



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

The management costs of alternative forest management strategies in the Lake Tahoe Basin

Timothy G. Holland^{1,2}, Samuel G. Evans³, Jonathan W. Long⁴, Charles Maxwell⁵, Robert M. Scheller⁶ and Matthew D. Potts¹

ABSTRACT. Wildfires play an important ecological role in fire-adapted landscapes throughout California. However, there is a growing awareness that large wildfires in increasingly populated areas incur costs that may not be acceptable to society. Various forest management strategies have been proposed that seek to reduce the prevalence and severity of wildfires in areas where these costs are high. In this study we estimate the financial costs of various hypothetical forest management scenarios in the Lake Tahoe West landscape of Northern California. The objective of the study was to quantify trade-offs and cost constraints that would affect the feasibility of each scenario. The scenarios ranged from minimal forest management to several options for more intensive fuels management that relied to varying degrees on thinning and prescribed burning. We assessed stand-level costs associated with thinning, prescribed burn management, and timber and biomass transport, as well as revenues from timber and energy chips sold. Using modeled fire occurrence and severity metrics, we also used historical wildfire data to estimate plausible fire suppression costs. Our findings suggest that increased forest management, through the use of either hand/mechanical treatments or prescribed fire, can reduce fire suppression costs relative to recent practices by more than US\$400,000 per year. These more intensive management scenarios differ in their cost-effectiveness. Scenarios that increase the use of prescribed fire appear to be the more cost-effective management interventions available with annual costs roughly half as much as a scenario focused on increased hand and mechanical thinning. The results are useful for understanding the financial implications of modifying forest management practices designed to lower the private and social costs of wildfire in the region.

Key Words: *economic cost; forest management; Lake Tahoe; prescribed fire; wildfire*

INTRODUCTION

Across much of the Western United States, forest landscapes have become increasingly susceptible to ecological damages from wildfires, which are increasing in both frequency and severity (Dennison et al. 2014, Abatzoglou and Williams 2016, Parks and Abatzoglou 2020). Whereas historically these landscapes were often well adapted to frequent, low intensity wildfire regimes, contemporary forest landscapes differ considerably in stand heterogeneity, species composition, and density (Taylor 2004, Van de Water and Safford 2011, Stephens et al. 2015, Haggmann et al. 2021). The drivers of these changes vary across the West, but often include a history of intensive logging and fire exclusion from the landscape (Stephens and Sugihara 2018).

In the absence of direct efforts to reduce the risk of high-severity wildfires in the West, the damages are likely to continue as wildfire activity is projected to increase in both frequency and intensity (Westerling and Bryant 2008, Keeley and Syphard 2016, Mann et al. 2016). Recent wildfires in California and throughout the West have imposed large costs on society in terms of property damage, public health impacts, and other social and economic impacts (Jones and Berrens 2017, California Council on Science and Technology 2020, Wang et al. 2021). The increasing costs of these high severity wildfires highlights the need for significant investments in mitigation and prevention.

Managers and scientists have highlighted the need to increase the scale and pace of fuel load reduction treatments in order to return Western forests to a more fire-resilient state, and reduce the likelihood and extent of severely damaging wildfires (North et al. 2021, Prichard et al. 2021). Hand and mechanical thinning treatments are effective but can be expensive and difficult to scale

across large landscapes (North et al. 2015). Prescribed fire treatments, on a stand-level scale, and managed wildfires, on a landscape scale, are also effective, and can be less costly, but face constraints because of local air quality regulations, workforce shortages, and legal liabilities (Schultz et al. 2019, Miller et al. 2020). Both treatment methods, when carried out appropriately, play an important role in restoring ecosystem function (North et al. 2009). The appropriate forest management strategies will also vary based on landscape and management objectives (Syphard et al. 2017, Syphard and Keeley 2020).

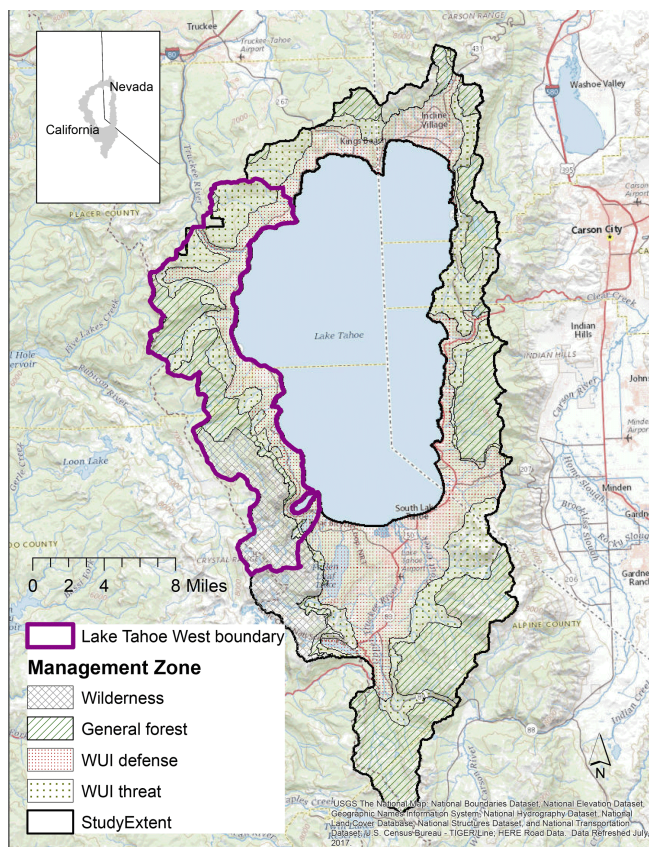
As managers and policy makers design these forest resilience strategies for specific landscapes in the West, trade-offs between ecological benefit, fire risk mitigation, and economic feasibility need to be understood in order to make effective decisions. In this study, we quantified the net management costs associated with five possible forest management strategies in the Lake Tahoe West (LTW) region of the Lake Tahoe Basin Management Unit (LTBMU). This analysis was part of a larger effort in the LTW study area to understand the ecological and economic impacts, and associated trade-offs, of various management options for improving forest resilience. In the mixed conifer forests of the Lake Tahoe Basin, fuels reduction strategies under consideration include increased mechanical and hand thinning treatments, and the increased use of prescribed fire and managed wildfire to reduce fuel loads and return the landscape to a more fire-resilient state (Safford et al. 2009, Safford et al. 2012). However, achieving large-scale impact can be cost prohibitive for management agencies. This research is meant to support decisions for cost-effective management options that can be scaled across the landscape in order to manage the growing threat of high severity wildfire.

¹University of California, Berkeley, Department of Environmental Science, Policy, and Management, ²Tetra Tech, ³Department of Public Policy and Political Science, Mills College at Northeastern University, ⁴USDA Forest Service, Pacific Southwest Research Station, ⁵Spatial Informatics Group, Pleasanton, California, ⁶Department of Forestry and Environmental Resources, North Carolina State University

METHODS

The study area for this analysis is the Lake Tahoe West Restoration Project, that encompasses approximately 23,900 hectares along the west shore of Lake Tahoe in the Central Sierra Nevada Mountain range (Fig. 1). The land is managed by the Lake Tahoe Basin Management Unit in California and Nevada. The LTBMU of the U.S. Forest Service (USFS) manages approximately 62,700 hectares of predominantly mixed conifer forests in the Lake Tahoe Basin. Predominant species include white fir (*Abies concolor*) and Jeffrey pine (*Pinus jeffreyi*) at lower elevations, and red fir (*Abies magnifica*) and western white pine (*Pinus monticola*) at higher elevations. The entire Lake Tahoe Basin was intensively logged during the Comstock Era (1880–1920) to support mining activities in the region (Moody et al. 2009). This period of intensive logging drastically reduced the stand diversity common in the pre-European era and the contemporary landscape comprises relatively young, homogenous forest stands. Following broader trends in Sierra Nevada forests, decades of fire suppression policies in the Basin have resulted in denser forests with smaller average tree sizes than was the case in the early 20th century (Stephens et al. 2018). This structural change over the last 150 years has further increased the fire risk in the Lake Tahoe landscape.

Fig. 1. Lake Tahoe West study area.



Management scenarios

Five forest management scenarios were co-developed with local stakeholders and used as management inputs into an integrated

landscape change model (Table 1). Scenario 1 (S1) assumes no active forest management activities except for wildfire suppression. Scenario 2 (S2) represents a management strategy focused on the wildland-urban interface (WUI). The WUI is divided into two zones: the WUI defense zone is the area closest to settlement that presents the highest risk to human populations whereas the WUI threat zone is not immediately adjacent to population areas. Scenario 2 includes hand and mechanical treatments in the WUI, with a particular emphasis on the WUI defense zone and hand thinning. This WUI-focused scenario, which treats approximately 1000 acres per year, is most similar to recent management practices in the region. Approximately 25% of these treatments are mechanical and 75% are hand treatments. These treatments, as modeled, generally follow the current practice in the Basin where thinnings are either piled on the forest floor and burned or removed off site (California Tahoe Conservancy 2019, Low et al. 2021). Scenario 4 (S4) treats a similar acreage using hand and mechanical treatments as the WUI-focused scenario (S2) but also includes a fire-focused strategy that treats and additional 420 acres annually using prescribed burning. In addition, natural ignitions in the general forest, outside the WUI, are managed for resource objectives rather than suppressed. Scenarios 3 (S3) and 5 (S5) represent two options for more active forest management in the region. Scenario 3 increases the scale and pace of vegetation thinning treatments to approximately 3600 acres per year, including mechanical (17%) and hand thinning (83%) treatments in the WUI and the general forest, with some hand treatments occurring in the wilderness as well. Scenario 5 is an expanded fire-focused strategy combining approximately 1000 acres per year of WUI thinning with much greater use of prescribed burning (approximately 1800 acres per year) and some managed natural ignitions for resource objectives. Scenarios 3 to 5 represent three different management options for increasing the scale and methods for forest treatments in the region and thus allow for an evaluation of the ecological and economic trade-offs of moving beyond the relatively modest treatment levels currently in place in the Basin.

Table 1. Annual treated acreage for forest management scenarios evaluated for management cost outcomes for the Lake Tahoe West project, Lake Tahoe, California. Scenarios differ primarily by the number of acres treated, location of treatment by management zone, and the use of hand/mechanical treatments vs. prescribed fire treatments.

Management Area	Hand/Mechanical Thinning (acres)				Prescribed Fire (acres)	
	S2	S3	S4	S5	S4	S5
WUI Defense	639	1351	864	872	219	985
WUI Threat	284	1045	96	95	192	774
Wilderness	1	216	1	1	12	61
General Forest	28	1002	14	13	-	-
Total Acreage Treated	952	3,614	975	981	423	1820

Landscape change forecasts

We forecast how the five management scenarios would influence the forests of the LTW over the 21st century using the LANDIS-

II integrated landscape change model. LANDIS-II incorporates social processes (i.e., management decisions about thinning and prescribed fire), ecological processes (growth and succession, wildfire), and climate change to forecast forest conditions decades into the future. LANDIS-II has been used in the Lake Tahoe Basin to estimate the effects of fuel treatments, insect outbreaks, and climate on wildfire (Loudermilk 2014), carbon (Loudermilk et al. 2016, Maxwell et al. 2022a), smoke emissions (Long et al. 2022), and wildlife (White et al. 2022). Details on model selection, parameterization, and results for the Lake Tahoe West modeling exercise can be found in Maxwell et al. (2022a) and on GitHub (<https://github.com/LANDIS-II-Foundation/Project-Lake-Tahoe-2017>).

Treatment location and method with the LANDIS model are determined using a set of ex ante assumptions and modeling constraints. For thinning treatments, total acreage by management zone and fraction of treatment by method (hand vs. mechanical) were determined ex ante based on consultation with regional managers and stakeholders. The model then determines which stands are eligible for thinning based on slope, distance to road, and the time since the last treatment or disturbance. Ground-based mechanical treatments were allowed on slopes up to 30% in scenarios 2, 4, and 5. The 30% criteria was based on regulatory restrictions in the region. In order to increase the pace and scale of treatments in scenario 3, ground-based mechanical thinning was allowed on slopes up to 50% and aerial-based mechanical thinning was allowed on 50–70% slopes. An additional criterion for mechanical treatments was that ground-based thinning had to occur within 1000 feet of the nearest road and in scenario 3, aerial treatments had to occur within 0.5 miles of the nearest road. These constraints were set based on consultations with regional managers and published literature (North et al. 2015). Hand thinning was allowed on slopes up to 70% but occurred primarily on slopes greater than 30% where mechanical treatments could not take place (except in scenario 3). Finally, a small amount of hand thinning treatments occurred within the wilderness area under scenario 3 to represent an expanded treatment scenario.

Based on these criteria, LANDIS then determines eligible stands in those zone-slope-road distance combinations based on the time since the last treatment or last disturbance. Of the stands that have not been treated or disturbed recently, LANDIS randomly selected stands for treatment. This allows the model to adapt to the stochastic nature of disturbances so that treatments are not occurring on empty or very low volume stands. Over the analysis time frame, most stands will be treated in the scenarios but the retreatment interval will vary based on the target treated area in each scenario. The retreatment interval was approximately 20 years in all scenarios, except for scenario 3, which had an approximately 11-years retreatment interval (Maxwell et al. 2022b).

Prescribed fire treatment location decisions are less restrictive than the thinning treatments. The user provides the model with a target fire size and number of fires per year (totaling a targeted prescribed fire treatment area for scenarios 4–5). The model then randomly selects fire location, limited only by the number of days within the prescribed fire window. Prescribed fire selection was not correlated to thinning treatments or other disturbances. Making this connection, in order to prevent modeling a prescribed

fire on previously treated or disturbed stands, is an important area of future model improvement.

LANDIS-II results on treated acreage and wildfire size and location were used as inputs into a cost modeling framework to determine the net management costs of each scenario. These cost components included: wildfire suppression costs, in-stand costs of prescribed fire and thinning, net revenue after transport from timber, and biomass sold.

Wildfire suppression costs

One of the main objectives of forest management in the region is to modify current wildfire regimes and the risks of catastrophic wildfire events. Understanding how wildfire suppression costs vary across the management alternatives is therefore an important component in understanding the overall cost structure. We used data provided by USFS on past fire events (1987–2018) to assign average suppression costs in each of five fire size categories (Table 2). Larger fires had lower costs per acre suggesting that there may be some economies of scale for suppression. However, the data suggests that this pattern begins to plateau with the largest fires. This observation was supported by managers in the basin who told us that the complexity of the largest fires often led them to be as expensive or more expensive than medium-sized fires on a per-acre basis.

Table 2. Assumed costs of suppression based on size of wildfire; based on USFS data (1987-2018)

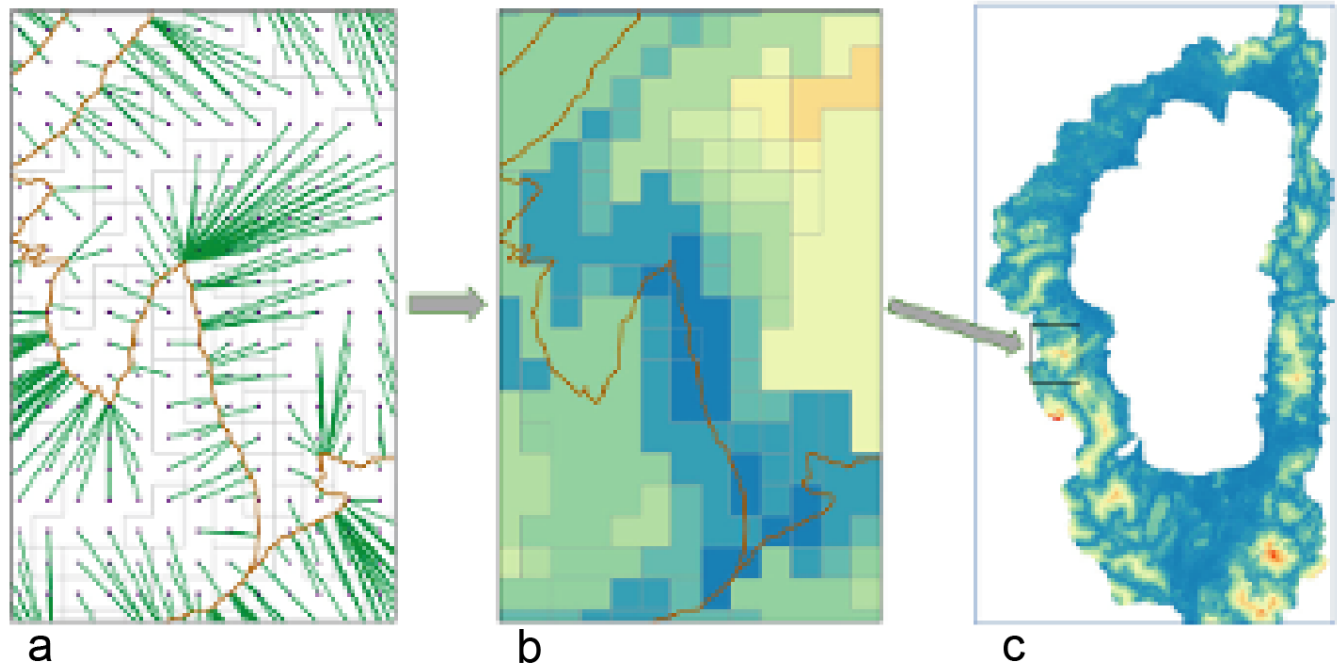
Wildfire Response	Fire Size	Cost per acre (US\$2018)
Suppression [†]	1–10 acres	\$798
	10–100 acres	\$6109
	100–300 acres	\$3017
	300–1000 acres	\$3,053
	1000–5000 acres	\$2732
Management (monitoring for safety but not suppression) [‡]	All sizes	\$583

[†] Based on data on fire suppression events from USFS Lake Tahoe Basin Management Unit. Fires were both in LTBMU area and in Tahoe National Forest. Data cover 1987 to 2018 but costs are adjusted to 2018 dollars. Values are average cost per acre observed in each of the size categories shown.

[‡] Based on data from 2011 Long Fire.

Wildland and prescribed fires were modeled using the LANDIS-II Social-Climate Related Pyrogenic Processes (SCRPPLE v. 2.1) extension (Scheller et al. 2019). In the modeling framework, wildland fire ignitions are probabilistic and derived from data on previous ignitions. Fire spread is modeled based on weather and fuel loadings, and is spatially interconnected based on the intensity of the simulated fire and fuel loadings of neighboring cells. Detailed LANDIS-II fire modeling results are presented in Maxwell et al. (2022a). LANDIS-II fire modeling generates fire events with two key characteristics that are important for this analysis: the size of the fire, and whether or not the fire took place within the WUI. We assumed that all fires in the WUI would be suppressed, whereas fires outside of the WUI may be either suppressed or managed for resource objectives. Scenarios 2 and 3 assume suppression of wildland fires, whereas scenarios 4 and 5 assume some wildfires outside the WUI are managed for resource objectives and some are suppressed. Managing for

Fig. 2. Yarding distance calculation methodology. The position of each forest stand in the model (black dots in Fig. 2a) was combined with information on road locations (brown lines in Fig. 2a). Average yarding distances were aggregated for each plot (Fig. 2b) in the entire basin (Fig. 2c).



resource objectives is a practice that involves monitoring a wildfire but otherwise allowing it to burn unless it poses a threat to human safety or to infrastructure. The cost for managed wildfires, which tends to be lower than actively suppressed wildfires, was taken from the experience of the 2011 Long Fire in the Basin. Based on conversations with managers in the region, the average per-acre management cost of the Long Fire was US\$583. We tested different assumptions on the relative use of suppression vs. management outside of the WUI and found that the total cost difference between suppressing all wildfires outside of the WUI and managing all fires outside of the WUI for resource objectives was only about 10%. This is because the majority of fires simulated by LANDIS-II were taking place within the WUI and were therefore suppressed in either circumstance. Our assumption for the analysis is that outside of the WUI, half of fires would be suppressed, and half would be managed.

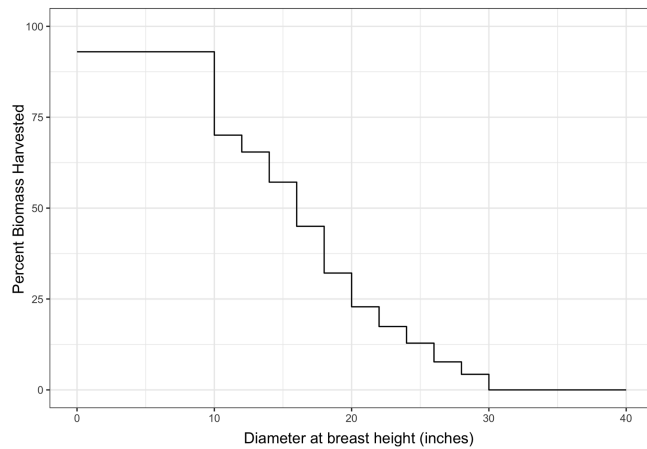
Thinning costs

We estimated thinning costs by using the OpCost forest operations cost model, which is a component of the BioSum modeling software (Bell et al. 2017). OpCost estimates operational costs for different harvest systems that are based on stand characteristics and the volume of material affected. We then adjusted the mean OpCost results using thinning contracts from the basin that were provided by the LTBMU. Operational costs vary greatly among locations, and the Tahoe Basin in particular is known to be expensive for forestry operations. Without the contract adjustments, the OpCost estimates are likely to provide unrealistic underestimates of thinning operations in the region.

For each harvest system, OpCost requires data on slope, yarding distance from stand to road, stand density (stems per area), and the volume of timber and chips extracted in each of several different size classes. To calculate yarding distance, we combined the position of each forest stand in the model (black dots in Fig. 2a) with information on road locations (brown lines in Fig. 2a).

Stand density and estimated size classes of material being removed were calculated by combining three sources of information: the LANDIS-II outputs, Forest Inventory and Analysis (FIA) data, and data on harvest practices within the LTBMU. First, LANDIS-II outputs provide values for standing biomass in different species and age classes as well as values for the amount of biomass harvested in each species and age class. We then analyzed data from the Forest Inventory and Analysis (FIA) Database to estimate size distributions for each species at the age classes used in LANDIS-II. We used FIA data to estimate parameters for size distributions (using Weibull distribution) in each species' age category. These distribution parameters were applied to the LANDIS-II outputs in order to estimate size distributions of the stands, both by biomass and by number of stems. LANDIS-II outputs provide amount of biomass material removed from a stand. We used LTBMU data on harvest practices in the basin, specifically on the portion of biomass that is generally removed in each size class for specific species (Fig. 3), to translate the harvest intensity values into estimates of the number of stems taken in each size class. These estimates of the total amount of biomass harvested and the size distribution of that harvest were used as inputs into OpCost.

Fig. 3. Harvest intensity of difference stem size classes. Assumptions on the fraction of biomass removed during harvest were based on recent harvest practices in the basin.



Based on the stand-level slope, yarding distance, stand density, and volume by size class of harvested material inputs, OpCost generates raw cost estimates. We used thinning contracts in the basin to adjust the mean of these raw estimates to reflect actual average costs in the basin. The thinning contracts from the basin were bid on through a competitive process and should be a good approximation of real costs. All of the contracts were for either hand thinning, ground-based cut-to-length (CTL), or ground-based whole tree (WT) operations. In addition to these three harvest systems, we also added cable yarding and helicopter logging. We assumed that cable yarding costs were about 45% more expensive than ground-based CTL for a similar volume, and that helicopter logging was about double the cost of cable yarding (Hayes et al. 2011). Therefore, the costs for the basin were based directly on average costs-per-acre from contracts for hand thinning, ground-based CTL, and ground-based WT, and they were indirectly based on those contracts (via the expansion factor) for cable yarding and helicopter logging (Table 3). For each harvest system, we scaled the OpCost results based on the basin contract costs. This approach captures the variation in cost that results from different stand conditions, generated by OpCost, but to also ensures that the average thinning costs reflect realistic values for the basin.

For Scenarios 4 and 5, where prescribed fire treatments are utilized as a management strategy, we assume a cost of US\$750 per acre. This estimate was based on discussions with managers at the California State Parks, who have utilized prescribed fire treatments in the region.

Wood product revenue

Net revenue was calculated based on the sale price of forest products received at the gate of a processing facility minus the cost of transporting the material from the stand to that facility. We assumed that in stands that were hand thinned, all biomass was left in the stand. With mechanical thinning treatments, 85% of the biomass was removed with the assumption that the 15% of biomass that remained in the stand were the smallest stems. We

assumed that everything under 10" diameter at breast height (DBH) was turned into chips for bioenergy generation whereas everything over 10" diameter was used for saw timber. We assumed that the price of energy chips was US\$20 per bone dry ton. For saw timber, we used the prices shown in Table 4 (based on data from Fried et al. 2016).

Table 3. Average costs used for each harvest system. Derived from competitively-bid contracts in the Lake Tahoe basin and used to scale OpCost results to an appropriate average cost. CTL = cut to length; WT = whole tree.

Harvest System	Assumed average cost per acre (US\$)	Source
Ground-based CTL	\$2559	Management contracts in the basin [†]
Ground-based WT	\$2013	Management contracts in the basin
Hand Thinning	\$779	Management contracts in the basin
Cable WT	\$3711	Ground-based CTL + 45%
Helicopter	\$7422	Cable WT + 100%

[†] Average costs per acre taken from management contracts in the basin (subtracting the value of timber credits).

Table 4. Timber value in USD per cubic foot for species and size classes.

Species Group	Tree DBH Class (inches)			
	8–14	14–20	20–40	> 40
Pine	\$1.30	\$2.00	\$3.00	\$3.00
Douglas-Fir	\$1.30	\$2.00	\$3.00	\$3.00
True Fir	\$0.90	\$1.40	\$2.10	\$2.10
Cedar/Sequoia	\$1.40	\$2.10	\$3.20	\$3.20

To estimate the costs of transporting material to the processing facility, we calculated the distance from every landing in the basin to nearest bioenergy facility and the nearest sawmill (using gDistance package in R statistical software), the shipping weight of the material, and the average travel time based on road type. We assumed a \$7 per ton-hour price for transportation (Fried et al. 2016). We assumed that all energy chips would go to the nearest bioenergy facility (Buena Vista or Loyalton) and all timber to the nearest sawmill (SPI Quincy, SPI Lincoln, or Jackson). We assumed that the facilities had the capacity to accept all delivered material.

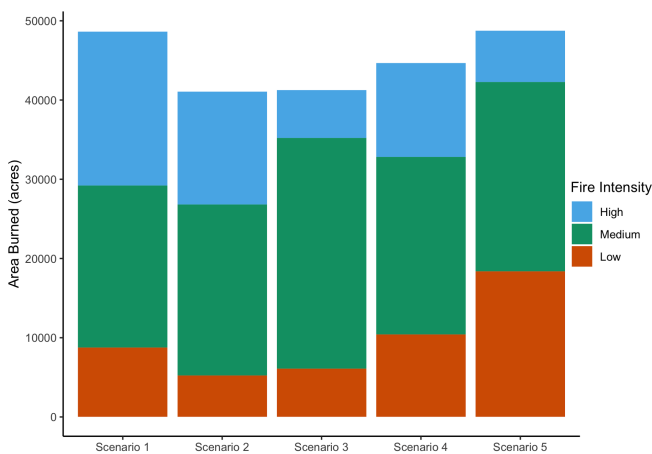
RESULTS

Wildfire and suppression costs

The effects of the management scenarios on wildfire behavior shows important differences by fire severity category over the 30-year analysis period (Fig. 4). Total acreage burned was highest for scenarios 1 and 5, with approximately 49,000 acres experiencing a wildfire over 30 years. For scenarios 2 and 3, total area burned was approximately 41,000 acres (15% below S1). In scenario 4, approximately 45,000 acres were affected (8% below S1). Although total wildfire acreage dropped relative to scenario

1, in all of the expanded treatment scenarios (S3–S5), wildfire area increased relative to the business-as-usual scenario 2. However, the wildfire regime structure changed as a result of the expanded treatments. In all expanded treatment scenarios, high severity wildfire acreage was much lower. Relative to S2, the fire-focused scenarios, S3 and S5, reduced the area of high severity wildfire by 58% and 55%, respectively. Scenario 4 reduced the area of high severity wildfire by 17%. The increase in total wildfire activity was therefore entirely in low and medium severity wildfires.

Fig. 4. Total wildfire acreage burned by scenario and severity category over a 30-year period (2010–2040). Scenario 1 assumes wildfire suppression only. Scenario 2 assumes wildland-urban interface (WUI)-focused thinning management. Scenario 3 assumes a high level of mechanical and hand thinning treatments in multiple management zones. Scenario 4 assumes moderate thinning and prescribed fire treatments. Scenario 5 assumes moderate mechanical and hand thinning in WUI and high levels of prescribed fire in all management zones.

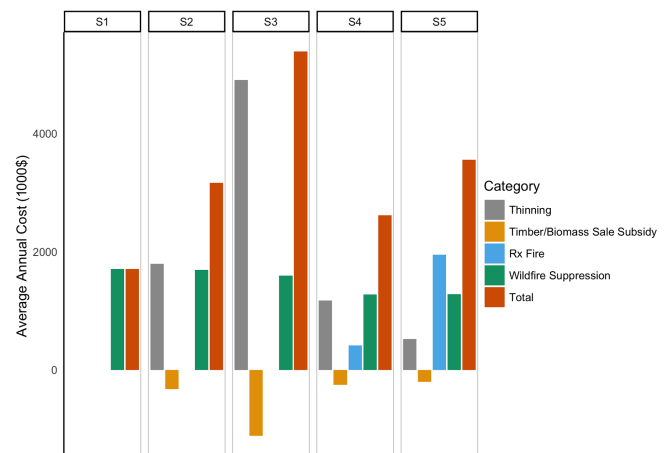


There were pronounced differences among scenarios in the costs of wildfire suppression (Fig. 5). The suppression-only (S1) and WUI-focused/business-as-usual (S2) scenarios were relatively similar in their total suppression expenditures over the first 30 years of the model runs. Both scenarios show approximately US\$1.7 million in annual suppression costs, or US\$51 million over the 30-year analysis. However, the scenario that expanded only thinning efforts (S3) resulted in cost savings relative to the fire suppression only costs associated with scenario 1 (US\$3.2 million, or 6%, over 30 years). Scenarios 4 and 5, that focused on increased use of prescribed fire, generated savings of US\$12.8 and US\$12.6 million over 30 years (US\$427,000 and US\$420,000 per year, respectively) relative to scenario 1. This represents an approximately 25% reduction in suppression costs relative to the suppression only scenario (S1) and the business-as-usual scenario (S2).

Net management costs

Net management costs, which included wildfire suppression costs, thinning and prescribed fire costs, and biomass revenue, varied substantially by management scenario. Total costs were lowest

Fig. 5. Projected average annual management costs by category for five management scenarios over a 30-year period (2010–2040). Scenario 1 assumes wildfire suppression only. Scenario 2 assumes wildland-urban interface (WUI)-focused thinning management. Scenario 3 assumes a high level of mechanical and hand thinning treatments in multiple management zones. Scenario 4 assumes moderate thinning and prescribed fire treatments. Scenario 5 assumes moderate mechanical and hand thinning in WUI and high levels of prescribed fire in all management zones.



for the suppression only scenario (approximately US\$1.7 million annually) and were highest for hand/mechanical treatment scenario, S3 (approximately US\$5.4 million annually). The high thinning costs in scenario 3 were offset by approximately 25% because of the greater revenue generation through forest product sales. The low revenue-to-cost ratio was driven by the high transportation costs to deliver forest material in the LTW area to regional processing facilities. Scenarios 4 and 5, which make greater use of prescribed fire, had costs that were 17% lower and 12% higher, respectively, to the business-as-usual scenario 2. Overall, hand and mechanical thinning costs in these expanded management scenarios were lower than the BAU, whereas prescribed fire costs increased the gross management costs over BAU. However, these higher gross management costs were partially offset by lower wildfire suppression costs and timber/biomass sales. Comparing scenario 5 and scenario 3, which both treat more acres than the other scenarios but through different strategies, shows that the enhanced use of prescribed fire was a lower cost approach to reducing fuel loads in the Basin. Scenario 3 (hand/mechanical treatments) incurred total management costs of US\$5.4 million per year and scenario 5 (prescribed fire treatments) US\$3.6 million per year, a reduction of approximately 33%. On a per acre basis, treatment costs from thinning and prescribed fire, not including fire suppression, were lower for the fire-focused scenarios, S4 and S5, compared to the expanded mechanical/hand treatment scenario S3 (Fig. 6). Relative to the BAU scenario costs of US\$1888 per acre, S3, S4, and S5 per acre treatment costs were 28%, 40%, and 53% lower, respectively.

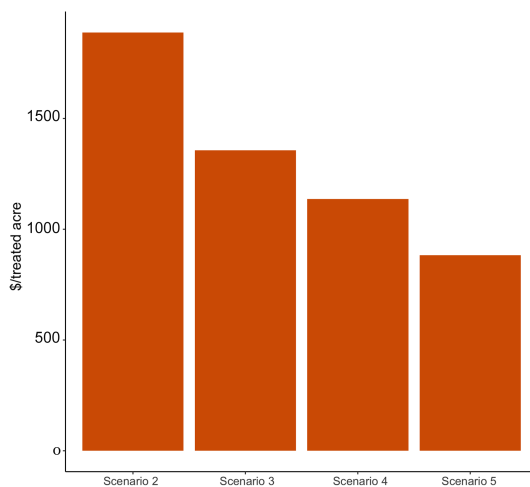
We also evaluated overall management costs over three time horizons: the first 10 years of model runs, the first 30 years, and

Table 5. Annualized management costs (1000 \$2018) for each of five management scenarios assessed for each of three different time horizons. Scenario 1 assumes wildfire suppression only. Scenario 2 assumes WUI-focused thinning management. Scenario 4 assumes moderate thinning and prescribed fire treatments. Scenario 3 assumes a high level of mechanical and hand thinning treatments in multiple management zones. Scenario 5 assumes moderate mechanical and hand thinning in WUI and high levels of prescribed fire in all management zones.

Timeframe Scenario	First 10 years					First 30 years					100 years				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Wildfire suppression cost (V1)	1257	1263	1113	1046	1117	1705	1692	1597	1276	1282	1810	1890	1868	1450	1653
In-stand mechanical/hand thinning, or Rx fire costs (V2)	0	1775	6179	1704	2828	0	1797	4903	1589	2473	0	1976	5650	1588	2344
Net chip and timber revenue† (V3)	0	306	1460	249	245	0	325	1112	250	199	0	377	1135	268	130
Net in-stand management costs (V2 - V3)	0	1469	4719	1455	2583	0	1472	3791	1339	2274	0	1599	4515	1320	2214
Total costs (V1 + V2 - V3)	1257	2732	5833	2501	3700	1705	3164	5387	2614	3556	1810	3489	6382	2770	3867

† After accounting for transportation cost to nearest facility

Fig. 6. Per acre management costs by scenario. Total treatment costs do not include fire suppression costs. Forest product revenue is deducted from the treatment costs.



all 100 years (Table 5). Annual values are presented in all cases so as to facilitate comparisons. Patterns were similar across time horizons and the ranking of scenarios did not differ among time horizons for any of the costs evaluated. The results show that scenario 3 was more expensive than other scenarios. Looking at the 30-year time horizon, and taking scenario 2 (WUI-focus and closest to business-as-usual) as a baseline, Scenario 3 (increased thinning) was 70% more costly; scenario 4 (increased use of prescribed fire) was 17% less costly; scenario 1 (fire suppression only) was 46% less costly; and scenario 5 (heavier reliance on prescribed fire) was 12% more costly.

DISCUSSION

Our findings show that more aggressive forest management strategies can achieve wildfire reduction objectives by reducing fuel loads and the incidence of high severity wildfire on the landscape. In all of the expanded treatment scenarios (S3–S5), the total area of high severity wildfire dropped (Fig. 4), both relative to the business-as-usual scenario (S2) and the suppression-only scenario (S1). The scenarios that treated more acreage (S3 and S5) reduced high severity fires by more than the mixed treatment scenario (S4). This is not necessarily indicative of the relative efficacy of these two treatment types on reducing fire severity, because the treated acres varied considerably between the scenarios. However, the results are consistent with empirical evidence showing the effectiveness of fuel treatments at reducing fire severity broadly (Fulé et al. 2012, Martinson and Omi 2013, Kalies and Kent 2016) and within the Lake Tahoe Basin specifically (Safford et al. 2009, Low et al. 2021).

On a per acre basis, our results show that treatment costs range from approximately US\$1400 to US\$1900 per acre in the scenarios with only hand and mechanical treatments (S2 and S3) to approximately US\$900 to US\$1100 per acre for the scenarios that utilize greater prescribed burning (S4 and S5; Fig. 6). These estimates are generally higher than what have been reported elsewhere in the literature, although this is consistent with anecdotal evidence on relative costs in the Basin (Calkin and Gebert 2006, Hartsough et al. 2008, Rummer, 2008). Our results are most consistent with the upper range of estimates reported for the Central Sierra Nevada in Hartsough et al. (2008). Hartsough et al. (2008) also find that mechanical treatment costs are higher than prescribed fires; however, their analysis showed that after factoring in revenue from harvested products, mechanical treatments were less expensive than burning treatments. This appears to not be the case in the Basin where harvested product revenue offsets some mechanical and hand treatment costs but not enough to reduce average costs per acre below prescribed fire treatments. This is partially because of the high treatment costs in the region, but also reflects a lack of forest

product processing infrastructure within a financially feasible distance of the treated plots. This makes it difficult for forestry operations, intended to reduce fuel loads, to profitably recover costs from thinning through wood product markets. The transportation costs are a critical factor driving the result that prescribed fire is more cost-effective than other thinning operations that produce wood products. Under the current economic and policy environment, California's forest product processing capacity is not likely to grow substantially to support the greater supply of forest biomass from these expanded fuel treatments. Biomass energy capacity has remained relatively stable since expanding in the early 2000s, whereas sawmill capacity has continued to decline in the state for decades (Marcille et al. 2020).

The high costs of mechanical and hand thinning treatments, that are not significantly offset by harvested product revenues, as well as the high costs of prescribed burning present a challenge for managers in the Basin seeking to scale up cost-effective forest resiliency strategies. Prior research has found there could be economies of scale in treating more acres (González-Cabán and McKetta 1986, González-Cabán 1997, Loomis et al. 2019), although this possibility was not incorporated into the cost framework for this study and is an important area of future research. Significant investments, maintained year after year, are therefore required to scale up the pace of fuel treatments in the region in order to restore the landscape to a more fire resilient state.

An important limitation to the study is that none of the management scenarios were optimized based on economic criteria. Site selection for the treatment scenarios was primarily chosen to achieve ecological and wildfire mitigation objectives. There is the possibility that a more integrated approach, that more directly considers costs in management decisions, may yield results that reflect thinning-based approaches as more economically favorable and perhaps even competitive with fire-based approaches. Future work could consider modeling approaches that optimize treatment levels, locations, and treatments across all dimensions of management importance.

From the purely financial perspective, the costs associated with the various treatment scenarios in this analysis are not recovered in wood product revenue. However, these treatments are not meant to provide financial returns. Instead, they are designed to provide benefits to society by reducing the adverse impacts of severe wildfires and restore ecological function to the landscape. Other papers in this special feature quantify these benefits for improved air quality (Long et al. 2022) and lower structure loss risk (Evans et al. 2022). Future work should develop methods for synthesizing these costs and benefits into a single analytical framework. Such a framework would help managers comprehensively evaluate the trade-offs for different management strategies.

Acknowledgments:

We thank the two anonymous reviewers for their constructive comments on an earlier version of this manuscript. This research

was supported in part by the U.S. Department of Agriculture, U.S. Forest Service. We specifically thank project funders for the larger Lake Tahoe West modeling effort, including the National Forest Foundation, the California Tahoe Conservancy, the U.S. Bureau of Land Management through the Southern Nevada Public Land Management Act, the U.S. Forest Service Lake Tahoe Basin Management Unit, and the U.S. Forest Service Pacific Southwest Research Station. The findings and conclusions in this article are those of the author(s) and should not be construed to represent any official USDA or U.S. Government determination or policy.

Data Availability:

Details on the LANDIS-II model and parameters used in this analysis are available at <https://github.com/LANDIS-II-Foundation/Project-Lake-Tahoe-2017> Code used for the cost analysis is available at https://github.com/lsgcevans/LakeTahoeWest_ManagementCost

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