Lake Tahoe West Science Summary of Findings Report

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Cover Photo: Looking north to the Lake Tahoe West area from a prescribed burn at Baldwin meadow, with the burned area from the Emerald wildfire of 2016.

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Abstract

As part of the Lake Tahoe West Restoration Partnership, a science team worked with resource managers to evaluate effects of forest dynamics and management strategies on social and ecological values within a 59,000-acre landscape in the western part of the Lake Tahoe basin in California. Forest growth and fire dynamics were modeled across the landscape using the LANDIS-II platform over 100 years; interconnected models were used to evaluate changes in wildlife habitat, water quality, and economics. Additional modeling and some field monitoring were conducted to evaluate how treatments would affect fire behavior, fuels, and snow hydrology within forest stands. These investigations evaluated how different management strategies would affect outcomes important to stakeholders, including abundance of old trees, wildlife habitat, fine sediment, water quantity, implementation costs, fire characteristics and threats, air quality, cultural resource quality, and carbon sequestration. The scenarios spanned a wide range of management approaches, from wildfire-suppression only, fuels reduction near communities, moderate and extensive restorative thinning and/or prescribed burning. The results indicated that moderate and extensive thinning or burning treatments would promote overall objectives better than no treatment or thinning only near communities, except for carbon sequestration and treatment costs. Over the long-term, more treatment would reduce the wildfire threat to communities, the risk of unnaturally large patches of high intensity burns, and days of extreme emission of smoke into downwind communities. More extensive treatments were projected to increase water yield and promote the growth and occurrence of pine and aspen trees. Increased treatments, especially burning, may promote cultural resources important to the Washoe Tribe of Nevada and California (hereafter the “Washoe Tribe”), who consider Lake Tahoe the center of their ancestral homelands. On the other hand, greatly ramping up prescribed burning may pose a challenge in terms of avoiding near-term impacts of treatments on air quality and water quality, even though such a strategy may yield long-term net benefits.

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1 INTRODUCTION

The Lake Tahoe West Restoration Partnership (Lake Tahoe West) is a multi-stakeholder collaborative initiative convened by California Tahoe Conservancy, USDA Forest Service Lake Tahoe Basin Management Unit, California State Parks, Tahoe Regional Planning Agency, Tahoe Fire and Fuels Team, and the National Forest Foundation. The goal of Lake Tahoe West is to restore the resilience of the west shore's forests, watersheds, recreational opportunities, and communities to disturbances including wildfire, drought, and climate change. The planning area includes approximately 59,000 acres of federal, state, local, and private lands. The USDA Forest Service Pacific Southwest Research Station was engaged to convene and lead a large team of researchers from Forest Service research stations and several university research institutions to evaluate potential effects of different management strategies on important objectives identified by the collaborative. This Science Team worked closely with an Interagency Design Team comprising agency managers and technical experts and with two Stakeholder Committees representing conservation, fire protection, recreation, homeowners and businesses, and local government.

Through this collaboration, the Lake Tahoe West Science Team undertook an ambitious effort to evaluate the effects of alternative forest management strategies for the Lake Tahoe West study area (Figure 1-1). The effort focused on modeling with some supplemental field data collection. The modeling evaluated forest development, succession, and disturbances (mortality caused by fire and bark beetles) under scenarios that represented various management strategies, all under a projection of moderate changes in climate. Under a second round of landscape modeling, multiple potential future climates were evaluated.

Figure 1-1—Map of Lake Tahoe West study area.

Additional modeling and monitoring efforts addressed finer-scale issues, such as how removing individual trees up to specific sizes affected both fire behavior and water yield/snowpack, as well as resulting forest structure (including gaps between trees that help to sustain shade-intolerant species such as aspen). This additional modeling evaluated the effects of removing individual trees on snow dynamics and fire behavior using very fine scale data (<1-meter resolution) collected through LiDAR or field inventories.

The results of the modeling effort were used to inform the Lake Tahoe West Landscape Restoration Strategy, released in December 2019. Results will also be used to inform on-the-ground restoration project planning and analysis on the Lake Tahoe West landscape.

1.1 LANDSCAPE-SCALE MODELING

We connected several existing modeling platforms to evaluate effects of potential management strategies over time on the forested areas of the Lake Tahoe basin. Central to this effort was LANDIS-II (hereafter abbreviated as LANDIS; http://www.landis-ii.org/), a forest landscape model that simulates dynamics of future forests (both trees and shrubs) over long time scales (decades to centuries) and across large spatial scales in response to natural disturbances and forest management. The modeling projected how the combination of treatments, changing climate, fires, and insect outbreaks would alter vegetation composition and structure, air emissions of fine particulate matter, water emissions of fine sediments and phosphorus, and habitat for wildlife including various species of concern as well as biodiversity more generally.

Spatial scale: Model units were 1-hectare (2.5-acre) sites. This scale allowed modeling of important landscape processes. It does not yield results at the scale of individual trees and is too coarse for modeling narrow riparian systems and most meadows. The entire Lake Tahoe basin was simulated although we limit our results in this report to the Lake Tahoe West landscape (Figure 1-1).

Temporal scale: The modeling extended for a full century (representing years 2010-2109), with annualized steps and conditions characterized every decade for key indicators. The long timeframe is important for evaluating responses to climate change, the effects of repeated disturbances, and effects on carbon stocks and greenhouse gas emissions. However, uncertainty regarding outcomes also increase with time, especially given uncertainty regarding the effects of climate change.

1.2 INTEGRATED EVALUATION OF SOCIAL AND ECOLOGICAL VALUES

We integrated the results of the modeling within a decision support framework and economic analyses to evaluate advantages, disadvantages, and tradeoffs among different strategies in terms of key resource values. Our landscape modeling provided a broad and integrated evaluation of how different management strategies would perform in terms of social and ecological indicators that scientists, managers, and stakeholders deemed important for maintaining system resilience. Key components of the long-term landscape modeling are shown in Figure 1-2.

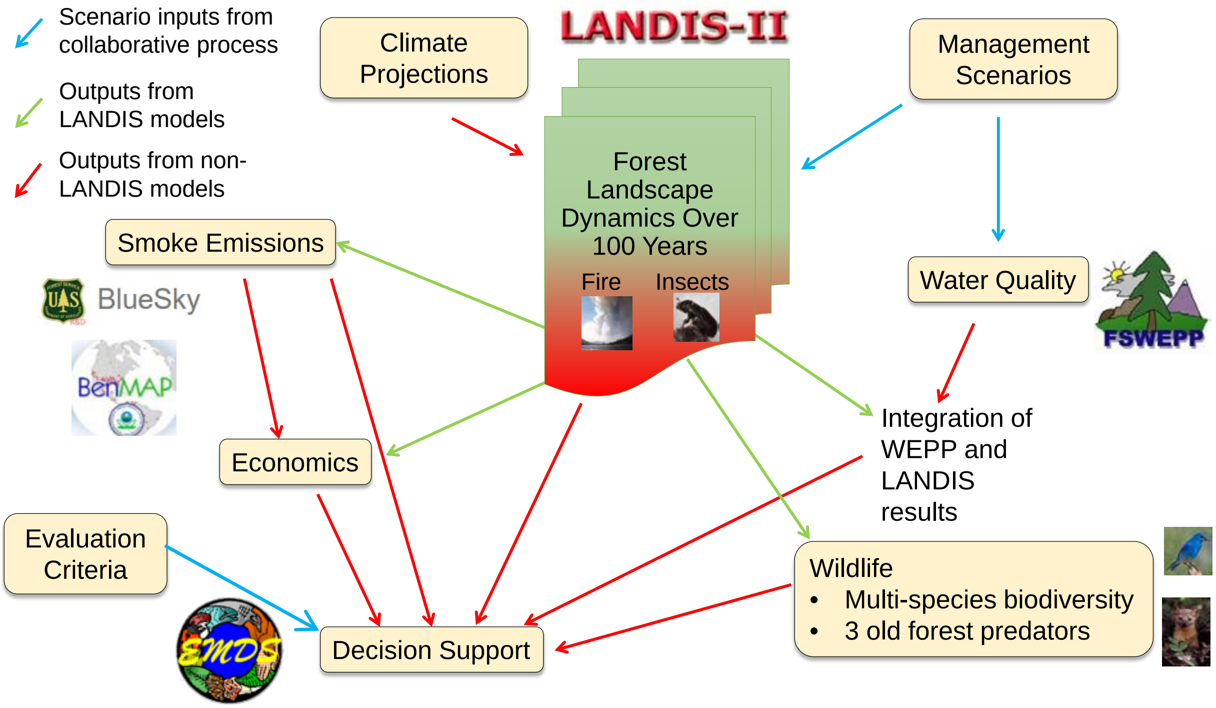

Figure 1-2—Topics of modeling, tools used to evaluate them, and interconnections. Inputs from the Interagency Design Team and stakeholders guided the assumptions used to represent management scenarios and the indicators used for evaluating scenario performance.

The list of topics and indicators addressed in the research were developed through dialogue among agency staff, scientists, and stakeholders to identify key questions and concerns, and to identify topics that could be adequately represented through landscape modeling. Some topics, such as the quality or quantity of recreational opportunities, are important to some stakeholders, but there were not sufficient data from which to build predictive models. In some of these cases, the team relied on proxy variables that related to the topics of interest, such as summertime daily emissions of particulate matter, which is a primary limitation for summertime outdoor recreation.

Previous modeling efforts in the Lake Tahoe basin and Sierra Nevada have tended to focus on vegetation, fires, wildlife habitat, and carbon; but our approach incorporated many more resource topic areas, such as water quality, water quantity, air quality, cultural values, wildlife habitat, and economic costs and benefits. Specific elements of the modeling approach that were distinctive include:

- The modeling considered a range of management approaches including hand and mechanical thinning, wildfire suppression, prescribed burns, and lightning-ignited wildfires to achieve resource objectives.
- The core landscape modeling evaluated interactive dynamics over a century to consider climate change, the effects of infrequent but impactful disturbances (wildfire and insect-related

mortality), and management regimes. Evaluating how the system responds over time helps to evaluate resilience directly, rather than relying on measures of vulnerability as an indicator of .

- The modeling effort also used the Ecosystem Management and Decision Support (EMDS) Tool in a novel way, by evaluating performance of management scenarios over time. This tool compared various indicators to threshold values associated with resilient and non-resilient conditions, and aggregated the results based upon weights suggested by managers and stakeholders.
- Habitat modeling considered not only a range of socially and ecologically important vegetation measures (e.g., area of late seral forest), but a vast array of wildlife species, including old forest associated species of special concern (marten, California spotted owl, northern goshawk), species that have special cultural significance to the Washoe Tribe (e.g., deer), and groups of terrestrial wildlife that have similar functional roles (e.g., decomposers, herbivores, insectivores, predators, seed dispersers, and soil aerators).

1.3 Climate Scenarios

The landscape modeling accounted for continued climate change based upon projections associated with different global scenarios for greenhouse gas emissions, described as representative concentration pathways (RCPs), and different global circulation models (GCMs). RCP 4.5 describes a scenario in which greenhouse gas emissions level off by mid-century and then decline, while those emissions continue to rapidly increase under RCP 8.5. Debate about which trajectory is currently more likely are ongoing, with Schwalm et al. (2020) reporting that emissions have continued to follow the high (RCP 8.5) trajectory, while Hausfather and Peters (2020) contend that the trajectory is much more likely to bend toward an intermediate level of emissions (close to RCP 6.0). Running models under a wider range of climate scenarios helps to understand the extent to which the relative or absolute performance of management scenarios is tied to particular climate trends. The initial round of modeling considered a single climate projection, the CanESM GCM with a moderate level of emissions, represented by the RCP 4.5 emissions pathway. The second round considered eight different projections based upon four different GCMs and two RCPs (**Table 1-1**), which were the same projections used in California's 4th Climate Adaptation Plan (Westerling 2018). These climate models had been selected to realistically represent variability for California in selected hydrologic variables. For example, CanESM2 was warmer with little precipitation change from contemporary; CNRM was cooler and wetter than the others; MIROC5 was warmer but drier; and HadGEM had moderate increases in summertime temperatures, little change in yearly precipitation, larger increases in wintertime temperatures, and slightly higher frequency of drought conditions than CNRM but less than the other two.

Table 1-1—Summary of landscape scenarios modeled over 10 decadal time steps (2010-2109) per management scenario in LANDIS.

Scenario	Round 1	Round 2
Climate GCMs	1 (CanESM2)	4 (CanESM2, CNRM5, HadGEM2-ES, MIROC5)
RCPs	1 (RCP 4.5)	2 (RCP 4.5 and RCP 8.5)
Replicates within Climate	10	3
Total Model Runs	40	120

1.4 Management Scenarios

The management strategies and criteria for evaluating performance vary across four different geographic zones within Lake Tahoe West, each of which represents about one quarter of the total area (Figure 1-3). The Wildland-Urban-Interface (WUI) is a zone of transition between unoccupied area/ "wildland" and urban/occupied/developed areas.

1. WUI defense zone: the part of the WUI that is closest to communities.
2. WUI threat zone: the part of the WUI that is farther from communities.
3. General forest zone (13,675 acres): area outside the WUI that is removed from communities.
4. Wilderness (13,257 acres): land managed strictly for wilderness values.

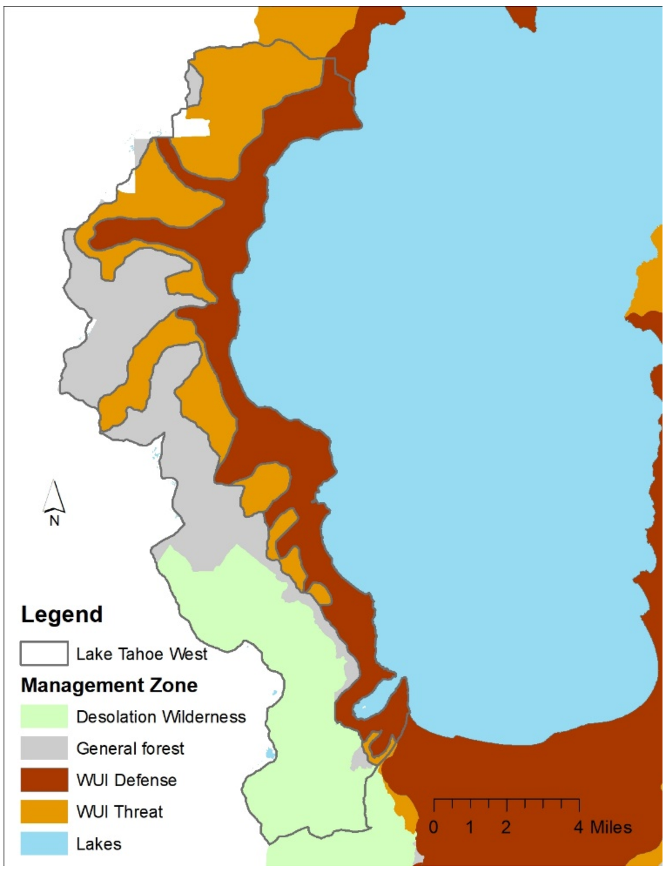

Figure 1-3—Management zones within Lake Tahoe West.

Through landscape-scale modeling we quantified expected effects of several contrasting management strategies, which are listed below and shown in Figure 1-4. The scenarios were developed through a collaborative process, led by the Interagency Design Team in articulating goals and targets with input from the Stakeholder Committees. The Science Team set assumptions based upon guidance from the Interagency Design Team. We initially processed results for four scenarios, and then we added the fifth scenario after reviewing the initial results. The scenarios were intended to represent strongly contrasting management approaches ("pin-the-corner") rather than to precisely emulate a specific alternative.

- Scenario 1—Suppression only: No treatment other than continued fire suppression.

- Scenario 2—WUI-focused: A WUI-focused strategy similar to recent management, although it assumes no prescribed understory burning. This scenario includes hand and mechanical treatments in the WUI. Thinning treatments could recur after 20 years.
- Scenario 3—Increased thinning: A strategy of increasing pace and scale of vegetation thinning treatments, including hand and mechanical treatments in the WUI and the general forest, with some hand treatments occurring in the wilderness as well. Thinning treatments could recur after 11 years following thinning or burning.
- Scenario 4—Fire-focused: A fire-focused strategy that focused on using fire by combining modest WUI thinning with prescribed burning in all zones and managed, lightning-ignited wildfires managed for resource objectives in the general forest and wilderness. Thinning treatments could recur after 11 years without thinning or burning; prescribed burns did not have a set retreatment interval. Scenario 4 averaged 550 acres of prescribed burning per year, plus an average of 100 acres per year of managed natural ignitions for resource objectives, within Lake Tahoe West.
- Scenario 5—Fire-focused, expanded: A fire-focused strategy combining the modest WUI-focused thinning under scenario 4 with *much* greater use of prescribed burning in all zones, averaging 2600 acres per year in Lake Tahoe West, in addition to an average of 100 acres per year of managed wildfires.

The expanded thinning (scenario 3) and the fire-focused scenarios (scenario 4 or 5) are reflected in the Lake Tahoe West Landscape Restoration Strategy. Expected levels of thinning and prescribed burning under that Strategy fall in between those in scenarios 3, 4, and 5.

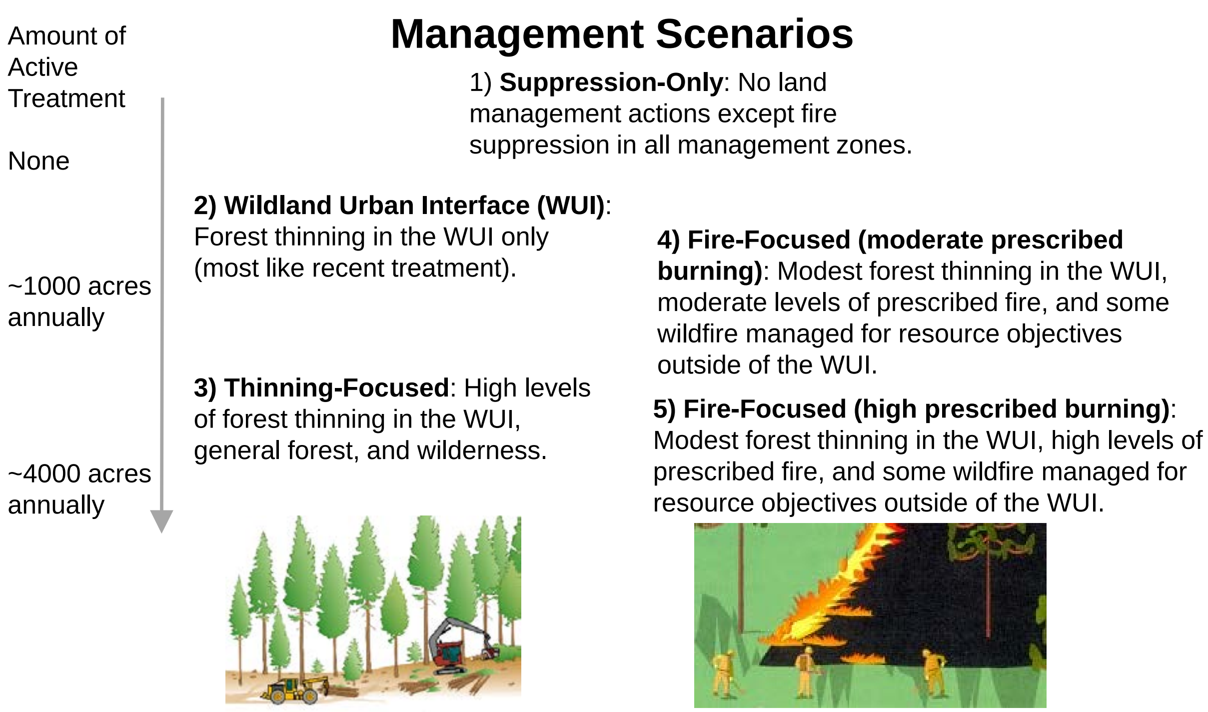

Figure 1-4—Overview of management scenarios used in the landscape modeling

In addition to broadening climate change projections, the second round of modeling updated some assumptions regarding treatment effects and species dynamics, both to better reflect the original Interagency Design Team intent for scenarios (such as the frequency of retreatment and amount of dead biomass removed) and to incorporate adjustments to more precisely represent certain system dynamics, including climatic triggers for insects outbreaks, species' relationships to temperature, and maximum stand biomass.

1.4.1 Variation in treatment across scenarios

For the landscape modeling, the amount of area thinned under different management scenarios was set to targets for different management zones. However, the amount of area treated with prescribed fire and natural ignitions managed for resource objectives reflected iterative results from the LANDIS model to approximate targets suggested by the Interagency Design Team to achieve treatment objectives based upon a reference disturbance interval. Figure 1-5 shows the area treated under different management strategies per year. Scenarios 2, 4, and 5 confined thinning to the WUI zones, while scenario 3 thinned in the general forest and the wilderness zone.

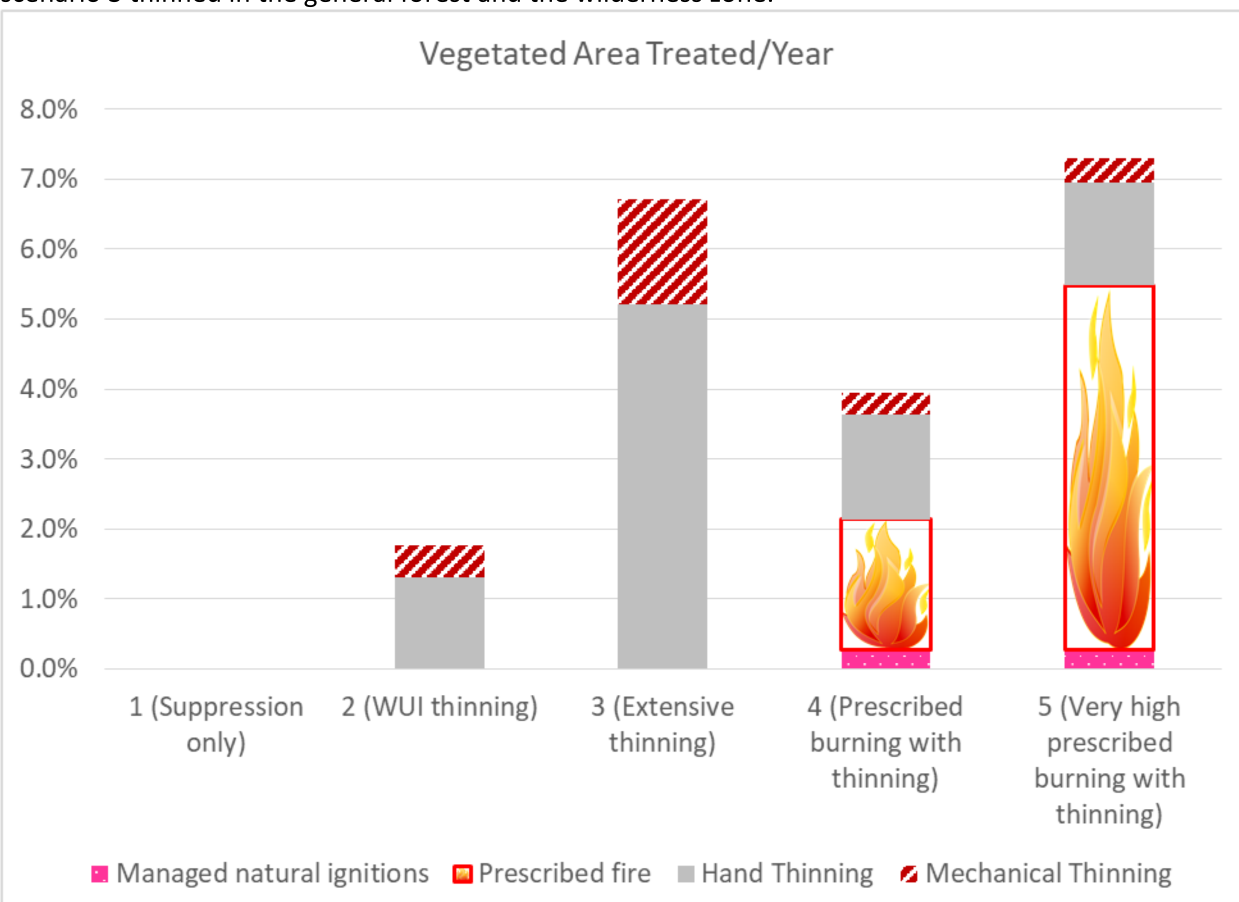

Figure 1-5—Percent of landscape treated under different scenarios.

1.4.2 Projected treatment intervals

Actual return intervals were slightly longer than the minimums described above, but they were still within reference levels for disturbance. The most typical (modal) return intervals for thinning treatments were 26 years under scenario 2, 12 years under scenario 3, 15 years under scenario 4, and 17 years under scenario 5. Increased prescribed burning reduced the frequency of thinning slightly because recently burned areas were considered sufficiently treated as to be ineligible for thinning.

Scenario 4 simulated prescribed burning only in the fall (mid-October to mid-November) and limited burns to 100 acres/day. To facilitate the increase in prescribed burning compared to scenario 4, scenario 5 also allowed prescribed burning whenever fire weather conditions were suitable, resulting in burns during any of the seasons. In scenario 5, the area burned in a day was expanded to about 180 acres/day. These burns were concentrated in the spring and fall, but some occurred throughout the year as weather permitted.

1.5 Indicators and Target Conditions

A set of indicators with associated target conditions were used to evaluate scenario performance based upon priorities and thresholds developed through collaboration among the Interagency Design Team, Stakeholder Committees, and Science Team members (Table 1-2). The science modeling included a diverse range of indicators that build upon topics featured in the Lake Tahoe West Landscape Resilience Assessment and identified as important to stakeholders. Several of the indicators modeled by the Science Team relate closely to indicators used in the Landscape Resilience Assessment, and the modeling added many indicators for topics like biodiversity and upland health. It also included indicators for which historical temporal data were not already compiled for Lake Tahoe West, such as all areas burned by severity, forest landscape water quality, air quality, and management costs. Most of the indicators were included as input to the Ecosystem Management Decision Support (EMDS) analysis, which evaluated scenario performance across all indicators based on ecological objectives and stakeholder priorities. Targets for favorable conditions were set based upon dialogue between members of the Science Team and the Interagency Design Team. The Landscape Restoration Strategy discusses the indicators and considered the results in refining goals and guiding implementation.

Table 1-2—Indicators used in the landscape modeling, sorted by topic, and with relationships to the Landscape Resilience Assessment (LRA), Landscape Restoration Strategy (LRS), and decision support analysis (EMDS).

Category	Sub-category	Indicators	LRA Indicator	Discussed in LRS	Evaluated in EMDS
Community Values	WUI fire risk	Percent of WUI threat and defense zones burned at moderate and high severity		☑	☑
	Threats to property	# of residential properties in areas likely to burn at moderate or high severity		☑	☑
	Air quality	Fine particle (PM2.5) emissions		☑	
		Days of moderate, high, very high, and extreme emissions (based upon tonnes/day), year-round		☑	☑
	Recreation quality	Days of moderate, high, very high, and extreme emissions (based upon tonnes/day), summertime		☑	☑
	Cultural resource quality	Area burned at low-severity fire; % of landscape dominated by aspen; and high-quality habitat for mountain quail, flicker, deer		☑	☑
	Carbon storage	Whole-system carbon storage		☑	☑
	Restoration by-products	Volume of lumber and bioenergy material harvested		☑	☑
Environmental Quality	Functional fire	Percent of landscape burned by wildfire at different severities		☑	☑
		Area burned in large high severity patches size	☑	☑	☑
		Fire return interval	☑	☑	
	Upland vegetation health	Percent of forest in different seral stages (early, mid, late)	☑	☑	☑
		Percent of shrub, aspen, and conifers (and relative abundance among tree species)		☑	☑
		Area with old trees (>150 years)		☑	☑
	Wildlife conservation	Species richness (terrestrial wildlife)		☑	☑
		Habitat quality for wildlife functional groups (e.g., insectivores)		☑	☑
		Territories for California spotted owl, marten, and northern goshawk		☑	☑
	Quality water	Very fine sediment (<16 microns)		☑	☑
		Total phosphorus		☑	☑
		Stream nitrogen			
	Water quantity & timing	Leaf area index (as proxy for water yield)		☑	☑
Operational Feasibility	Net treatment cost	Expected net costs of thinning and prescribed burning treatments		☑	☑
	Suppression cost	Estimated cost to suppress wildfires		☑	☑
	Staffing	# of staff for treatments		☑	☑
	Days of intentional burning	# of days for prescribed understory and pile burning		☑	☑

2 KEY FINDINGS

2.1 LANDSCAPE FIRE

Many dimensions of fire regimes are important; in this section we focus on cumulative area burned overall and at different severities, area burned in uncharacteristically large high severity patches, areas burned within the WUI areas, and fire return intervals. The Lake Tahoe West Landscape Restoration Strategy focused on reducing the risk of high severity wildfire, particularly in WUI areas and in patches larger than 40 acres. The latter could indicate a loss of resilience, since such patches tend to be rare under reference fire regimes (Safford and Stevens 2017). Mean fire return interval departure condition class was suggested in the Lake Tahoe West Landscape Resilience Assessment as an indicator of ecological resilience, and the Landscape Restoration Strategy calls for prescribed burning to restore a more frequent fire return interval, particularly in lower elevation forests that have a more departed fire regime. The results include multiple metrics for fire outcomes for the overall landscape, within the WUI defense zone (e.g., surrounding inhabited areas and critical infrastructure) and within the WUI threat zone, which lies between the defense zone and general forest zone.

2.1.1 Area burned

LANDIS simulations projected increases in area burned by wildland fire in Lake Tahoe West over time. Within the first decade, projected area burned was over 5% across scenarios 1, 2, and 3, and reached 6% and 7% per decade in the fire-focused scenarios 4 and 5, respectively. A warming climate drove an approximate doubling in area burned across all scenarios, reaching levels of about 13% per decade by the end of the century. Snowpack is expected to decline over time, which will translate to longer fire seasons and greater opportunity for fire spread. This projected increase is generally consistent with projections by Westerling et al. (2011) that area burned would double in montane forests of Northern California from the late 20th century to late 21st century. For comparison, between 1984 and 2010, yellow pine-mixed conifer and red fir forest types with national forests in the Sierra Nevada region experienced approximately 3.7% area burned per decade in fires greater than 200 acres (Miller and Safford 2012). In the most recent decade, those levels have likely increased. However, area burned by wildfire in Lake Tahoe West and the Lake Tahoe basin has been modest by comparison. Records in the California Fire and Resource Assessment Program database indicate that the annual average of area burned by wildfire within the basin from 1994-2016 was only about 200 acres, which translates to approximately 1% per decade. The basin's relatively high elevation and precipitation reduce the expected level of wildfire compared to the larger region (and relatively fast response times to wildfires may also contribute to more effective suppression). LANDIS modeling for Lake Tahoe West projected higher total amounts of burned area in Lake Tahoe West in the first decade (2010-2019) than what actually occurred (in the Emerald Fire of 2016).

Although the modeling projected increases in area burned compared to **recent** decades, the total area burned remained well below **historical reference levels** under all scenarios. For reference, the natural range of variation for a reference fire regime in yellow pine/mixed-conifer forests of northern California is about 50% per decade, or 5% per year (Safford and Stevens 2017). The fire-focused scenarios shifted more towards a historical reference through increases in prescribed burning.

The modeling also indicated that increased prescribed burning would reduce areas burned by wildfire. While scenario 1 was projected to have the lowest amount of burned area in the first decade, it experienced the most burned area late in the century, all of which was burned in wildfires. By contrast, scenario 5, which heavily used prescribed fire, burned the most area in the first decade, but resulted in the least total area burned in some later decades throughout the century.

2.1.2 Amount of landscape burned at low, moderate, and high severities

Increased treatments moderated the severity of fire overall, specifically by increasing the amount of low severity fire (especially under the fire-focused scenarios that used prescribed burning) and reducing the amount of high severity fire. The fire-focused scenarios 4 and 5 greatly increased area burned at low severity through application of prescribed burns (which were assumed to burn only at low severity). Relative to the natural range of variation for low severity burn area, scenario 4 resulted in about 20% of area per decade, while scenario 5 resulted in about 50% of area per decade. In contrast, all areas burned under scenarios 1, 2, and 3 were the result of wildfire. Those first three scenarios, which did not use prescribed fire, resulted in much less low severity fire than the historical references. However, scenario 3 resulted in more low severity fire than scenarios 1 and 2, which indicates that treatments did moderate wildfire severity.

In terms of area burned at moderate severity, most scenarios performed similarly, keeping totals below 5% per decade until the end of the century. That amount of moderate severity fire was generally below the levels (8-19% per decade) that would be expected under a more natural historical fire regime. Moderate severity generally represents a gray area between low and high, which may make it difficult to consistently model and interpret (for example, the Landscape Resilience Assessment categorized flame lengths greater than six feet as indicative of high severity, while the fire modeling in LANDIS associated moderate intensity with flame lengths between four and eight feet). As the distribution of fire severities shifted under different scenarios, the amount classified as moderate remained relatively stable, while the amount classified as low or high tended to change.

The amount of high severity fire was highest under the suppression-only scenario 1 and roughly declined with more area treated under the other scenarios. This result is consistent with research explaining how fire suppression tends to shunt fire effects into more extreme conditions, while treatments, including thinning and use of fire, moderate fire severity (Safford et al. 2009, Safford and Stevens 2017, Steel et al. 2018). Scenarios 3 and 5 reduced the amount of high severity fire overall, although scenario 3 kept levels low throughout the century, while scenario 5 performed better in early decades but not as well later in the century.

2.1.3 Amount of landscape burned in large high severity patches

Increasing treatment affected the amount of area burned in large (>40 acre) high severity patches similarly to how it altered high severity fire overall. Scenario 1 resulted in the most area in such patches, scenario 2 had the second most, and scenario 4 had the third most. Scenario 3 kept the number of such patches low over a century, while scenario 5 started off with the fewest patches, although such patches increased over time. These results suggest that treatments delay the occurrence of severe fires, but that eventually climatic factors may allow more severe burns to occur. Scenario 3 may have been more effective in reducing severe fires than scenario 5 because those thinning treatments explicitly targeted areas with ladder fuels, which were a key determinant of fire severity (unlike the simulated prescribed burns).

Previous work has reported that large patches often make up a substantial proportion of area burned at high severity even in areas with more natural fire regime. For example, in the Illilouette basin, such patches represented 64% of area burned at high severity between 2000 and 2009 (Collins et al. 2009).

2.1.4 Fire return interval

By increasing the amount of fire overall, fire-focused scenarios 4 and 5 greatly lowered the fire return interval, which is consistent with restoration of a more natural fire regime. Those restorative effects were most pronounced in the lower-elevation forests that are most departed from historical frequencies of fire.

2.1.5 Percent of WUI zones burned at high and moderate severity

The results indicate that increasing treatments were effective in reducing fire severity in community areas. None of the scenarios eliminated all wildfires in this zone. Within the WUI defense zone in Lake Tahoe West, increasing treatment reduced the area burned at high severity, while area burned at moderate severity was similar across the scenarios. The suppression-only scenario 1 performed worst (averaging 5.7% high severity and 7.4% moderate severity per decade), indicating that a lack of treatment would not support community resilience objectives. The WUI-focused scenario 2 performed second worst (averaging 3.9% high severity and 8.4% moderate severity per decade), indicating that a business-as-usual strategy also would not sufficiently promote resilience. Scenario 4 was somewhat better (averaging 3.2% high severity and 8.0% moderate severity per decade), scenario 3 was much better (averaging 1.9% high severity and 8.1% moderate severity per decade), and scenario 5 performed best (averaging 1.1% per decade high severity and 8.3% moderate severity per decade).

For a recent reference, consider that about 1.8% of the 70,000-acre (28,000 ha) WUI defense zone in the Lake Tahoe basin burned at high severity from 2000-2009 during the Gondola and Angora fires; however, those fires did not burn any areas in Lake Tahoe West.

Patterns in area burned at high and moderate severity within the WUI threat zone were quite similar, although the amount burned was generally lower, reflecting that ignitions are highest within the WUI defense zone. Treatments also reduced incidence of high severity fire in this zone, although the differences in performance between management scenarios were much less pronounced than in the WUI defense zone. The scenarios that involved the least treatment performed worse in terms of high severity than the others (scenario 1 averaged 3.4% high severity and 4.0% moderate severity per decade, while scenario 2 averaged 3.4% high severity and 4.4% moderate severity per decade). Scenario 4 was somewhat better (averaging 2.5% high severity and 3.5% moderate severity per decade), scenario 3 was even better (averaging 2.2% high severity and 4.3% moderate severity per decade), and scenario 5 performed best (averaging 1.5% per decade high severity and 4.4% moderate severity per decade).

The overall results suggest that scenarios 1 and 2 are not likely to sustain resilient conditions in terms of WUI high severity fire risk, so increases in treatment, as outlined in the Landscape Resilience Strategy and as reflected in results for scenarios 3, 4, and 5, are supported by these findings for these indicators.

2.1.6 Sensitivity of fire dynamics to climate

When a wider range of climate projections was evaluated in the modeling, fire outcomes did change, however, the relative performance of different management scenarios compared did not. Under all climate change projections, temperatures increased, and the increases were larger under the RCP 8.5 pathways. However, precipitation was far more variable by projection. Notably, the CanESM with RCP

8.5 projection resulted in more summertime precipitation than others, which moderated wildfire activity. In contrast, the MIROC5 4.5 and 8.5 climate projections result in more extended droughts, which intensified wildfire activity. Averaging across the climate projections, higher emissions were projected to increase fire activity, and area burned at high severity fire both directly due to more extreme fire weather and indirectly due to increased insect activity in the latter half of the century. There remains substantial uncertainty regarding how climate change will be expressed, but treatments were projected to remain effective in moderating wildfire activity across climate scenarios.

2.1.7 Implications

Alternatives based upon no-treatment or business-as-usual approaches would not be as effective in promoting desirable fire effects as increased treatment, both thinning and prescribed burning. Therefore, the Landscape Restoration Strategy, by calling for increased treatment in ways that are comparable to scenarios 3, 4, and 5, is expected to promote resilience, particularly by reducing high severity fire in WUI areas and in large patches. Greatly increasing the amount of prescribed burning, as under scenario 5, is expected to reduce undesirable effects of high severity fire, while promoting more desirable effects of low severity fire. On the other hand, a suppression-only approach would tend to allow the high severity effects of wildfire while limiting the beneficial effects of low and moderate severity fire. The indicator value of moderate severity fire is complex to evaluate, since for much of the landscape it may be effective in restoring forest structure (Kane et al. 2019). In community areas, moderate severity fire is preferable to high severity fire, but it may still signify a risk to property and safety. The Landscape Restoration Strategy considered burning at more moderate severity to more closely approximate effects of reference fire regimes. Recent research by Striplin et al. (2020) suggested that greater use of fire may depend on relaxing burn prescriptions to allow for moderate severity.

The results also suggested that increased treatment under scenarios 3, 4, and 5 would perform better in the near term decades than would scenarios 1 and 2. Uncertainty of course increases with time, but the modeling indicates that late in the century, treatment scenarios will be less able to maintain favorable conditions as climate drivers intensify disturbance regimes. The results indicate that treatments are likely to moderate and forestall high severity fire rather than eliminate it. However, unlike in our modeled scenarios, managers can also adapt their strategies to conditions to achieve more favorable outcomes. For example, they could ramp up or scale down treatments in response to climatic and fuel conditions, which drive fire regimes.

2.2 Forest Structure and Composition

2.2.1 Dominant vegetation types

Management scenarios were evaluated based upon the percentage of landscape area dominated by conifers, hardwoods, and shrubs (based upon relative biomass in each type of vegetation). Favorable conditions for conifer ranged between 70-86%, with the most favorable condition being the starting value of 78%. Favorable conditions for shrub-dominated ranged between 18-23%, with 21% being most favorable. Hardwood was represented only by aspen, with an optimal value of 1%. These criteria were based upon an assumption that shifting much of the landscape to dominance by either conifers or shrubs would not be resilient. However, previous research found that the area of chaparral stands declined by an average of 62.4% from historical reference levels within the western part of the Lake Tahoe basin (Nagel and Taylor 2005). Therefore, it may be important to reconsider whether recent levels of forested area are most favorable, or instead, whether some increase in shrub-dominated areas might be restorative.

The modeling results indicated that the scenarios would generally maintain conifer forest within a range close to recent conditions. However, under scenarios 1-4, conifer forest tended to increase (exceeding ~86% by 2070), while scenario 5 maintained conifer-dominated areas in a range between 70-75%. These numerical values may differ from more detailed assessments based upon remote sensing, but the trends are still useful to consider when considering forest resilience.

The projected increase in forest contrasts with the expectations that conifer forests will be replaced by shrubs and hardwoods within much of the Sierra Nevada and California overall, since increases in high severity fire and warming conditions may limit conifer regeneration especially in drier, lower elevation areas (Lenihan et al. 2008, McIntyre et al. 2015, Steel et al. 2018). Compared to such areas, Lake Tahoe West is less vulnerable to forest loss because it is comparatively wet and at a high elevation. A recent field study discussed later in this report (Low et al. 2021) supports the relative resistance of Lake Tahoe West forests, as they found that trees maintained growth despite a severe statewide drought that caused significant mortality in other areas.

2.2.2 Trends in forest species composition

Objectives for forest restoration in Lake Tahoe West include promoting the abundance of shade-intolerant and fire-dependent species such as Jeffrey pine, sugar pine, western white pine, whitebark pine and aspen. The landscape modeling evaluated abundance of these species in terms of their proportion of overall biomass. These species were suggested as priorities because previous research found that these species have been declining in recent decades as fire suppression, historical timber harvest, and the white pine blister rust pathogen have favored shade-tolerant and fire-intolerant species such as white fir, incense cedar, and lodgepole pine (Dolanc et al. 2014, Harris et al. 2019, Taylor 1990).

The modeling results projected that most of these historical trends would generally continue unless treatments were increased, particularly under scenarios 3 and 5. For example, white fir increased in scenarios 1, 2, and 4 (which treated fewer acres), was relatively constant under scenario 3, and declined under scenario 5. Furthermore, yellow pine generally declined across scenarios except under scenario 5. On the other hand, the modeling projected that lodgepole pine would decrease, with the largest decrease under scenario 5. That particular result is consistent with the expectations that reintroduction of fire would reduce that species (Taylor 1990).

White pines, notably western white pine, increased in relative abundance across management scenarios, as future climate appeared relatively favorable for that species. Previous climate modeling (Richardson et al. 2010) had suggested that western white pine would encounter relatively stable conditions within high elevation areas in the Sierra Nevada of California, while projecting increases at higher latitudes within the interior northwestern United States. Projections for white pine blister rust are complicated by uncertainties associated with the blister rust disease and the effects of planting resistant strains.

Red fir was projected to decline in the modeling, including in runs when a broad range of climate projections were considered. Red fir is relatively intolerant of drought, and the modeling indicated that red fir would experience both increased mortality and reduced regeneration. Forest monitoring in California has reported that mortality in red fir has been increasing due to climate change, but that the populations have been stable overall (Mortenson et al. 2015). However, a recent review reported that several climate studies have projected large percent range reductions in red fir dominated in California by the end of the 21st century (Meyer and North 2019). Additional research in the Sierra Nevada has indicated that red fir populations have been stable recently, but they are vulnerable to further climate change (Nelson et al. 2020).

Aspen as a percentage of biomass tended to increase across scenarios, although its overall biomass remained low. Higher levels of treatment (especially increases in prescribed burning) were associated with larger relative increases in aspen biomass and in total landscape area where aspen was dominant. Scenario 5 best achieved favorable conditions for aspen, as extensive prescribed burning under that scenario may have reduced competition from conifer trees. A review of aspen in the Sierra Nevada by Shepperd et al. (2006) was consistent within this finding, as they suggested that increases in fire activity could support aspen expansion, although they cautioned that there was substantial uncertainty regarding aspen trends.

2.2.3 Seral Stage

Much of the Lake Tahoe Basin, including Lake Tahoe West, is currently dominated by mid-seral forest, which reflects a historical legacy of early logging that reduced old trees, combined with fire suppression that has facilitated dense regrowth of younger trees. Managers identified an objective of increasing the abundance of late seral forest. Late seral forest is particularly important as habitat for three forest predators (marten, California spotted owl, and northern goshawk) of special concern in the basin, as well as overall biodiversity and carbon sequestration. Early seral conditions are also important for biodiversity, especially “complex early seral forest” that retains snags and other dead wood following disturbance such as stand-replacing wildfire. Only areas classified as “forest”, not shrub-dominated areas, were included in these seral stage measures. The evaluation of seral stage was based upon the relative amounts of biomass in different age classes.

Modeling results indicated that under all scenarios, the proportion of conifer forest in late seral conditions would dramatically increase over the next century. This trend held for both lower montane forest (yellow pine and mixed conifer) and high elevation forest types (red fir, lodgepole pine, western white pine, and subalpine white pine). The increase was greater in the lower elevations where late seral is currently more limited. Both mid-seral and early seral forest generally decreased over time. Increased treatment accelerated the shift toward late seral conditions.

In the lower montane areas, 35% late seral was suggested as a lower threshold for most favorable conditions. Scenario 5 reached 40% by 2030 and then gradually increased to 49% by 2110. Scenario 3 increased to 33% by 2040, largely plateaued at that amount for the next four decades, and then increased again to nearly 47% by 2110. Scenario 4 reached 35% by about 2080, while scenarios 2 and 1 reached the 35% threshold 10 and 20 years later, respectively.

The trends in higher elevation forest were somewhat different, in that scenario 5 still accelerated a shift toward late seral compared to the other scenarios, but it did not continue to increase late seral as much as the others did in the later part of the century. Instead, early seral increased under scenario 5 in high elevation forest areas, presumably as fire activity reduced biomass in those areas.

Manager guidance indicated an objective of relatively low amounts of early seral forest in lower elevations, with most favorable conditions set between 7-18%. Across all five modeled scenarios, early seral forest conditions declined from 39% down to that most favorable range (13-17%) by 2110. However, scenario 5 reached and then sustained that target by 2050, while the other scenarios gradually reached that threshold. Within high elevation forests, the range for most favorable condition was set at 5-17%. Most scenarios began with and maintained low levels (<3%) of early seral forest at high elevations, with only scenario 5 during the middle of the century reaching a level (8%) in the most favorable range.

2.2.4 Areas with old trees

The modeling considered another indicator of old-growth forest by tracking areas with old trees. The size of individual trees is not directly tracked in LANDIS, but older tree cohorts translate to larger trees (diameter and/or height). An old tree was defined as >150 years old, which, at the start of the modeling period, corresponded to trees established before extensive Euro-American colonization (the Comstock Era in the Lake Tahoe basin).

The modeling indicated that across all scenarios, areas with old trees would dramatically increase over the first half-century of the model, and then largely plateau, regardless of management strategy. Scenario 3 achieved slightly more areas of old trees (peaking at over 17,000 acres), while scenario 5 resulted in somewhat fewer areas of old trees (peaking below 15,000 acres), with the other scenarios intermediate. When the model was run to consider a wider range of climate projections and to make insect outbreaks responsive to climate, areas of old trees tended to decline late in the century, although the relative performance of scenarios was similar.

2.2.5 Implications

Overall, the results suggest that increased treatments, as outlined in the Landscape Restoration Strategy, would bring forest composition and structure closer to historical conditions associated with more natural fire regimes that were deemed favorable. Increased prescribed burning under a fire focused scenario 5 particularly promoted favorable composition of shade-intolerant tree species and shrubs, as well as fostering late seral structure. The modeling projected that conifers would continue to increase, and amount of late seral forest and areas with old trees would substantially increase with time under all management scenarios. However, the area with old trees might not be sustained over long periods, especially if insect-related mortality increases with climate change. More treatment, as proposed under the Lake Tahoe West Landscape Restoration Strategy, is expected to accelerate this increase in the proportion of late seral forest, particularly in the lower montane zone, by several decades.

Increased thinning and prescribed burning would promote individual species that are priorities for restoration in the Lake Tahoe basin, including yellow pine and aspen. Without such interventions, several shade-tolerant species, including incense cedar and white fir, are likely to increase. Treatments in high-elevation forests would also help to mitigate expected declines in red fir.

Because the modeling did project long-term declines in shrubs and early seral forest under most strategies, managers may want to emphasize several strategies, mentioned in the Landscape Restoration Strategy, to promote such vegetation. These include using more fire, increasing tolerance for more severe burns under managed natural ignitions or prescribed burns, and using harvest to create more and larger forest openings. Previous research has suggested that regeneration and growth of several species, including western white pine and Jeffrey pine, may be enhanced using silvicultural treatments that create such openings (Bigelow et al. 2009, Jain et al. 2004, York et al. 2004). Consequently, these approaches can promote various vegetation objectives.

2.3 CARBON

2.3.1 Forest ecosystem carbon

In all scenarios, forest ecosystem carbon generally increased over time for at least 60 years, as the forests matured and experienced longer growing seasons. Increasing management reduced those increases in forest ecosystem carbon storage, particularly as both harvest and prescribed burning reduced carbon stored in live and dead trees as well as in duff. Treatments did reduce carbon emissions from wildfires and increase growth of the residual live trees, but those gains were not enough to overcome the direct losses from the treatments. Consequently, suppression-only (scenario 1) resulted in the highest average level of forest ecosystem carbon over time, although it also had the widest variation in carbon storage. Use of prescribed fire (scenario 4) stored slightly greater carbon on average than the WUI-focused scenario 2. Scenario 5 resulted in the lowest levels of forest ecosystem carbon, especially by reducing stores in dead trees, while scenario 3 stored the second lowest amount. Scenario 3 resulted in an initial decline in stored carbon, although increased growth of the remaining forest gradually narrowed the gap between it and less intensive scenarios.

2.3.2 Whole system carbon

Whole system carbon, which considers carbon pools outside of the forest, follows a similar pattern to forest ecosystem carbon. All scenarios provide for increased carbon storage, although the scenarios that treat more area resulted in less storage. Changes in forest ecosystem carbon are several orders of magnitude larger (on the order of millions of metric tons over the 100-year model time frame) than changes in external pools of harvested wood products, bioenergy substitution, and emissions from transportation. The more intensive treatment scenarios stored less carbon overall (Table 2-1), although there were some temporal differences. Over the first three decades, Scenario 3 stored the least amount of carbon, but over a full century, Scenario 5 stored the least.

Table 2-1—Increases in forest carbon relative to starting value of 2.48 million metric tons in 2010 in the Lake Tahoe West study area.

Scenario	Change 2010-2040	Change 2010-2110
1	+ 30%	+ 95%
2	+ 23%	+ 85%
3	+ 11%	+ 64%
4	+ 25%	+ 88%
5	+ 15%	+ 32%

Harvesting biomass, rather than burning it in piles, provides for carbon storage in harvested wood products and substitution benefits from bioenergy through displacement of fossil fuels. Consequently, accounting for harvested wood product utilization narrows the gap modestly between scenarios that involve harvest, especially scenario 3, and scenario 1, which does not. However, that modest narrowing did not allow scenario 3 to store as much carbon as scenario 1.

2.3.3 Sensitivity to climate projections

Projections of stored carbon were reduced when the landscape modeling considered a wider range of climate projections, including higher emissions pathways (RCP 8.5 emissions) and linked insect outbreaks to droughts. However, the relative performance of scenarios remained mostly the same, as scenario 1, on average, still sequestered the most carbon overall, while scenarios that increased treatment resulted in less sequestered carbon. Most scenarios continued to increase forest ecosystem carbon over time; however, scenario 5, showed declines after several decades. Overall, both fire-focused strategies stored less carbon more than the thinning-based treatments, particularly by reducing the soil and dead wood carbon pools.

2.3.4 Implications

Forests in Lake Tahoe West were projected to continue to serve as a carbon sink for many decades. As temperatures in the Lake Tahoe basin continue to warm, forests are likely to store more carbon overall due to longer growing seasons, despite the potential for warming-related insect and wildfire disturbances to reduce carbon. This result differs from projections for many forests in California, which are expected to become carbon sources by the middle of this century unless greenhouse gases emissions are sharply reduced (e.g., an RCP 2.5 emissions pathway) (Dass et al. 2018).

It is important to recognize that the more intensive management scenarios, as well as the Landscape Restoration Strategy, were designed to shift conditions close to historical references for tree densities and fuels. Historical levels of carbon were likely much lower than in present-day fire suppressed forests, as much as 2.5 times lower in a study by Harris et al. (2019). In a study within the Lake Tahoe basin, Taylor (1990) found that contemporary Jeffrey pine-white fir forests had on average, five-fold more trees and nearly two-fold more basal area than forests prior to Euro-American colonization. Because the more intensive management scenarios reduce tree densities and fuels toward more historical levels, they entail both a near-term reduction in carbon storage and greater likelihood of a long-term reduction by design.

Previous LANDIS modeling in the Lake Tahoe basin, which had shown greater potential for treatments to increase long-term carbon storage, focused only on reducing small trees (ladder fuels) within the WUI zones and/or excluded bark beetle mortality (Loudermilk et al. 2017, Loudermilk et al. 2013). Other studies have found that treatments may achieve a long-term positive carbon return when the expected incidence of wildfire is high and fire conditions are expected to be intense (Chiono et al. 2017, Foster et al. 2020, Krofcheck et al. 2017, Liang et al. 2018). Many of those studies were conducted throughout the Sierra Nevada or within smaller regions where extreme wildfires have occurred. The lack of a carbon payoff in this modeling reflects the fact that Lake Tahoe West is less disposed to such extreme wildfires.

Consequently, treatments to restore less dense and more diverse forest conditions entail a carbon cost that may not be recouped even after accounting for carbon stored long-term in harvested wood products and avoided fossil fuel emissions from biomass utilized for energy. However, utilizing the residual materials from harvests, rather than burning them in piles, would offset some of the reductions in carbon.

2.4 NITROGEN

The landscape modeling in LANDIS tracked losses of system nitrogen to streams, although nitrogen dynamics in the model have not been extensively calibrated. Reducing forest biomass via thinning or fire tends to reduce nitrogen demand by vegetation, thereby increasing nitrogen runoff. On the other hand, reductions of litter and duff can reduce decay and therefore release less nitrogen in stream runoff. Furthermore, increased treatments also reduced the incidence of stand-replacing fires that tend to release nitrogen. Results under scenario 3 (extensive thinning) were similar to those under the no-treatment scenario 1. However, the fire-focused scenarios 4 and 5 were associated with slightly higher (up to 4% more) nitrogen loading than the others.

The Landscape Resilience Assessment and Landscape Restoration Strategy did not focus on nitrogen, but it is important to note that currently, nitrogen levels appear to be beyond the natural range of variation, as reported by Karam et al. (2013), who found that fire exclusion has substantially increased nitrogen pools in the Lake Tahoe Basin.

2.4.1 Implications

Our model results suggest that there would be neither a large benefit nor a substantial risk from increasing treatment in terms of nitrogen loading to Lake Tahoe. However, further refinement of models could provide better guidance, and such work is continuing for the WEPP model in particular.

2.5 LANDSCAPE WATER QUALITY DYNAMICS

Results from WEPP analysis of expected loads under different types of disturbed condition were overlaid with LANDIS outputs regarding future treatments and wildland fires to predict the overall effects of each management scenario on very fine sediments (<16 microns) and total phosphorus over the 100-year period. WEPP results (available through an online portal: https://wepp1.nkn.uidaho.edu/weppcloud/) were obtained for 20 watersheds on the west side of Lake Tahoe. Those results represented loads under the following conditions: undisturbed (primarily categorized as "old forest" or "shrub"); uniform forest thinning; uniform prescribed burning; and uniform low, moderate, or high severity wildfire.

2.5.1 Effects of treatments on very fine sediment and phosphorus yield

The WEPP modeling predicted relatively modest increases in very fine sediment (<16 mm) (about 7% higher per unit area) and phosphorus yields as a result of thinning. Particulate phosphorus is the predominant form of phosphorus delivered from these watersheds, so management that reduced sediment yield will also reduce phosphorus. Based upon the conservative practices used in the Lake Tahoe basin, the modeling assumed that thinning treatments, even on steep slopes, would retain high levels of ground cover. The WEPP modeling indicated that increases in very fine sediment and phosphorus yields under prescribed burning would be low as well (about 1.5 times the undisturbed condition per unit area), although slightly higher than for thinning, and less than under wildfires. A field study of thinning and prescribed burning in the Lake Tahoe basin found that erosion was generally deterred when there was at least 25% residual ground cover (in the form of surface fuels and duff) following treatment (Harrison et al. 2016). Managers in the basin indicated that prescribed burning would rarely result in patches that would be intense enough to consume mature trees, and that such patches would be much smaller than 1 hectare. Therefore, burn severities comparable to wildfires would not be expected.

2.5.2 Effects of wildfire on very fine sediment and phosphorus yield

Wildfire is associated with large increases in discharges of very fine sediment and phosphorus per unit area, and increases associated with high soil burn severity are particularly extreme (27 times greater than the undisturbed condition across the entire landscape). That result is comparable to findings from previous field research in Colorado on sediment yields (Benavides-Solorio and Macdonald 2005). Wildfires reduce ground cover, and more severe fires result in lower levels of residual ground cover. However, erosion rates are more directly related to soil burn severity than to vegetation burn severity. Analyses of recent wildfires within and near the Lake Tahoe basin found that soil burn severity was often driven by inherent landscape factors (i.e., slope, soil type, and climate) rather than by vegetative biomass. Furthermore, soil burn severity is often less than vegetation burn severity, as some fires that burn intensely enough to kill trees may still leave residual ground cover in the form of needles.

2.5.3 Effects of alternative management scenarios on very fine sediment and phosphorus

The effects of alternative management scenarios were evaluated by combining the LANDIS projections of thinning and fire disturbances across the landscape with the WEPP estimates of very fine sediment and phosphorus for particular areas given such disturbances. Loads of fine sediment and phosphorus varied from year to year and decade to decade, although they generally increased over time as wildfire activity increased with climate change, particularly in the second half century (Table 2-1). Treatments were projected to modestly increase loads, but over time those increases were largely offset by reduced loads from wildfires. The fire-focused scenarios were projected to increase loads more than thinning, because prescribed burning is expected to reduce ground cover more and increase disturbance of shrub areas.

Table 2-2—Average very fine sediment and phosphorus loads in percent relative to baseline for first fifty years and the full century, using initial LANDIS modeling assumptions (including a climate change projection based upon the CanESM GCM with a RCP 4.5 emissions pathway)

Scenario	1	2	3	4	5
Very fine sediment load over first 50 years	104.7	104.1	104.0	105.3	105.5
Very fine sediment load over full century	104.7	106.2	105.3	106.3	107.4
Phosphorus load over first 50 years	103.6	103.0	103.2	104.1	104.3
Phosphorus load over full century	103.8	104.8	104.3	104.9	106.1

2.5.4 Areas of high erodibility

The Lake Tahoe West modeling identified Blackwood and Ward, both underlain predominantly by volcanic soils, as major sediment source watersheds. Previous research had also identified Blackwood watershed as the largest source of fine sediments in Lake Tahoe West (Stubblefield et al. 2009). Within the Blackwood watershed, about 92% of the sediment under the current condition originated from relatively steep (>30% slope) Melody and Ellispeak rock outcrop complexes. Because many of these steep areas are relatively barren or more sparsely covered with shrub vegetation, thinning is not likely to occur. Prescribed burning could include those shrub-dominated areas. Previous field study has found that erosion was low following thinning and burning on areas with slopes less than 30% (Harrison et al. 2016). However, landscape prescribed burning in steeper areas has not been widely conducted nor studied, so there is more uncertainty regarding its effects. Additional analysis as part of Lake Tahoe West science is underway to evaluate effects of thinning on slopes over 30%.

2.5.5 Effects of changing climate on storm intensity and future loading

The WEPP models were run using a baseline climate and using a future climate based upon projections by Coats et al (2013) that were associated with a high emissions pathway (specifically an "A2 emissions scenario" that is most comparable to the RCP 8.5 emissions pathway used in the LANDIS modeling). Those results indicated that average yields of very fine sediment would roughly double. This result suggests that ground disturbances in the future, when storms are more intense, are likely to have much greater impact than the same amount of disturbance in the near term.

2.5.6 Implications

Treatments are likely to increase fine sediment and phosphorus, but the increases are expected to be small relative to baseline loads, and they may be offset by reduced loading from wildfires over the long-term. Scenarios that increased prescribed burning are more likely to increase loads than thinning, because such burns are expected to reduce residual ground cover and treat shrub-dominated areas that are more erodible. However, the projected differences in loads are so small (only a few percentage points relative to the baseline) that they would be difficult to detect through monitoring given the wide natural variation in loading. The Landscape Restoration Strategy calls for increasing disturbance above business-as-usual, but likely not to the extent of the most extensive scenarios (3 and 5) that were modeled. Furthermore, increasing treatment as proposed in the Landscape Restoration Strategy, could reduce the risk of very high loads from wildfires that may be difficult to otherwise mitigate. Present water quality frameworks in the basin, such as the Total Maximum Daily Load, do not factor in the risk of loading from wildfires, which is substantial. Factoring in the likelihood that storm intensity will increase in the future due to climate change would make the payoff from increased treatments occur sooner.

2.6 Water Quality and Roads

2.6.1 Sedimentation from the current forest road network

Sediment loading (<2 mm) from the current forest road network in Lake Tahoe West was evaluated using the WEPP:Road tool in a report by Elliot et al. (2019). The study estimated that 54 Mg of sediment (<2 mm) is generated annually by the existing forest road network in Lake Tahoe West. Very fine sediments (<16 microns) comprise a smaller percentage of that total sediment load; for example, the watershed modeling found that in Blackwood Creek, very fine sediments made up 32% of the sediment load. The total load from the road network is estimated to be less than 1% of the amount generated from hillslopes. This result reflects the generally high quality and relatively low density (1.2 miles/square mile of area) of the forest road network in Lake Tahoe West compared to other public forested areas in the western U.S.

Results indicate that closing unpaved roads that are currently trafficked would reduce erosion from those roads by 20 percent. On the other hand, actively using unpaved forest roads would, on average, increase sediment delivery by 19 times from those segments for the years in which the thinning operations are active. However, following active use for harvest, those estimated loads would rapidly return to their pre-use values. Consequently, the increased sediment delivery associated with harvesting operations can be estimated by multiplying the estimated delivery by the fraction of time that the roads are used for harvest. For example, if the roads are likely to be opened for harvest every 4 years out of 20, then the average increase from those roads could be about 4.6 times greater than current loads over the entire period of analysis.

2.6.2 Implications

Managers can use the current road network analyses to analyze potential impacts of opening or removing specific road segments. Steep road segments that are close to streams pose the greatest risk of sedimentation. There are opportunities to mitigate impacts through greater application of best management practices that dissipate runoff from roads prior to reaching stream networks.

2.6.3 Water quality impacts from opening abandoned roads

Sediment loading from abandoned roads (also called “ghost” or legacy roads) was evaluated using WEPP:Road tool within the Blackwood Creek watershed. Details on the methodology and results are included in a separate report by Cao et al. (2020). The analysis identified 43 km of abandoned roads compared to only 16 km of active roads in the Forest Service Lake Tahoe Basin Management Unit road database. Because the abandoned roads have revegetated, they generate little sediment, but they increase erosion in downstream channels. Nearly 20% of the predicted sediment delivery at sub-watershed outlets would be reduced if all those abandoned roads were recontoured to the former topography. Reopening such roads, on the other hand, would tend to increase erosion, particularly in downstream channels. If all roads in the Blackwood Creek watershed were reopened using an insloped profile, sediment delivery is estimated to increase by 15.5%, and by 6% if using an outsloped profile. Steeper roads tend to cause more sedimentation; for example, road with gradients above 15% yielded more than 3 times the sediment of roads between 5% and 10%. Reopened roads that pass through more finely textured (e.g., volcanic-derived) soils are likely to generate more sediment than roads in more coarsely textured (e.g., granitic-derived) soils. Roads close to streams also posed greater risk of sedimentation.

2.6.4 Implications

Projecting the impacts of reopening or recontouring abandoned roads is best done on a segment-by-segment basis rather than trying to generalize such management activities. Managers can use the abandoned roads analysis to identify opportunities for reducing sedimentation in the Blackwood Creek watershed. The results illustrate the importance of evaluating road impacts within specific segments. The impacts from road reopening could be mitigated through several practices, including outsloping roads, installing surface cross drains or ditch relief culverts on insloped roads, and installing slash windrow filters (leftover from fuel management activities) on critical outsloped segments.

2.6.5 Erosion dynamics and interactions with roads following the Emerald Wildfire

WEPP tools were used to model erosion following the 2016 Emerald wildfire and compare those results to predictions made by the postfire rehabilitation team and to loads measured by road managers. Details on the methodology and results are included in a separate report by Elliot et al. (2018). The Emerald wildfire burned 173 acres south of Emerald Bay, along the southern border of Lake Tahoe West. The modeling projected that the Emerald wildfire would significantly increase erosion, but a considerable volume of the eroded sediments would be detained in road ditches and detention basins. The modeled estimates were consistent with observed quantities of sediment removed from the two roads and detention basins in the wake of the fire. Instream monitoring the year after the fire also did not show increases in sedimentation above background levels. The resulting erosion rates (between 16-25 Mg ha^{-1} across three precipitation events) were also consistent with predicted rate of 21 Mg ha^{-1} made using the rapid assessment tool (ERMiT) applied by the rehabilitation team in the immediate aftermath of the fire. The results confirm that such coarse-scale predictions are reasonable for rapid post wildfire erosion analysis.

2.6.6 Implications

The impacts of wildfires, even when severe, can be mediated by roads and detention basins. Roads had complex and variable effects on runoff and sediment transport. Road fill slopes within the burned areas were predicted to be at high risk of onsite soil loss, as were channels downstream of roads. However, both the modeling and field observations indicated that roads and detention basins intercepted sediments eroded following wildfire. Consequently, good design and maintenance of the road system, including well-spaced culverts with energy dissipating outlets, can help to limit the impacts of wildfires.

2.7 Water Quantity and Snow Dynamics

The hydrology team applied the SnowPALM and GSFLOW modeling tools to evaluate changes in water input from snow and duration of snowpack. The methodology and results from the SnowPALM analysis are detailed in two papers (Harpold et al. 2020, Krogh et al. 2020), while those of the GSFLOW analysis are included in a report (Harpold et al. 2020). The detailed hydrologic modeling found that Leaf Area Index (LAI) (the combined surface area of leaves per unit area) was a key determinant of water quantity, and LAI is one of the values modeled in LANDIS. Therefore, the water quantity effects of management scenarios over time were approximated using the LAI values from LANDIS.

2.7.1 Effects of forest thinning on water quantity

Simulations using the SnowPALM model indicated that thinning would increase water input from snow by about 380 mm on average across the entire landscape with the removal of all trees <20 meters (65 feet) tall, with increases up to 450 mm, or 60%, in the most responsive areas (Krogh et al. 2020). Forest patches that have the largest increase in net water input from tree removal were those that are relatively dense (forest cover >75% or LAI >3 m^2/m^2) with an average vegetation height of 5 to 15 m (including non-vegetated areas). Reductions in LAI, derived from LiDAR imaging, were associated with increases in melt volume for all snow zones, but the effects were larger at middle to low elevations where forests are denser. Consequently, across a range of watersheds in Lake Tahoe West, responses to thinning were greater in watersheds that include more dense forests at low elevations, such as Burton, McKinney, and Little Rubicon Creek, than in larger, higher elevation watersheds such as Eagle and Cascade Creek. Results also suggested slightly larger responses from south-facing slopes at mid to low elevations (<2300 m or 7550 ft, which corresponds with lower mixed-conifer and yellow pine forests). Changes in both melt volume and peak snow accumulation relative to values before thinning were greater in drier years than in wetter ones.

The hydrology team applied a second model (GSFLOW) to four instrumented watersheds in Lake Tahoe West: Ward Creek, Blackwood Creek, Meeks Creek, and General Creek. They found that thinning of trees less than 20 m could increase annual stream flow by about 8% on average (ranging from -5 to 15%), with potential to increase groundwater as well as low flow in streams, although effects varied from year to year. Effects were greater in the Blackwood and Ward watersheds than in General and Meeks watersheds.

2.7.2 Effects of forest thinning on snowpack duration

The hydrologic modeling found variable effects of forest thinning on snowpack duration. A detailed analysis using SnowPALM found that more snow would accumulate, but it did not find a consistent effect on the timing of snowmelt (Krogh et al. 2020). Application of a second model (GSFLOW) found that thinning would cause snowmelt to increase and occur earlier, resulting in earlier snow disappearance in the areas with the greatest thinning effects; however, the modelers had less confidence in that result because the snow model in GSFLOW was not as detailed (Harpold and Rajagopal 2020). Overall, results suggest that while thinning would likely increase water yield, it was not likely to extend the duration of snowpack. Furthermore, results differed by elevation zone, with some high elevation areas appearing less likely to accumulate and retain snow following thinning.

2.7.3 Translation to landscape, long-term scales, and modeled scenarios

Because hydrologic modeling indicated that LAI was a key indicator of water yield, management scenarios were evaluated using the LAI projections from the LANDIS modeling. LAI in LANDIS is not precisely equivalent to the LAI used in the hydrological modeling, in particular because the hydrologic modeling used LAI inferred from LiDAR scanning of trees greater than 2 m tall, while LANDIS estimates LAI based upon all trees and shrubs. The integration analysis assumed that a reduction in LAI would increase water yield overall and that it did not matter whether the reductions were the result of thinning or fire. The kinds of understory thinning treatments simulated in LANDIS were generally comparable to those in the more detailed hydrologic analysis, as both focused on understory thinning to remove small trees. However, the detailed hydrologic modeling did not evaluate changes due to fire or changes in shrubs and other short vegetation types. Recent research supports the expectation that reducing biomass, whether through wildfire, managed fire, or mechanical thinning, will lower evaporative demand and increase water available for runoff (Roche et al. 2020).

Across the first four scenarios, LAI increased over time as overall forest growth exceeded losses from treatments and wildfires. However, by removing biomass, treatments reduce LAI. Under scenario 5, the reductions were great enough to keep LAI from increasing. These results indicate that water yield is likely to decrease over time under current trajectories, even without factoring in climate change effects on precipitation. Furthermore, increasing treatment would increase water input to groundwater and surface waters. That finding is consistent with recent research in the nearby Yuba and American watersheds, which concluded that large scale reductions in forest biomass by restorative thinning or fire, if sustained with frequent retreatments, could increase runoff by 4-10% (Roche et al. 2020).

2.7.4 Implications

Forest understory thinning is expected to increase water yield, which would help counteract expected reductions in water availability in streams, groundwater, wetlands, and Lake Tahoe. The results identify stands that would yield the greatest water quantity benefit, particularly high-density forest patches on south-facing slopes in lower mixed-conifer and yellow pine forests. However, a modest increase in water yield due to management may not be enough to stave off expected declines in water yield due to a warming and possibly drying future climate. The potential to at least partially counteract such declines may be important for helping to sustain riparian and aquatic biodiversity and other water-dependent values.

2.8 Treatment Effects on Fire Behavior and Forest Structure in Aspen Stands

A team modeled effects of thinning conifers within stands previously dominated by aspen trees on fire behavior and forest structure in three field sites in the Lake Tahoe basin (two of which were in Lake Tahoe West). Details of the study have been published in Ziegler et al. (2020). The modeling found that both actual and simulated, light thinning (removal of <14" diameter at breast height [DBH] conifers) had marginal effects on surface fuel and overstory structure, which would likely fail to enhance resource conditions sufficiently to sustain aspen. Raising the diameter limit both shifted surface fuels from predominately aspen litter to conifer litter, reducing the average fuel load, and significantly reduced conifer stocking, especially conifers close to aspens. In scenarios that represented no thinning or light thinning (which included thinning as actually implemented), fires did not carry well under low and moderate winds. Under more severe burning conditions in the untreated stands, canopy consumption ranged from 13-35%. On the other hand, heavier thinning (removal of >=22" DBH conifers) increased the likelihood of fire spread and rate of spread when winds were low to moderate, while minimizing the potential for crown fire activity (< 5% canopy consumption) even under high winds.

2.8.1 Implications

Within aspen stands that have experienced encroachment by conifer trees, cutting specifications that relax diameter limits and remove a substantial portion of conifer overstory could better promote aspen restoration and mitigate fire hazard. These findings are supported by previous field studies in the Lake Tahoe basin (Berrill et al. 2016). Previous research in the Lake Tahoe basin also suggested that use of fires would help to promote aspen regeneration, but that such fires might need to be more intense than is typical for prescribed burns (Krasnow and Stephens 2015). The new modeling results suggest that managers might be able to judiciously use fire as a primary treatment, particularly by using more active firing techniques to carry prescribed fires through untreated stands. Although aspen crowns rarely burned in the simulated fires, aspen stems may still die after burning. Therefore, preferred treatments would depend on many objectives such as retaining mature aspens, promoting aspen regeneration, and mitigating potential for crown fires.

2.9 Stand-Scale Treatment Effects on Forest Structure, Composition, and Fuels

A team conducted field monitoring to compare observed changes in forest structure, tree species composition, and downed woody fuel loads and tree resistance to drought 10 years after thinning; the results of this field study are published as Low et al. (2021).

The study found that thinning treatments reduced tree density and basal area while retaining both larger-sized and shade-intolerant trees, and they mitigated post-thinning tree mortality. Treatments were also associated with significantly lower snag basal area. Fine and coarse woody surface fuel loads were positively related to snag basal area and time since treatment. The analysis of tree rings indicated that treatments improved drought resistance as well, especially in units that had been thinned to lower amounts of live basal area. However, despite experiencing unusually severe drought conditions (reduced precipitation and high temperatures), average radial growth was not severely impacted in untreated areas, which may also reflect a lengthening growing season. That finding is consistent with other science findings that suggest that the Lake Tahoe West landscape is likely to continue accumulating forest biomass and is less vulnerable to drought disturbance than lower elevation areas in the Sierra Nevada.

2.9.1 Implications

Thinning-from-below (removing mid- and under-story trees) is effective in meeting short- and longer-term restoration objectives, including lowering surface fuels, restoring forest structure (shifting biomass toward larger trees), restoring forest composition (shifting biomass toward more shade-tolerant species), promoting drought resistance, and reducing mortality. Additional understory burning could prolong and augment the fuel reduction effects of thinning, particularly where the initial thinnings are relatively intensive.

2.10 Wildlife Conservation

The modeling addressed multiple objectives of biodiversity conservation, including maintaining sufficient habitat for native species, maximizing diversity, and sustaining ecological functions provided by wildlife. Given the high degree of uncertainties associated with predicting longer-term wildlife response to disturbance, we evaluated scenarios based on the amount of habitat available for individual species. As the amount of any given habitat will fluctuate over time, we established a risk threshold in which a >30% loss of high-quality reproductive habitat for any given species would be cause for concern. This approach resulted in coarse-scale metrics that reduced the number of assumptions required for comparison. As a counterbalance, the evaluation also included a wildlife conservation metric based upon the number of reproductive territories each scenario was projected to provide for apex predators, for which more data exists.

2.10.1 Biodiversity

Biodiversity, including diversity of species and functional groups, were largely resilient to modeled changes in forest management. All five scenarios promoted heterogeneity in wildlife habitat. Scenario 5 performed highest in maintaining high-quality reproductive habitat for existing biodiversity. By maintaining the highest redundancy in insectivores, decomposers, herbivores, soil aerators, seed dispersers, and predators, scenario 5 also performed best in terms of functional diversity. Scenario 3 tended to lead to a better biodiversity outcome than either scenario 2 or 4, which all performed better than scenario 1. Increases in the number of species supported in scenario 5 led to smaller patches of habitat overall and finer-scale heterogeneity compared to the other scenarios. Finer-scale heterogeneity may in part explain why scenario 5 did not perform as well as other scenarios did for old forest predators, as these species are associated with larger patches of old forest habitat. Scenario 3 shared many of the benefits of scenario 5 but resulted in larger patches of older forest types.

2.10.2 Old Forest Predators

Pacific marten, northern goshawk, and California spotted owl are three predatory wildlife species associated with old forests in Lake Tahoe West. In the modeling projections, recruitment of old forest across the Lake Tahoe basin, and within Lake Tahoe West, drove increases in suitable habitat for all three species. Forest growth (over time but accentuated by a warming climate) appeared to drive these gains more than the differences in management across the scenarios due to the current composition of the landscape that includes a large proportion of forest habitat that transitions into the late seral stage in the next few decades. Trends within both Lake Tahoe West and across the entire Lake Tahoe basin were generally similar; results are summarized for Lake Tahoe West to be consistent with the rest of this summary report.

Within Lake Tahoe West, female pacific marten territories increased over time by about 60-75% from the baseline for scenarios 1-4 and about 25% for scenario 5, and those increases were sustained over time. A key driver was the increases in the abundance of late seral mesic forest types. Scenario 3 performed best for marten, with scenarios 2 and 4 close behind, followed by scenario 1, and lastly scenario 5. While scenario 5 remained below the others throughout the modeling, it still increased the number of territories above initial levels and sustained that increase. The reduced performance of scenario 5 may reflect that it tended to break up patches of suitable habitat into smaller and more fragmented patches.

Northern goshawk territories increased by about 25% from the baseline under each of the first four management scenarios, although scenario 5 was associated with a doubling (100% increase) of territories in the first half of the century. The increases were also sustained over time. These trends were driven by the model's emphasis on late seral forest habitat as a key driver, and scenario 5 shifted forest toward late seral conditions sooner than any scenario. Unlike the marten, the goshawk appears to benefit from the higher forest patch diversity produced in scenario 5, which likely has benefits for several species in their more diverse prey base.

California spotted owl territories increased by 33-100% until the mid-century, and then generally declined to levels that were still 25-75% above the baseline. Scenario 1, 2, and 4 all peaked in year 40, with scenario 1 peaking at a doubling of territories, slightly higher than scenarios 2 and 4. Scenario 5 peaked earlier than the other four scenarios (year 20) and then began a more gradual decline. Scenario 3 was generally below the other scenarios, and it more gradually built to a later peak (year 80) than did the other scenarios. Scenario 4 sustained high number of territories late in the century better than the other scenarios did, although that particular result only held for Lake Tahoe West, not the larger Lake Tahoe basin. Key drivers in the owl model were elevation, large amounts of forest habitat with high biomass, and patches of old trees in territory core areas. Differences in performance across scenarios likely reflect the importance of high biomass in the model, because scenarios that increased treatments tended to reduce forest biomass. The late century declines likely reflect the early peaks in the recruitment of suitable habitat present within their low elevation range in the Lake Tahoe basin from forest growth and then the gradual reduction in suitable habitat from the accumulation of treatments and wildfire.

The modeling results suggest that the kinds of management activities would not generally threaten sustainability of these species, given the unique forest composition of the Lake Tahoe landscape containing a high proportion of forest that will soon become more suitable for each of these old forest associated predators through the natural process of forest growth. The results also suggest that managers may also be able to apply a mix of thinning and prescribed burning to sustain more favorable outcomes overall, since scenarios 3, 4, and 5 each performed best overall for different species at different times. Research does suggest that the three species have somewhat distinctive niches, so that treatments could be customized to promote and retain favored habitat for each. However, because the modeling was based upon forest habitat quality, it did not account for other influences, including direct effects of changing climate on owls, displacement by barred owls, rodenticide poisoning, and nonstructural effects of human disturbance. Those factors could help temper the projected gains in habitat for the three species.

2.11 Cultural Resources

The modeling results suggest that more treatment would generally promote cultural resources important to the Washoe Tribe. Scenario 5 performed best overall, since it increased the amount of low-intensity fire and potential water quantity (as measured by the proxy variable of Leaf-Area-Index). The amount of low-intensity fire increased under each successive scenario, ranging from 4% to over 50%, with scenario 5 having four times more low-intensity fire as the next highest value in scenario 4. Scenario 5 had the greatest expected benefit in terms of water availability (see water quantity section) due to reduced tree biomass. Consequently, scenario 5 would be likely to best promote culturally important plant resources.

Scenario 3 best promoted high quality reproductive habitat for three wildlife species selected to represent culturally important species. Increased thinning under that scenario yielded gains for deer and northern flicker. The increased use of fire under scenario 5 was associated with a decline in reproductive habitat for mountain quail. However, it is important to recognize the analysis based upon high quality reproductive habitat does not consider potential benefits from enhanced forage quality, which would likely increase with more fire and thinning.

Greater use of fire is likely to enhance values associated with culturally important plants. Through engagement with the Washoe Tribe, treatments could be designed to promote cultural resources much more precisely than could be represented in the landscape modeling. Prescribed burning could be explicitly aligned with cultural burning led by or involving the Washoe Tribe, which could promote favorable ecological conditions while also promoting tribal social objectives.

2.12 Air Quality

Our analyses looked at both daily emissions of fine particulates ($PM_{2.5}$) and potential smoke impacts from such emissions on downwind populations. Previous work had suggested that reducing high levels of daily emissions would reduce smoke impacts by allowing particulate emissions to remain below harmful thresholds, minimizing the populations exposed to such smoke, and also affording greater opportunity for people to avoid smoke (Long et al. 2018b).

2.12.1 Emissions of fine particulates

Increased treatments, both thinning and burning, reduced fuel consumption, expected emissions from wildfires, and days of very high and extreme emissions. Scenario 3 resulted in the lowest total emissions of particulate matter, while scenario 1 was intermediate among the scenarios. Modest levels of burning under scenario 4 lowered total emissions compared to scenario 1, but the high level of burning under scenario 5 increased total emissions. The use of prescribed fire effectively shifted emissions into more frequent but lower level emissions. Similarly, pile burning was projected to result in many days of low emissions in the late fall, but not high daily emissions. Prescribed burning emissions occurred in late fall under scenario 4, and throughout the year under scenario 5.

Suppression-only management (scenario 1) averaged over 10 days of very high or extreme emissions per decade, while scenarios with the most treatment (scenarios 3 and 5) reduced the average number of such days below 2 per decade More modest levels of treatment (scenarios 2 and 4) were intermediate, averaging 7 and 5.5 days per decade, respectively.

The modeling indicated that emissions and high emissions days would increase over time, particularly in the second half of the century. However, high emission days did become more frequent in earlier decades under scenarios 1, 2, and 4, while scenarios 3 and 5 sharply reduced their incidence even in early decades.

These findings generally comport with those from a recent global review of emissions modeling studies, which founded that increased treatments, including prescribed burning, would reduce emissions from wildfires (Hunter and Robles 2020). They also found that decreases in total emissions (from wildfire and prescribed burning combined) were found only in studies where the expected frequency of wildfire was high.

2.12.2 Smoke impacts

Smoke modeling results suggested that increases in treatment would reduce not only emissions, but also health impacts from future wildfire events. Modeling of individual events indicated that extreme wildfires could have very large impacts to downwind communities, possibly in the tens of millions of dollars based upon increases in mortality.

The results suggest that increased thinning would be very effective in reducing the incidence of extreme smoke events from wildfires, which would have wide-reaching impacts not only within the Lake Tahoe basin, but in more distant populated areas including the greater Reno metropolitan area and the Central Valley in California.

Fire-focused strategies would also be effective in reducing extreme events, but they might still result in smoke impacts, especially due to their frequency. Due to computational challenges, we were not able to quantify the cumulative smoke impacts of multiple wildfires and prescribed burns; however, previous work has suggested that releasing emissions through prescribed burns rather than wildfires will tend to reduce health impacts by limiting the intensity of smoke and size of exposed populations (Long et al. 2018b). The results of modeling individual events illustrated that weather conditions greatly influence the impacts of daily emissions on downwind populations. Managers can time and manage prescribed burns to minimize smoke impacts, but as such burns become larger and more frequent, there is greater risk that some will result in impacts. A remaining challenge is to better quantify the conditions under which such emissions will occur.

2.13 Implementation Feasibility

2.13.1 Staffing

Increasing management would require more staff to oversee both thinning and prescribed burning treatments, although all scenarios were evaluated as feasible in terms of staffing. Scenario 3 required the most staffing because areas treated with hand thinning would also require follow-up pile burning.

2.13.2 Days of Intentional Burning

The days of international burning increased under each scenario from 0 under scenario 1 to about 10 under scenario 2, about 30 days under scenario 3, about 37 days under scenario 4, and about 96 days per year under scenario 5. The latter value was at, and sometimes exceeded, the historical average of 96 days available for burning. It could be challenging to implement the high level of prescribed burning under scenario 5 because the number of days of intentional burning reached and sometimes exceeded the historical average of such of operational burn days. This result is consistent with recent research on burn day windows. Increasing availability of specialized fire personnel in the fall and spring and adjusting prescriptions to burn more in the spring might be necessary to substantially increase burning. Greater acreage of prescribed burning could be accomplished per day by burning larger areas, but such burns may require multi-day burn windows in the fall. The modeling did not explicitly consider whether multi-day burn windows would be necessary or not; such evaluations can be made in planned analyses to support use of fire.

2.14 Economic Costs and Benefits

2.14.1 Implementation costs

The economics team evaluated the cost to implement management strategies for the first three decades (2010-2040). Their analysis of historical cost data indicated that prescribed burning is less costly to implement per acre than mechanical thinning and fire suppression. When comparing the five management scenarios, they found that implementation costs rose with area treated annually, ranging from a low of $1.7 million annually for scenario 1 (fire suppression costs only) to a high of $5.4 million annually for the scenario that greatly increases thinning (scenario 3). The two fire focused scenarios were slightly below (scenario 4 - $2.6 million) and slightly above (scenario 5 - $3.6 million annually) the cost of the current, business as usual, WUI-focused scenario (scenario 2 - $3.2 million annually). Greater reliance on prescribed fire under scenarios 4 and 5 was projected to reduce fire suppression costs relative to business-as-usual by more than $400,000 per year. That effect largely balanced out the cost of prescribed burning under scenario 4, although it did not offset the greater costs of additional burning under scenario 5. Given an emphasis on removing mostly small trees, revenue from timber and biomass sales had relatively small effects on reducing the net implementation costs of thinning.

2.14.2 Risk to property

The economics team counted the number of residential properties that were in areas exposed to moderate and high severity fire in at least 50% of replicates of the landscape modeling. The results demonstrated that increasing the pace and scale of forest management, through increased thinning and use of prescribed fire, sharply reduced the risk of property loss compared to a suppression-only scenario 1 and WUI-focused thinning scenario 2 (Table 2-2). This effect held both within Lake Tahoe West and the broader Lake Tahoe basin. Assuming that the average property is worth about $500,000, these results suggest that intensifying management could yield a benefit of $4 to 6 million annually over the next 30 years.

Table 2-3—Residential properties within Lake Tahoe West projected to be at risk of medium or high severity fire from 2010-2040.

Scenario	1 (Suppression only)	2 (WUI focused)	3 (Thinning-focused)	4 (Fire-focused, moderate prescribed burning)	5 (Fire-focused, high prescribed burning)

Number of properties	1731	1773	681	350	224
Percentage	19%	19%	7%	4%	2%

2.14.3 Public health

The reduced rates of wildfires are also associated with significant reductions in the health costs of extreme wildfires, as discussed in the air quality section. These costs vary greatly depend on fire emissions, location, weather patterns, and the size and composition of exposed populations. The economic costs of the health impacts of an individual large wildfire occurring within Lake Tahoe West ranged from $5-70 million based upon potential increases in mortality, indicating that these costs are important to consider.

As discussed previously, all scenarios were projected to realize increased carbon storage with the forest ecosystem, beyond the baseline of approximately 2.5 million metric tons in Lake Tahoe West in 2010. Carbon storage in the forest ecosystem dwarfed the amounts in harvested wood products, biomass substitution for forest fuels, and energy used to transport harvested materials. Nevertheless, the results indicated that more carbon could be stored by utilizing harvested wood for lumber and to generate energy rather than burning that waste material in piles. The use of harvested materials was not large enough to generate positive revenues from treatments, but such utilization would support jobs in related industries. The economic analysis translated the sequestered carbon into dollar values based upon recommendations by the Interagency Working Group on Social Cost of Carbon (2013) using a 3% discount rate (Table 2-3).

Table 2-4—Average annual value of stored carbon relative to a baseline represented by scenario 2.

Scenario	Annual Average Value of Stored Carbon (in 2017 dollars)
1	$154,000
2	$0
3	-$17,000
4	-$280,000
5	-$529,000

2.14.4 Implications

There are trade-offs among different economic values, with no single scenario being an unambiguous winner. However, the scenarios that intensified management generally performed better than the suppression-only and business-as-usual scenarios. One of the most substantial benefits of increasing intensity of forest management (via thinning and/or prescribed fires) is to reduce the risk of property loss from medium and high intensity wildfires. Reducing fuel loads through intensive management also is likely to reduce the health impacts of large wildfires. The value of those benefits could well exceed the extra cost of implementation as well as the social cost of reduced carbon storage. Increasing the use of prescribed fire is highly cost-effective–about half the annual cost of a scenario focused on increased thinning—while effectively reducing fire risk.

2.15 INTEGRATED DECISION SUPPORT

To integrate across the large range of topics and indicator variables, an Ecosystem Management Decision Support (EMDS) analysis was conducted to summarize the results. It is important to note that the results reflect how the indicators were scored and weighted. The Lake Tahoe West Stakeholder Committees informed the weighting based on the status of information and certainty at the time they were queried, but those weightings would likely vary over time as particular problems become more apparent. As one example that affected the relative performance of scenario 5, the air quality and recreation indicators imposed penalties on infrequent, high emission events, while imposing a minimal penalty on frequent, low emission days; however, even low emission fires have the potential to create nuisance conditions and even air quality exceedances. The days of intentional burning indicator can capture some of those social impacts. There is uncertainty over both the indicators and the criteria used to evaluate them, and EMDS modeling can help identify data gaps and uncertainties that most affect management planning and effectiveness.

The decision support analysis suggested that the fire-focused scenario 5, with greatly expanded prescribed burning, performed the best overall by cultivating highly favorable conditions (Figure 2-1). Overall performance was rated as excellent to very good with little variation across decades until the very end of the century when changing climate spurred intense wildfire activity. Scenarios that expanded thinning (scenario 3) or involved more modest increases in prescribed burning (scenario 4) performed the next best, yielding a good rating overall. Finally, the WUI-focused scenario 2, which approximated recent management, and the suppression-only scenario 1 performed worst overall, being rated as good to intermediate.

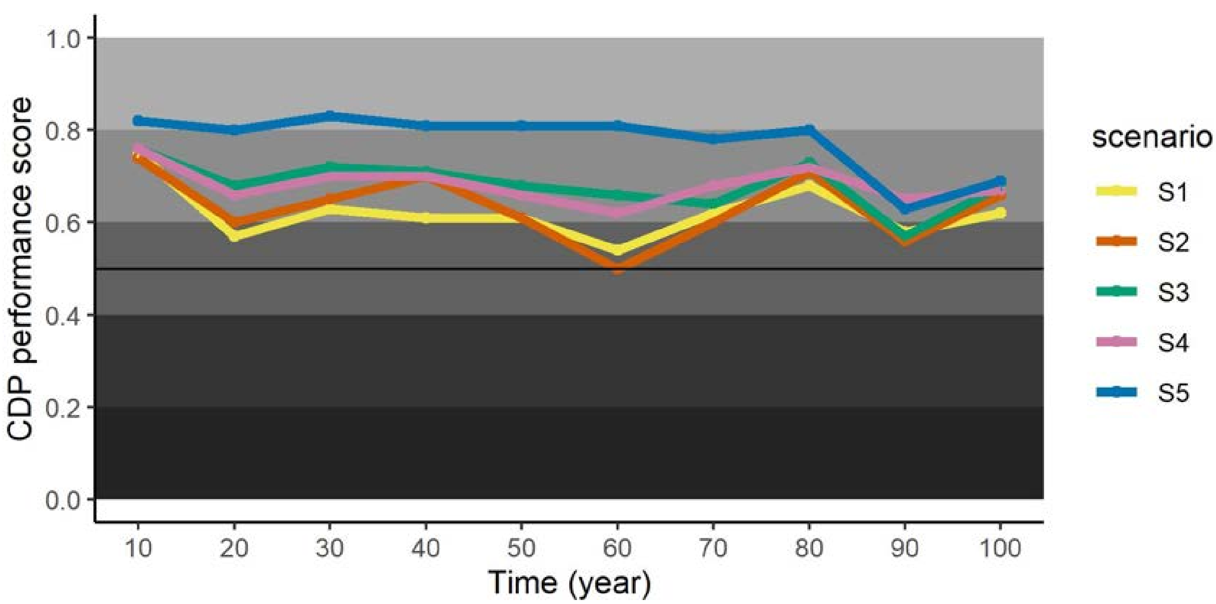

Figure 2-1—Overall scenario performance scores over the full century from least favorable (0) to most favorable (1).

In addition to how well a scenario performs in absolute terms, decade-to-decade variability can also be important, since leaders and stakeholders may prioritize avoiding declines even more than maintaining a higher overall average. During the first 80 years, not only does scenario 5 markedly outperform the other four scenarios but its performance is highly stable. During the same time period, scenarios 3 and 4 also have relatively little between year performance variability. Scenarios 1 and 2 show the greatest amount of inter-year variability. Near the end of the century, all scenarios experience a downgrade in performance that reflected heightened wildfire activity due to climate change.

The evaluation was weighted heavily toward several topics deemed important to stakeholders, including water quantity, water quality, wildlife conservation, functional fire (measures of area burned by severity), threats to property, , and fire in WUI areas (Table 2-4). Overall scenario performance is strongly linked to the occurrence of extreme wildfires, which is projected to increase over the next century in all management scenarios, reflecting the pressure of a warming climate. More extreme outcomes become especially frequent late in the century, resulting in a predicted decrease in forest conditions as reflected in declining EMDS scores over time (Figure 2-1).

Table 2-5—Weighting of topics used in the decision support evaluation

Topic	Weight
Quality water	15%
Water quantity	15%
Wildlife conservation	13%
Functional fire	13%
Threats to property	11%
Fire in WUI areas	11%
Suppression cost	5%
Staffing	4%
Upland vegetation health	4%
Carbon storage	2%
Days of intentional burning	2%
Quality air (daily particulate emissions)	2%
Cultural resource quality	2%
Net treatment cost	1%
Restoration byproducts	<1%
Recreation--summertime emissions	<1%
Total	100%

Values that were particularly sensitive to incidence of large and severe wildfires are risk of residential property loss, incidence of moderate and high severity fire in the WUI, and air quality. These all fall under health and safety, which represent about 25% of the weight in the decision model, which is less than either terrestrial or aquatic ecological conditions (each comprises approximately 30% of the decision model). Cost of wildfire suppression also is driven upward over time. During recent decades in the Lake Tahoe basin, all these indicators have been comparatively quite favorable, the Angora wildfire being the most notable exception. For these indicators, management appears very important to mitigate the impacts of more fire under a hotter climate. For example, the modeling suggested a steady decline in air quality (based upon indicators of very high and extreme emission days) under a no-treatment scenario, while increasing treatment reduced such days.

Forest growth drives improvements in terrestrial ecological quality by increasing late seral forest, which in turn helps to sustain populations of old forest associated species. Management does influence the trajectories of those indicators, but not as much as some other indicators.

Carbon storage and water quantity were both responsive to both forest growth overall and to management, yet they moved in opposite directions, suggesting a fundamental tradeoff. However, in the EMDS evaluation, water quantity was weighted far more heavily than carbon storage, contributing to scenario 5's overall favorable performance.

Scenarios 3 and 4 both performed well overall and across many of the same metrics, although they each had strengths. Scenario 3 was particularly effective in reducing WUI fire risk and extreme emissions, while scenario 4 achieved more functional fire conditions (by design) and had lower implementation costs and staffing burdens.

Scenario 5 performed better than other management scenarios in terms of several other metrics. It scored well on functional fire metrics, since it came closest to restoring a more natural fire regime dominated by low severity fire. It also scored the highest on upland vegetation health by promoting yellow pine, aspen, shrubs, and late seral forest; wildfire suppression costs; wildlife conservation metrics (particularly diversity of functional groups, species richness, and northern goshawk); and cultural resources (reflecting greater water quantity and aspen in particular). It also performed very well in terms of WUI fire risk and risk to properties except very late in the century. The main indicators that performed worse under scenario 5 than the other scenarios were reduced carbon storage and increases in days of intentional burning, both of which had low weights in the overall scoring. This result is consistent with research suggesting that restoration towards a more natural fire regime would promote many objectives, but not carbon, and that air quality constraints might be a key barrier.

The Lake Tahoe West Landscape Restoration Strategy suggests that managers would increase thinning and gradually increase prescribed burning, particularly as a maintenance tool. The results from EMDS indicate that thinning-focused and fire-focused strategies both promote some objectives (such as reduced risk of high severity fire, reduced leaf area index, and shade-intolerant tree species), but they each were linked to distinctive benefits. For example, thinning can store more carbon, while burning promotes landscape diversity associated with non-conifer areas including shrubs and aspen. These patterns suggest opportunities to combine the strengths of increased thinning, by targeting those treatments to reduce risks in priority areas in the short-term, with the strengths of increased burning, by ramping up use of more cost-effective fire treatments over time. At a stand scale, both aspen treatments and general thinning treatments examined in this study demonstrate that mechanical thinning of conifers can promote structural and fuel conditions that facilitate maintenance through prescribed burning. Gradually increasing prescribed burning would also help to evaluate whether the potential downsides of prescribed burning would be as small as suggested by the decision support analysis.

3 Integrated Findings

3.1 More Intensive and Extensive Treatment Promotes Multiple Objectives

Our findings suggest that most objectives would benefit from increasing treatment, including both thinning and prescribed fire. The scenario that entailed the most prescribed burning was the most favorable based upon the evaluation using the Ecosystem Management Decision Support system, due to several factors. Prescribed burning was expected to result in desirable changes in forest composition and structure at relatively low costs, while also bringing the fire return interval and severities closer to reference conditions, which is consistent with objectives in the Lake Tahoe West Landscape Restoration Strategy. Other scenarios that increased thinning and/or burning also scored better than a full-suppression scenario or a business-as-usual scenario that focused thinning in WUI areas. The values that responded most favorably included reduced risk to property and human health from wildfire, increased amount of late seral forest, and increased water yield. Indicators that were less favorably affected under expanded treatments included greater implementation costs, reduced carbon sequestration, and increased days of burning. Collectively, these findings support the Landscape Restoration Strategy of intensifying treatments, expanding treatment beyond the WUI, and ramping up the use of wildland fire in conjunction with thinning. These findings are congruent with other research findings suggesting that such approaches would promote overall social and ecological resilience (Long et al. 2014) as well as narrower objectives, such as conserving California spotted owl habitat (Peery et al. 2017), particularly by reducing the potential for high-severity fire. The economics analysis similarly suggested that increased treatments would pay social dividends, although that analysis is complicated by the fact that many important values involve substantial uncertainty (such as the health impacts of fire events).

3.1.1 Fire and thinning reduce wildfire severity and achieve other social benefits—and area treated is a key driver of those benefits

Increasing treatments would have important social benefits by reducing the risk of large and severe wildfires, particularly in WUI areas where lives and properties are vulnerable. Reducing the risk of extreme emissions from wildfires may benefit both local communities and populations in areas further downwind. By removing small trees, treatment would also increase potential water quantity benefits, specifically increased water available for infiltration and runoff. The value of these benefits is likely to outweigh the higher societal costs of increasing treatment in terms of implementation costs and challenges, as well as the social cost of foregone carbon sequestration. The current level of treatment, which is focused on the WUI, does not appear to achieve objectives as well as alternatives that also treat areas outside the WUI, including a scenario that would significantly expand treatments beyond the WUI. Many objectives evaluated in the decision support modeling and articulated in the Landscape Restoration Strategy also depend upon restoring conditions beyond the WUI.

3.1.2 Increasing carbon storage may not be consistent with achieving other objectives

The modeling results indicated that stocks of carbon would decline with increased treatment. Some of those losses would be recouped over time, as treatments both reduce the expected losses from wildfire and can stimulate greater storage (high rates of sequestration) among the remaining trees. Furthermore, losses may be mitigated by substituting biomass harvest for energy instead of pile burning. However, even over a full century, a suppression-only strategy was projected to sequester the most carbon despite increasing variability in the carbon stocks. The results revealed a tradeoff between carbon storage and potential water yield, as increased tree biomass stored more carbon but reduced available water. The estimated dollar value of additional carbon storage under suppression-only scenario was modest compared to implementation costs, suppression costs, and risks to property. Furthermore, increasing storage of forest ecosystem carbon may not be consistent with forest restoration, since historical forest conditions that existed prior to the era of fire suppression had reduced levels of carbon compared to current conditions. Therefore, continuing to store more forest carbon would seem inconsistent with multiple resilience objectives.

3.1.3 Thinning smaller trees can promote multiple objectives

The landscape simulations found that thinning, which targeted small trees, would promote a variety of landscape objectives, including reduced impacts from large and severe wildfires. These results are consistent with previous landscape modeling in the Lake Tahoe basin (Scheller et al. 2018, Stevens et al. 2016) and science synthesis efforts (Long et al. 2014). This finding is also consistent with the recently developed California Spotted Owl Conservation Strategy, which indicated that reducing small trees is likely to maintain or improve owl habitat in both the short and long term (USDA Forest Service 2019). That strategy was informed by recent research (North et al. 2017) that found California spotted owls avoid areas with dense patches of smaller trees (2-16 m tall). Water quantity modeling indicated that thinning trees up to 20 m (65 ft)[1] tall would increase “net water input,” or the “total water emanating from the snowpack that is available for infiltration and runoff,” with larger increases in dry years and stands with dense growth of small trees (Krogh et al. 2020). The largest increases occurred in dense stands with lots of small trees (especially between 5 and 15 m tall) in lower elevation, south-facing forest stands, which are also likely to be most departed from reference conditions (Krogh et al. 2020).

3.1.4 Limiting treatments to 14” DBH (as in hand thinning) or 24” DBH trees might limit restoration effectiveness in certain conditions

Mechanical thinning may offer several advantages over hand thinning in some areas because removing trees above 14” DBH may help to restore certain ecological conditions, increase economic returns, and reduce the need for pile burning. Diameter-based limits could increasingly constrain structural restoration over time as more trees grow beyond those limits. The landscape modeling allowed for thinning of trees up to 38” DBH under scenario 3; that scenario nevertheless increased the amount of *area occupied* by old trees (because the LANDIS model operates at a landscape scale rather than the scale of individual trees, it does not generate estimates of large trees). The fine-scale aspen modeling illustrated one of the contexts in which removal of large trees might facilitate restoration objectives. That study (Ziegler et al. 2020) found that thinning conifer trees up to 30” DBH would promote more open stand conditions that would support aspen restoration.

3.1.5 Increasing use of prescribed fire was associated with the most favorable results overall

Landscape modeling results suggest that a management strategy would perform well by increasing the use of fire. These findings were consistent with recent research which suggested that restoration of fire as an ecological process is the most efficient means of promoting forest resilience (North et al. 2014) and securing carbon stored in large trees (Hurteau et al. 2019). Several of the advantages to relying on use of fire suggested by the modeling results are listed below:

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[1]Such trees may be up to 16-18 inches in diameter at breast height (DBH), based upon pers. communication from Brian Garrett, Forest Service Lake Tahoe Basin Management Unit, 6/23/2020.

- The field study of actual thinning projects noted that prescribed burning would be important to inhibit the rapid reaccumulation of surface fuels (Low et al. 2021).
- Increased use of fire promoted a more favorable fire regime by reducing high severity fires and increasing low severity fires. Our modeling assumed that prescribed fires would burn at low severity. However, the results also suggested that limiting prescribed fire to only low-severity effects would not approximate the conditions in areas where natural fire regimes have been restored, which is also consistent with other research (Collins and Stephens 2010).
- Conifer forest tended to increase over time, at the expense of shrub-dominated areas, except under scenario 5. Displacement of conifer forest by persistent shrublands due to wildfire and climate change is a broad concern in the Western United States and particularly in the Sierra Nevada (Buotte et al. 2019, Richter et al. 2019). However, those studies indicated that lower-elevation forests, dominated by oaks and ponderosa pine, were most vulnerable. Our modeling indicated that overall shifts from conifer forest to shrublands were not likely for Lake Tahoe West. Furthermore, previous research indicates that shrub-dominated areas in the area have declined from historical references (Nagel and Taylor 2005). The modeling indicated that increased use of prescribed fire would temper further declines in shrubs, while also promoting aspen and yellow pine in ways that are consistent with goals of the Landscape Restoration Strategy. These results highlight one of the important ways in which prescribed burning had different effects than thinning, since burning is applied broadly across the vegetated landscape rather than being confined to forested stands.
- Increased treatments, including thinning and use of prescribed fire, could also benefit cultural resource values important to the Washoe Tribe. Prescribed burning could include “cultural burns” traditionally used by the Tribe to achieve tribally desired conditions. By removing smaller trees, treatments were projected to enhance water yield and promote more open forest structures. More mesic, early seral, and open forest conditions may in turn support many tribally valued understory plants (Long 2019, Long et al. 2018a).
- Prescribed fire is generally less expensive than mechanical thinning; fire-focused scenarios were projected to be cheaper to implement on a per-acre basis.
- By targeting treatments to areas of departure more precisely, management strategies could be more effective than projected in the modeling, and prescribed burns in particular could be located and timed to achieve greater net benefits. Furthermore, the intensity of prescribed burns could be adjusted to achieve different objectives in different areas.

3.2 Opportunities to Mitigate Potentially Unfavorable Impacts

The modeling results identified a few indicators for which increasing treatments, particularly the use of fire, could have some undesirable impacts. Large-scale use of fire is an immediately riskier treatment than thinning, given the potential for fires to burn outside of prescriptions/expected conditions and beyond physical boundaries. The results also suggested that increased burning could impact air quality, water quality, and the areas with large trees more than increased thinning. It will be particularly important to consider use of more intense prescribed burns, which could help restore reference structural conditions (Kane et al. 2019) but could also entail greater near-term risks. These findings highlight potential benefits of active adaptive management to better understand and reflect the likely impacts of such treatments, and potentially to modify implementation over time. Managers would be able to adapt the timing, location, and intensities of fire to mitigate risks for both forests and local communities. The Landscape Resilience Strategy calls for increasing prescribed burning over time and public awareness of its benefits, which could support adaptation and social learning.

3.2.1 Air quality impacts from use of wildland fire

Modeling suggested that there could be impacts even from prescribed burns, especially under unfavorable wind patterns, although these were much lower than from individual wildfires. The landscape modeling indicated that expanded use of prescribed burning under scenario 5 would increase particulate emissions overall, predominantly through frequent, small prescribed burns, compared to infrequent, large emissions from wildfires under the suppression-only scenario 1.

Smoke modeling indicated that extreme wildfire events would have large social impacts; however, the impacts of frequent, small prescribed burns would not necessarily be negligible, especially if weather conditions were not favorable. A recent presentation (Hobbs 2020) reported smoke impacts, including exceedances of regulatory thresholds, from a relatively small (19 acre) understory burn in Lake Tahoe West in November 2019 during a nighttime inversion. Similarly, the 2019 Caples Fire (south of Lake Tahoe West on the Eldorado National Forest) was initiated as a prescribed fire but burned more intensely than planned and impacted air quality in downwind communities. Managed natural ignitions might also be effective, but they also have potential to impact air quality in downwind communities, as documented for a recent managed wildfire in the southern Sierra (Schweizer et al. 2020). Therefore, both modeling results and real-world examples illustrate the challenge that managers will face in ramping up the use of fire.

3.2.2 Feasibility barriers to increased prescribed burning

The extensive prescribed burning under scenario 5 was projected to require around 100 days of intentional burning per year (assuming a daily limit of 180 acres/day) to implement. That level of burning would fully utilize available burn days in the entire Lake Tahoe basin. That result, combined with the need to burn in other parts of the basin and the likelihood that more multi-day burn windows would be needed to burn large areas, suggests that it might be difficult to achieve the level of burning under scenario 5. The lower rate of burning under scenario 4 would be easier to implement. Increasing biomass utilization could also help to reduce the need for pile burning. Although currently pile burning can be done in the winter when weather often limits prescribed burning, given the likelihood of drier conditions in the future, there may be more times when prescribed burning could occur during seasons when piles were customarily burned.

3.2.3 Water quality impacts from prescribed burning

WEPP modeling determined that prescribed burns have higher potential for impact than thinning, but lower impact than wildfires. The initial water quality modeling treated prescribed fires as comparable to low severity wildfires, which contributed to the finding that a fire-focused strategy would increase pollutant loads, albeit by small percentages compared to baseline loads. However, those assumptions were revised to reflect findings that soil cover after prescribed burning in the Lake Tahoe basin has typically remained relatively high and effective in preventing erosion (Harrison et al. 2016). In the revised results, loads under the fire-focused strategies were more comparable to the other strategies, suggesting that modest increases due to treatments would be at least partially offset by reducing the impacts of wildfires. However, if prescribed burning were permitted at more moderate severities, which the Landscape Restoration Strategy does suggest might be warranted, erosion risks could be higher. Furthermore, erosion risks may also be higher than previously observed in wildfires when burns are conducted over larger areas, particularly if they include steeply sloped areas. Careful planning and mitigation measures would be warranted and can be effective in minimizing impacts to water quality in order to facilitate the positive benefits of fire in upland ecosystems, as well as aquatic habitats.

3.2.4 Impacts to large trees and carbon storage over the long run

Modeling results indicated that fire-focused strategies tended to reduce areas with large trees, as well as carbon storage, which may reflect both the long-term effects of culling smaller trees as well as the potential for prescribed fires to kill larger trees. Mortality of larger trees has been reported in field studies of restoration treatments that included mechanical thinning and prescribed burning (Fettig et al. 2010, Fulé et al. 2007, Maloney et al. 2008, Wiechmann et al. 2015). Given this potential for impact, managers may want to consider mitigation techniques to reduce the mortality of highly valued large trees when reintroducing fire to areas without recent burns. Previously suggested approaches include modifying prescriptions in areas with old trees; using spot or ring ignition patterns (Fulé et al. 2007); and raking accumulated fuels away from the bases of particularly vulnerable larger trees, especially when moderate intensity burns are expected (Nesmith et al. 2010), among other practices (Hood 2010).

3.2.5 Pollutant loads from increased use of road networks

The roads analyses indicated that pollutant loads would generally increase as more roads are placed into active use. However, the road network in the Lake Tahoe basin is generally considered to be well maintained; consequently, the overall increase in sediment loading from the forest road system was small compared to the background loads. The analyses did identify potential hotspots where rehabilitation (or closure) of existing or abandoned roads could yield benefits; those would need further evaluation in the context of specific projects to determine if they indeed pose risks or opportunities for improving water quality.

3.3 Management Can Affect Positive Change Despite Future Climate Influences

Forest development, changes in climate, and forest management were all important drivers of change in Lake Tahoe West. For indicators associated with late seral forest and carbon, forest development alone will shift indicators toward more favored conditions. However, climate change is expected to increase wildfires and insect disturbances, while also inhibiting regeneration of some forest species, notably red fir, the predominant subalpine tree species. Despite these trends, management can strongly influence many key factors, particularly the occurrence of extreme wildfires, which threaten life, property and human health. We did not find that certain management scenarios performed better than the others under one climate projection versus another; instead, individual management scenarios had similar relative outcomes when run under multiple climate projections.

There are a couple of caveats to the interpretation that management can affect desired changes in ecosystem conditions. First, there is substantial uncertainty regarding system dynamics under climate change, especially in the latter half of the century. Many forest dynamics, including the relative growth and regeneration of individual species and the incidence of bark beetle epidemics, are sensitive to climate-related assumptions, including the effects of elevated carbon dioxide, which was not included in the model. This does not diminish or strengthen the idea that management can affect positive outcomes for forest ecosystems, but rather that careful tracking of actual events, trends, and responses will be important.

The effects of warming temperatures and shifts from snow to rain were not directly factored into the long-term water quality and quantity modeling. Separate modeling results using the WEPP model indicated that changes in climate will increase pollutant loads as storms become more intense. This finding suggests that we should expect loads from forested areas to increase over time even without changes in forest management and fire regimes. Furthermore, it suggests that the long-term landscape results may overweight the effects of near-term disturbances (especially fuel reduction treatments), relative to the effects of future disturbances (especially wildfires)

Furthermore, direct effects of warming temperatures and reduced snowpack on wildlife were not factored into the modeling. Such effects could alter trajectories for important biodiversity indicators. On the other hand, modeling for spotted owl assumed that its favored habitat would be constrained by elevation. If owls can move upward, then the number of territories could increase as conditions become more favorable at higher elevations. These uncertainties point to the value of effective change monitoring systems so that management can be responsive to events and trends as they unfold.

3.4 Spatial Prioritization Aids Implementation of Strategies

The Landscape Restoration Strategy identified priority areas for treatment based upon results of science modeling and additional considerations. The landscape modeling randomly targeted thinning based upon preset criteria for fuels and stand structure within different management zones, while the prescribed burning was simulated based on relatively random ignitions whose growth depended on fuel availability. In the real world, managers can make treatment decisions based on better, higher resolution knowledge tailored to specific contexts. Consequently, the management strategies evaluated in our analyses could likely achieve more favorable outcomes by targeting specific areas for thinning and burning based upon greatest expected net benefit.

3.4.1 Potential priority areas for treatment

Several of the modeling results can help to identify the potential priority areas for treatment, including:

- WUI areas at high risk of property loss due to high severity fire.
- Areas at high risk of forming unusually large patches of high severity fire (e.g., 40 acres).
- Areas associated with more water yield potential, particularly in stands dominated by young conifers. The hydrology team extended their modeling results to identify areas where forest thinning is likely to have the most positive benefits for water supply across twelve watersheds in Lake Tahoe West (Krogh et al. 2020). They found that differences across watersheds were relatively small, suggesting that it would be most beneficial to target dense stands with young conifers.
- Aspen stands encroached by conifers.

3.4.2 Potentially sensitive areas

Certain parts of the landscape may be sensitive to disturbance, which may require a more careful analysis of the benefits and risks of treatments. For example, modeling indicated that pollutant loads were highest in several watersheds, particularly in the Blackwood and Ward watersheds that have more erodible volcanic soils. Further analysis is underway to evaluate risks and inform treatment strategies in more sensitive, higher-risk areas. Thinning treatments could be conducted in higher erosion risk areas with monitoring in an adaptive management framework to more precisely evaluate net effects in such places. Such an experimental approach may be more appropriate than a simpler avoidance strategy, since there may be opportunities to reduce potential load from such areas. Another possible mitigation strategy would be to prioritize treatments within areas of lower erosion risk that are close to areas of high erosion risk, to lessen the chance of fire reaching those high-risk areas. Similarly, intensive treatment might be particularly appropriate in areas that *surround* areas of high suitability habitat for old forest species that are at risk of stand-replacing fire. Treatments *within* such areas may be guided by careful consideration of net risks and benefits.

3.5 Opportunities for Monitoring to Support Future Science-Based Management

Monitoring various indicators considered in the Lake Tahoe West science effort would help to compare actual outcomes to model projections, to evaluate performance of management strategies and support potential shifts in management, and to enhance capacity for future modeling. The Landscape Restoration Strategy recognizes that modeling is important to inform future management, and the Lake Tahoe West Restoration Partnership has been developing a Monitoring Plan; both efforts explicitly incorporate an adaptive management framework.

Below are many of the indicators for which monitoring could improve our understanding of system dynamics in ways that might improve both modeling and management. The list includes data that were not readily available to inform assumptions in the research led by the Science Team:

3.5.1 Landscape fire regime indicators

Important indicators of fire regime include the frequency, severity, and size of fires, including both wildfires and prescribed fires. These metrics are often interpreted relative to a reference, such as with the Fire Return Interval Departure indicator. However, historical data on fire indicators used in the analyses, including area burned by severity, are not readily available, since they are routinely tracked only for fires greater than 1000 acres in the Monitoring Trends in Burn Severity national interagency program. The California Department of Forestry and Fire Protection's Fire and Resource Assessment Program (FRAP) has a database with perimeters of most fires but not burn severity details. Assessment based upon Google Earth Engine and Landsat data can be used to generate these indicators (Parks et al 2018). Tracking these indicators can address important uncertainty because there have been few large wildfires in the Lake Tahoe basin, yet our modeling and other research suggests that such fires are likely to become more frequent. Important indicators include:

1) Area burned as a percentage of the landscape by severity, ideally for both vegetation and soil burn severity.
2) Area burned in the WUI zones by severity.
3) Area burned in large patches of high severity, particularly relative to thresholds of 40 acres (16 hectares) and 250 acres (100 hectares).
4) Total number of fires by type, e.g., prescribed burns, lightning-ignited wildfires (ideally distinguishing natural ignitions managed for resource objectives), and human-caused wildfires.

Comparing these actual values to the projections would determine whether actual outcomes are beyond the range of variation assumed in the models, as well as whether the projections are over or under projecting actual outcomes. Information is particularly needed to model managed natural ignitions, which are relatively novel in the Lake Tahoe basin.

3.5.2 Ground cover for water quality

Because ground cover is a key determinant of erosion, monitoring residual ground cover could help to refine projected water quality impacts. Both agency staff and researchers have monitored project-level treatments in recent years and found that residual ground covers were generally sufficient to avert erosion. However, other treatments that have not been as widely studied include mechanical treatments and prescribed burns on steep slopes and wildfires managed to achieve resource objectives. Additional project-level monitoring could help to calibrate assumptions used in landscape and project-scale modeling.

Results from longer-term monitoring of fine sediment, phosphorus, and nitrogen could be compared to the combined projections from WEPP and LANDIS. When individual large fires occur, they could be monitored to evaluate more detailed model projections. We took this approach for the Emerald Fire (the first sizeable wildfire within Lake Tahoe West in decades), as managers of road systems estimated the volume of accumulated sediments removed from detention basins and ditches.

3.5.3 Water quantity

The effects of fires on water quantity were not directly examined in the modeling; future research could help evaluate whether effects on forest structure, particularly Leaf-Area-Index, are effective proxies for effects on water yield. The hydrologic modeling noted many simplifying assumptions that need further exploration in order to predict effects on stream flows. Researchers concluded that a combination of continued groundwater monitoring in key locations and an improved groundwater model is needed to better simulate the effects of restoration strategies on water flows.

3.5.4 Air quality and emissions

Tracking emissions from prescribed understory and pile burning in the Prescribed Fire Information Resource System (PFIRS) database on a daily basis would help compare actual emissions to projections, determine relationships between emissions and downwind air quality, and evaluate indicators such as days of burning per year and relative to available burn days. Monitoring the effects of management activities would also depend upon tracking air quality at monitoring sites, especially noting exceedances, complaints from the public, and emissions from both within the Lake Tahoe basin and large out-of-basin wildfire events.

3.5.5 Wildlife

Monitoring the number of occupied territories for California spotted owl, goshawks, and marten would help to evaluate whether trends are moving in ways that are consistent with modeling projections and with management expectations. While the numbers of territories were only specifically projected at 20-year intervals, more frequent monitoring can be evaluated against the trends in the projections. Furthermore, monitoring can help evaluate whether animals are relocating territories into higher elevation habitats, which was a question identified in the research.

3.5.6 Vegetation and ecosystem carbon

Considerable uncertainty in landscape projections stem from assumptions for how forest vegetation responds to climate change, forest densification, and natural disturbances. Actual trends in vegetative composition, in-forest carbon, seral stage, and areas with old/large trees, based upon the combination of remotely sensed (e.g., LiDAR) and Forest Inventory and Analysis (FIA) data could be compared to projections to improve models and identify areas of unexpected change.

Regeneration is a particularly important parameter for modeling forest landscape development for which data tend to be lacking. Consequently, having more data across species, over time, and across space would reduce uncertainties associated with this critical process. Some long-term plots have been established to track regeneration of white pines in the Lake Tahoe basin (Maloney 2014). Repeated sampling of plots like those over time would help to assess how temperature and precipitation may affect regeneration of different species. That in turn could provide indications of whether species like red fir are likely to decline with climate change.

3.5.7 Fuels

Additional field data would help to better quantify the extent to which treatments modify fuel beds; the upland fuels site monitoring (Low et al. 2021) examined changes over a decade due to thinning in conifer stands, but not the effects of understory burning. Aspen stand modeling indicated that fire behavior was affected by changes in fuel beds from conifer-dominated litter to aspen-dominated leaf litter. Within a larger set of nine aspen-conifer study plots, one research effort (Dagley et al. 2020) has been monitoring understory response to thinning and pile burning; data on litter quantity and/or quality from such work could be compared to the model assumptions and used to inform future modeling. It would be useful to evaluate responses in plots that are more heavily thinned as well as areas that receive understory burning. Having data on fuels before and after treatments and actual fires would help to validate predictions of fire behavior and canopy consumption and help managers to design restorative use of fire.

3.5.8 Cultural resources

Because the Washoe Tribe is concerned with a great many species and other cultural values, it is reductive to rely on only a few indicators to evaluate trends in cultural resources. Indicators used in the modeling, including habitat quality for deer, quail, and flicker, could be evaluated based upon relationships to forest vegetation conditions, and aspen could be monitored more directly based upon remote sensing and field monitoring. Some culturally important species could be considered as possible targets for monitoring, especially for species that may inform understanding of climate change, such as Belding’s ground squirrel. It may also be possible to leverage data from plant, mammal, fish, and bird surveys, including citizen science efforts. Quality and quantity of key materials derived from understory plants could be monitored at specific project sites to evaluate responses to treatment. It is important to evaluate outcomes in the context of accessibility for cultural harvest. Tribal engagement can help to prioritize locations for such monitoring.

3.5.9 Wood products and pile burning

Tracking volume of lumber and biomass utilized for energy removed as part of forest treatments, as well as material burned in piles, would help to track carbon pools and to compare actual yields with projections, which could help improve estimates of long-term supplies.

3.5.10 Management costs

Management costs evaluated in the Lake Tahoe West modeling effort could be targets for monitoring and systematic reporting, including staffing to support thinning and burning and suppression costs.

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