcomes (rows) and risk thresholds (columns).

In Scenario 2, which represents our business-as-usual scenario, approximately 2012 properties were at risk of a high-intensity wildfire using a 50% probability threshold. The expanded treatment scenarios (S3 and S5) substantially reduced, relative to S2, the number of properties at risk of a high-intensity wildfire (n = 76 and 4, respectively) based on the 50% probability threshold. This represents a 96–99% reduction in the number of properties at risk of a high-intensity fire under the more aggressive forest management scenarios modeled. In other words, the management scenarios that treated between 2000 and 3200 hectares annually nearly eliminate the risk of property exposure to high-intensity wildfire. There appears to be some diminishing returns to the extra area treated in Scenario 5, which reduces the number of properties at risk by several percentage points, relative to S4, despite increasing the treated area by approximately 60%.

Although the exposure results to high-intensity fires are valuable, it is perhaps even more useful to understand the effects of management on exposure to any potentially damaging wildfire, which includes both moderate and high-intensity fires. Using this metric and a 50% probability threshold, Scenario 2 results suggest that 10,982 properties are at risk of either moderate- or high-intensity fire. Similar to our results for high-intensity fires, scenarios with larger treatment areas reduce fire risk of moderate- or high-intensity fires, although the treatments do not fully eliminate fire risk from the landscape. The thinning-focused expanded treatment scenario (S3) reduces the number of at-risk properties from 10,982 to 6055 (45% reduction). The fire-focused scenario (S5) that treats the greatest area reduces property exposure to 2622 properties (a 76% reduction relative to S2). Although these results assume a 50% probability threshold, the trends were similar using a 25% and 75% probability threshold.

Fig. 5. Properties at risk by scenario. The y-axis shows the number of properties in the Lake Tahoe Basin that are exposed to a wildfire at a given intensity and probability threshold.



The expanded treatment fire-focused scenario (S5) created the largest reduction in the exposure of properties to both moderate- and high-intensity fires although the area treated was similar to the thinning approach. The difference between approaches was partially because the fire-focused approach also allows some restraint in suppression response to wildfires outside the WUI for resource objectives. Although this management strategy does not entirely eliminate wildfire risk to properties, it dramatically reduces exposure.

Cost–benefit analysis

Expanded forest management options, such as the fuel reduction treatments modeled in this study, are costly and can be guided in part by the benefits that these actions confer in terms of reducing wildfire risk. Using the results from our analysis, a back-of-the-envelope calculation was conducted to estimate whether the financial investment in expanded thinning and prescribed burning treatments can be justified based solely on reducing property risk. To illustrate this, we made several assumptions regarding home values and the susceptibility of homes to loss when they encounter a flame (referred to hereafter as the destruction rate). We used Zillow Home Value Forecast to estimate the average value of a home in 2020 for El Dorado and Placer counties in California, which was approximately $507,000. This is a relatively crude estimate of value for several reasons. First, property values are likely to vary in non-random ways that may be correlated with wildfire risk. Using an average estimate may therefore overvalue or undervalue depending on the nature of this variation. Second, real home prices are likely to increase over time and this makes our estimate a likely underestimate of the real value at risk. Estimating the value at risk requires an assumption about what fraction of homes that encounter a wildfire will actually be destroyed. This is a difficult number to predict with confidence, so we show three possible outcomes: 10%, 50%, and 90% destroyed. There is some empirical evidence supporting the lower rates (Kramer et al. 2019). Other studies have suggested much higher damages from encounters with moderate- or high-intensity fires (Scott et al. 2013, Knapp et al. *in review*). For the calculation presented here, we used property at risk estimates from the 50% probability threshold of encountering a medium- or high-intensity fire. That is, the number of properties that the model predicts will be in a model pixel that has a modeled moderate- or high-intensity wildfire in at least 50% of the replicates.

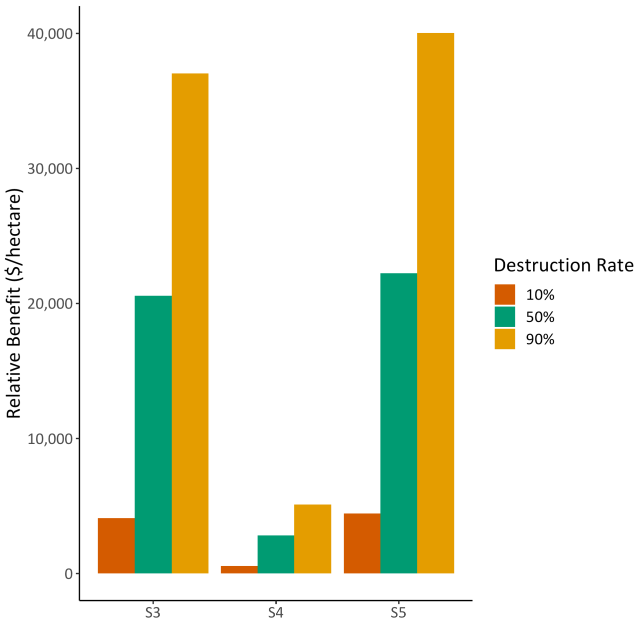
Table 1 shows the results of this back-of-the-envelope calculation of property value at risk across the five scenarios and three destruction rate assumptions. In the business-as-usual scenario (S2), where 10,982 properties have a 50% or greater risk of encountering a moderate- or high-intensity fire, the total value at risk is approximately $5.568 billion. If 10% of these properties are actually destroyed, this would be a loss of $557 million. As the destruction rate increases to 90%, the value would also increase to over $5 billion. The expanded treatment scenarios (S3–S5) decrease the property value at risk in proportion to the size of the treated area on the landscape. For example, the two scenarios that increase treatments the most, S3 and S5, decrease the value at risk to $307–$2763 million and $133–$1196 million, respectively, depending on assumed destruction rate. S3, which treats only a slightly greater area than S2, the business-as-usual scenario, results in similar property values at risk. There is not a substantial difference based on treatment type, whether hand/mechanical thinning or prescribed fire treatments.

Table 1. Property value at risk in US$million over the 30-year analysis time period. Results are presented across the five forest management scenarios (S1–S5) and three home destruction rate assumptions (10%, 50%, 90%).

Fraction of homes destroyed	S1	S2	S3	S4	S5
10%	$671	$557	$307	$536	$133
50%	$3355	$2784	$1535	$2679	$664
90%	$6039	$5011	$2763	$4822	$1196

We assessed the cost-effectiveness of the expanded treatment scenarios (S3–S5) by converting the total property value at risk results above to a benefit per treated hectare metric. The benefit from the expanded treatment is defined as the reduction in value at risk relative to S2, the business-as-usual scenario. Figure 6 shows these results for each of the expanded treatment scenarios and property destruction rate assumptions. For all destruction rates, there is a larger benefit per hectare for the scenarios that treated a greater area. The benefit per hectare is relatively similar between the expanded treatment scenario that utilized hand and mechanical thinning approaches (S3) and the fire-focused scenario (S5). Benefits per treated hectare also increase substantially as the assumed property destruction rate increases.

Fig. 6. Benefit, measured in $/acre, of the expanded forest management scenarios (S3–S5). Benefit is measured as the reduction in property value at risk in each scenario, relative to the business-as-usual scenario (S2). Results are normalized by dividing by the number of treated acres in each scenario.



The per hectare benefits can be compared to fuel reduction treatment costs in the region. Holland, Evans, Long, et al. (unpublished manuscript) show that treatment costs for the scenarios in this study were approximately $3500–$4700 per hectare for the hand/mechanical treatment scenarios (S2–S3) and $2200–$2700 per hectare for the fire-focused scenarios (S4–S5). S3 and S5 deliver property risk-reduction benefits on the upper range of these treatment costs for the 10% destruction rate assumption. As the assumed destruction rate increases, the benefit begins to exceed the scenario treatment costs. S4, the fire-focused scenario with a treated area similar to the business-as-usual scenario (S2), only delivers property risk-reduction benefits in excess of the treatment costs once the destruction rate approaches 90%. Of course, this simple cost–benefit comparison only considers benefits from avoided property loss or damage and none of the other potential ecological, health, or economic benefits from expanding fuels treatments.

DISCUSSION

Wildfire risk to residential property is driven by two factors: the probability of wildfire occurrence and the possible damage from that wildfire. This study assessed this risk by combining two unique datasets on the risk of wildfire and the location of structural assets. Applying this data to the Lake Tahoe Basin, we found that more intensive forest management aimed at reducing fuel loads inside the WUI and across the landscape outside the WUI can dramatically reduce the fire exposure risk of structures in the region. Under a WUI-focused business-as-usual scenario (S2) of minimal thinning and no prescribed fire, approximately 11,000 properties in the Basin were at risk of a moderate- or high-intensity fire over the next 30 years. The three more aggressive, but not unrealistic, management scenarios considered in this analysis reduced the number of properties at risk by 45–76% relative to this baseline.

Although this study emphasizes the risk to property from wildfire events, it is important to consider other factors driving wildfire hazard threats to physical capital assets, such as development patterns and social dynamics. For example, social networks are critical to sharing information and developing perceptions around wildfire risk (Brenkert-Smith et al. 2006). Infrastructure also plays a large role in wildfire risk planning. In many WUI areas in the western United States, housing density is growing without adequate increases in road networks to allow for evacuation (Cova et al. 2013). Public acceptance of prescribed fire is also dependent on local relationships with forest managers and an understanding of the practices and precautions being implemented (McCaffrey and Olsen 2012). Finally, zoning and housing policy in the WUI, which is driven by a diverse set of state and local stakeholders, requires an improved understanding of fire risk in order to plan future development effectively (Syphard et al. 2013, Mockrin et al. 2018).

We linked fire presence to property loss at a model scale, which is not a reflection of the reality of property defense. Syphard et al. (2014) showed that clearing a defensible space with low fuel levels around structures increases the likelihood of structures surviving, although landscape-scale factors were more important. Additionally, the choice of building materials and home design can mitigate fire risk (Quarels et al. 2010) and best practices pair flame-resistant materials and design with a well-enforced defensible space. Recent research on the 2018 Camp fire also suggests an externality effect in that proximity to a destroyed structure increased the likelihood of a home being destroyed (Knapp et al. *in review*). Despite the actions that can be taken at the structure level, we can still reasonably assume that fire risk as measured by the number and intensity of wildfires a structure is exposed to is an important metric for property owners and planners in the region.

Although this study clearly demonstrates the benefits of fuel treatments to reducing property risk in the Lake Tahoe Basin, forest managers face many obstacles in trying to meet their fuel reduction and restoration targets (Steelman 2016). Forest Service resources are spread thin and exploring alternatives to hand-thinning and controlled burns, such as industry-driven mechanical thinning, may be important if fuel load goals/reduction is to be successful regionally (Donovan and Brown 2005). Under expanded prescribed fire scenarios, managers will also need to consider feasible burn windows based on air quality regulations. Recent analysis suggests that in Lake Tahoe these windows are mostly available in Spring and Fall, and multiple-day windows are quite rare (Striplin et al. 2020).

There are several important limitations to our analysis. First, there is evidence that extreme weather events can reduce, or even eliminate, the effectiveness of fuel treatments in mitigating wildfire spread and severity (Ager et al. 2010, Lyderson et al. 2014, 2017). Our analysis does not factor in variation in weather conditions across the replicates and may be most representative of average weather conditions. Our results may therefore not be robust to extreme weather conditions, which are an important factor in the spread of high-severity wildfire. Similarly, we only considered a single future climate scenario and model, but there is variation across both of these dimensions, which may affect fire and the effectiveness of fuel treatments. Future work should examine the importance of both sets of factors when considering landscape-scale forest management planning.

Our analysis provides estimates of economic benefits to property owners of reducing the wildfire hazard threat in the Lake Tahoe Basin. Resource planning decisions must also consider tradeoffs in ecosystem services associated with thinning treatments, such as management costs, carbon sequestration, and adverse health impacts from smoke exposure. The potential benefits of more active forest management, under the assumptions identified above, are approximately \$8–\$14 million annually. Holland, Evans, Long, et al. (unpublished manuscript) show management costs of \$3.6–\$5.4 million annually in the expanded treatment scenarios. Long, Drury, Evans, et al., (unpublished manuscript) show damages of \$6–\$80 million from smoke exposure during simulated extreme wildfires in the region. On an annualized basis, the public health and property benefits from the expanded treatment scenarios are roughly similar and individually outweigh the costs of expanded management. These findings provide support for efforts in the region to invest in fuels reduction treatments that may not be profitable solely in terms of financial return.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/13169

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Data Availability:

LANDIS-II model and parameters for the Lake Tahoe management project are available at https://github.com/LANDIS-II-Foundation/Project-Lake-Tahoe-2017/. R code for reproducing results is available at https://github.com/sgevans/LakeTahoe_PropertyAtRisk.

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