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

Evaluating pathways to social and ecological landscape resilience

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ABSTRACT. Rapid environmental changes challenge the resilience of wildlands. The western portion of the Lake Tahoe Basin in California is an important ecological and cultural hotspot that is at risk of degradation from current and future environmental pressures. Historical uses, fire suppression, and a changing climate have created forest landscape conditions at risk of drought stress, destructive fire, and loss of habitat diversity. We prospectively modeled forest landscape conditions for a period of 100 years to evaluate the efficacy of 5 unique management scenarios in achieving desired landscape conditions. Management scenarios ranged from no management other than fire suppression to applying treatments consistent with historical fire frequencies and extent (i.e., regular and broadscale biomass reduction). We developed a decision support tool to evaluate environmental and social outcomes within a single framework to provide a transparent set of costs and benefits. Results illuminated underlying mechanisms of forest resilience and provided actionable guidance to decision makers. Sixteen attributes were assessed in the model after assigning weights to each. We found that removing forest biomass across the landscape, particularly when accomplished using extensive fire-based removal techniques, led to highly favorable conditions for environmental quality and promoted overall landscape resilience. Environmental conditions resulting from extensive fire-based biomass removal also had nominal variation over time, in contrast with strategies that had less extensive and/or used physical removal techniques (e.g., mechanical thinning). Our analysis provides a transparent approach to assess large datasets with complex and interacting variables. Ultimately, we aim to provide insights into the complexities of maintaining optimal conditions and managing landscapes to promote ecosystem resilience in a changing world.

Key Words: *decision support; ecology; forest management; Lake Tahoe; landscape resilience; scenario planning; wildlife conservation*

INTRODUCTION

Alterations to natural systems, ranging from local habitat loss to global changes in climate, have resulted in many sectors of society (government and private) working to understand and mitigate threats to ecological integrity (sensu Cleland et al. 2017) and the persistence of ecosystem function and services (Daily and Matson 2008). The concept of resilience offers a tangible beacon for a future that inevitably will be different, but that can also be ecologically diverse, productive, aesthetic, and meet the needs and desires of society in a sustainable manner. Resilience is the "capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al. 2004). Outcomes are typically evaluated based upon the condition or state of a system as opposed to ecosystem resilience for which the focus is on the response of systems to perturbations as a function of ecosystem processes (e.g., Holling 1973, Folke et al. 2002, Gunderson et al. 2010, Walker and Salt 2010). As such, resilience can only be truly evaluated after perturbations have occurred, the system has responded, and the outcomes are evaluated.

California's Lake Tahoe (and its surrounding basin; Fig. 1) is rich with both ecological (e.g., biodiversity) and social (e.g., aesthetic values, recreational opportunities) facets that are vulnerable to impacts from climate change. A recent vulnerability analysis commissioned by the California Tahoe Conservancy (California Tahoe Conservancy 2020) and supported by empirical studies (e.g., Coats et al. 2006, Scheller et al. 2019) concluded that both the lake and the upland watersheds are not only susceptible to future changing climates but are already exhibiting signs of stress and impact. The future of ecological integrity in the Lake Tahoe Basin is a core concern across a wide array of stakeholders, including scientists and land management agencies (Chilton 1995, Imperial and Kauneckis 2003, Weible et al. 2005).

Sustainability and resilience across multiple social and ecological values were the focus of this study in which we evaluated future ecological trajectories, across a 100-year time span, under different management scenarios in the face of climate change. Specifically, we examined long-term ecological and social effects of forest management activities; management activities that influenced biomass reduction and fire across the landscape. We hypothesized that the extent, type (e.g., prescribed fire, mechanical thinning), and location (e.g., wildland, wildland urban interface) of biomass reduction has impacts on ecological and social metrics over long time horizons. Large-scale ecological assessments have many moving parts that make defining the analytical problem, assembling large volumes of data, and evaluating and distilling results challenging; especially with a great number of relevant variables that interact in complex ways over space and time. We employed decision support tools (DSTs), which are increasingly used to help impart a transparent and synthetic understanding of spatial and temporal variability in conditions across multiple resources. Decision support tools also have great utility when decisions must be made that balance management objectives that are in conflict or difficult to achieve in an equitable manner (e.g., Bagstad et al. 2013, Vacik et al. 2013, Gordon and Reynolds 2014). Finally, DSTs can also provide transparency, credibility, trust, and confidence in the decision-making process (Reynolds and Hessburg 2014).

In past research, DSTs have been frequently used to identify optimal project areas and quantify the relative risks and benefits associated with various treatment approaches (Hessburg et al. 2013, Povak et al. 2017). In this study, we instead focused on identifying the ecological, social, and operational impacts of management activities with the goal of improving forest landscape resilience over a long time horizon. To this end, we modeled 100 years of forest conditions under 5 distinct management regimes (in the form of scenarios) to examine the underpinnings of landscape resilience. Landscape resilience in

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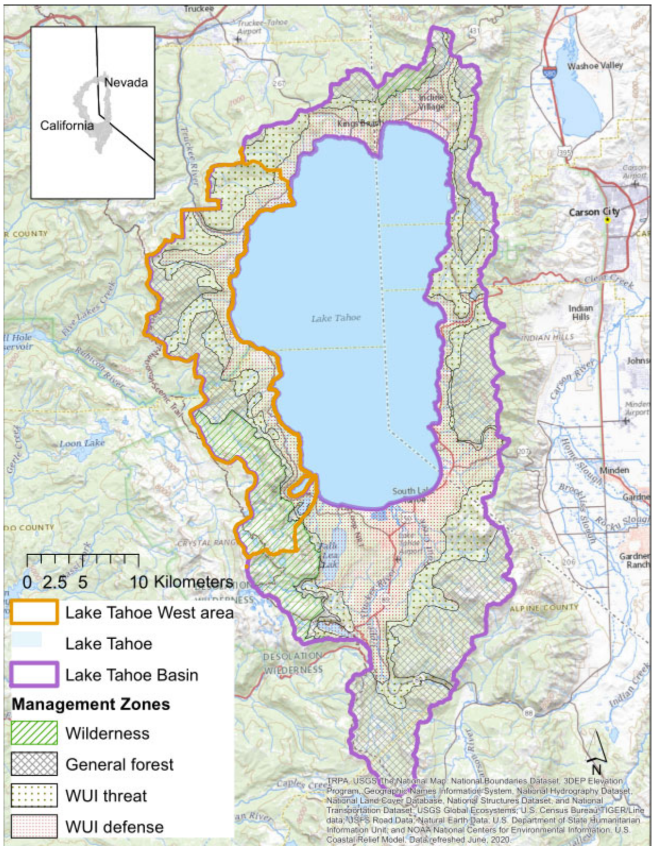
Fig. 1. Lake Tahoe West study area (outlined in orange) within the Lake Tahoe Basin (outlined in purple).



this area impacts forests, watersheds, and communities and, ultimately, we aim to provide insight into enhancing ecological and social conditions in the face of disturbances including wildfire, drought, and climate change.

METHODS

Study area

The Lake Tahoe Basin (Fig. 1) is an 88,000-ha lake basin that rests between the Sierra Nevada Range to the west and the Carson Range to the east and is along the California and Nevada border. Lake Tahoe itself sits at 1880 m in elevation, with the surrounding landscape consisting of over 60 forested watersheds that stretch from the lakeshore up to crests reaching over 3000 m. The landscape consists of extensive forests and many creeks that course through glaciated valleys and wet meadows before draining into the lake.

The forests on the west side of Lake Tahoe (hereafter Lake Tahoe West or LTW) have undergone a high degree of disturbance over the past 100 years. Although they have not experienced the large and severe wildfires that have had an impact on much of the Sierra Nevada Range in recent decades (Lydersen et al. 2014, Jones et al. 2016), there have been 2 fires in the past 15 years: the 2007 Angora Fire that burned over 1200 ha in the southern part of the basin causing enormous loss of property (Safford et al. 2009), and the 2016 Emerald Fire that burned just over 70 ha near Emerald Bay, California. In addition, the basin regularly experiences significant smoke events from fires outside the basin. The basin was extensively logged beginning in the 1860s during the Comstock silver mining rush in Virginia City in Nevada and continuing into the 20th century (Lindström 2000), creating a predominantly single cohort of trees, the survivors of which are greater than 100 years old. In recent decades, management has focused on restoration rather than the production of timber, livestock grazing, and other consumptive uses. The LTW landscape, the focus of this study, consists of 22 watersheds and approximately 23,600 ha of federal, state, local, and private lands on the western side of the basin.

Management scenarios

The project was intended to evaluate ecological and social trade-offs of alternative forest management approaches. Five management scenarios were employed (developed in partnership with local stakeholders) that spanned a range of activities including: (1) no active management aside from wildfire suppression (unrealistic in terms of implementation but useful as a contrast); (2) emphasizing thinning treatments within the wildland urban interface (WUI; the current status quo); (3) dramatically increasing thinning to reduce forest fuels and tree density across the entire landscape, including "back country" forests and designated wilderness areas; and increasing the use of prescribed fire and managed naturally ignited wildfires to (4) modest and (5) high levels (Table 1; North et al. 2021). Yearly landscape percent treated by each scenario (including prescribed fire) are as follows: Scenario 1, 0%; Scenario 2, 2%; Scenario 3, 7%; Scenario 4, 4%; and Scenario 5, 11%.

This approach was designed to illustrate the degree to which increases in the pace and scale of treatment would enhance the resilience of Lake Tahoe's social-ecological system (North et al. 2012, Stephens et al. 2014) while identifying inherent trade-offs associated with management approaches in meeting resource objectives. We developed criteria to evaluate effectiveness of extent, distribution, and type of management treatments for achieving desired conditions (Appendices 1, 2, 3, 4, 5) in collaboration with the Lake Tahoe West Restoration Partnership (LTWRP). The LTWRP is a multi-stakeholder collaborative initiative lead by the California Tahoe Conservancy, U.S. Forest Service Lake Tahoe Basin Management Unit, California State Parks, Tahoe Regional Planning Agency, and the National Forest Foundation. The LTWRP is a science-based management coalition, formed to develop and implement a large-scale landscape restoration strategy across the west side of the Lake Tahoe Basin. Specific criteria and thresholds were developed by members of the LTWRP science team (the scientists that conducted the environmental modeling represented here), managers from multiple agencies operating within the basin, and stakeholders representing a range of interests.

Assessing landscape condition

Resources essential to understanding forest resilience in response to management scenarios were determined by environmental experts, decision makers, and project stakeholders, and included not only resources pertaining to environmental quality (terrestrial and aquatic ecological conditions), but also community values and management operations, which can both drive and limit

Table 1. Management scenarios evaluated using ecosystem management decision support (EMDS) tool for the Lake Tahoe West restoration landscape.

Scenario number	Description	Management specifications
1	Fire suppression only	The only management activity was to suppress fires. No other management activities were implemented in this scenario.
2	Wildland-urban interface focus	Management activities were focused predominantly on forest thinning in the wildland-urban interface (WUI, areas near human habitation). This management strategy was designed to provide a buffer of defensible space around human-built structures and property, with the goal of protecting those properties and their inhabitants. It treated approximately 1.8% of the vegetated area each year, all in the WUI (58% of the landscape). This scenario most closely resembled current management activities in the Lake Tahoe Basin. Fire suppression efforts remain the same as scenario 1.
3	Thinning-based approach	This scenario builds upon scenario 2 by expanding management activities into the remaining forested landscape (42% of the landscape) in proximity to the WUI and used predominantly mechanical and some hand removal methods to thin the forest and reduce woody biomass. It treats approximately 6.7% of the vegetated area each year. Fire suppression efforts remain the same as scenario 1.
4	Fire-based approach	This scenario builds upon scenario 2 by expanding management activities into the remaining forested landscape. Although scenario 3 employs mechanical and hand methods to thin the forest, scenario 4 uses primarily prescribed fire and managed wildfire. This scenario treats approximately 4% of the vegetated area each year. Fire suppression efforts were the same as scenario 1 in WUI areas but natural ignitions were allowed to burn because they advanced resource objectives in the wilderness areas.
5	Extensive fire-based approach	This scenario builds upon scenario 2 by expanding management activities into the remaining forested landscape. Like scenario 4, scenario 5 predominately employs fire-driven techniques, but with a greatly expanded use of prescribed fire. This scenario treats a approximately 7.2% of the vegetated area each year, slightly more than scenario 3, but with the majority of treatments (75%) being fire. Fire suppression efforts were the same as scenario 1 in WUI areas but natural ignitions were allowed to burn because they advanced resource objectives in the wilderness areas.

implementation. For each of three focal areas (environmental quality, community values, and management operations), quantifiable metrics were identified based on available, relevant, and peer-reviewed data sources. The type and number of attributes varied among the three focal areas based on scientific merit (environmental quality), stakeholder priorities (community values), and management considerations (operations). Each focal area is represented by two tiers: topic areas and attributes. A total of 16 attributes were established across the 3 focal areas (Fig. 2).

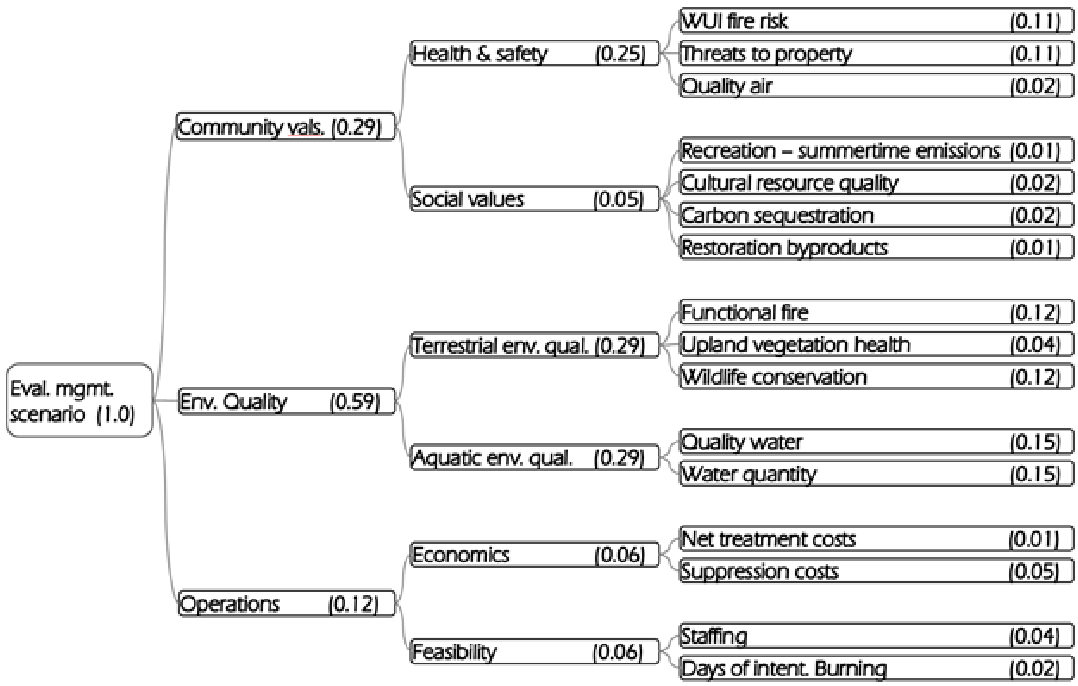
The 16 individual attributes were in turn represented by 1 or more metrics of condition. The number of metrics selected to represent each attribute varied based on the complexity of the attribute (see Miller and Saunders 2002, Saunders and Miller 2014), with those associated with environmental quality having the largest suite of metrics, and those associated with community values and operations typically being represented by single metrics (Appendices 1-3; see Abelson et al. 2021 for detailed methods). For example, the quality water topic was represented by 2 metrics (phosphorus load and fine sediment), whereas biodiversity conservation consisted of 13 metrics including 3 focal species of interest, 6 functional species groups, and 4 measures of species diversity (Appendices 2 and 3). Subject-matter experts (Table 2) identified data that were necessary to evaluate attributes and determined metric values that corresponded with poor to optimal conditions (Appendices 1 and 4). These values were used in the DST to evaluate forest conditions, propagating from the bottom of the hierarchy (attributes) to the top (resilience), for each incoming piece of data (Appendix 5) following methods described in Abelson et al. 2021.

LANDIS-II modeling

LANDIS-II is a forest landscape modeling platform that simulates forest community dynamics and growth through time while subject to disturbances, forest management, and a changing climate. Our analysis used 5 unique management scenarios in the LANDIS-II framework over a 100 year-time period. There is substantial uncertainty in projecting future vegetation conditions and fire dynamics, and complex shifts in forest composition are likely to occur; that said, forest landscape simulation modeling over long time horizons provides insight into the complex dynamics of carbon, forest composition, and other broad-scale landscape change (Scheller and Mladenoff 2007). Although many environmental impact analyses and other management decision-making processes tend to focus on short time horizons, longer term modeling may be important for encouraging considerations of ecological resilience (Schultz et al. 2019).

We generated the initial landscape condition from Forest Inventory and Analysis (FIA) data and from Soil Survey Geographic database (SSURGO; NRCS 2020, USDA 2020). We ran the LANDIS-II model with the Net Ecosystem Carbon and Nitrogen (NECN) Succession extension (v.6.1; Scheller et al. 2011), the Social-Climate Related Pyrogenic Processes and their Landscape Effects (SCRPPLE) fire extension (v.2.1; Scheller et al. 2019) to simulate natural processes and the Biomass Harvest extension (v.2.0) to simulate management activities over a 100-year period (2010 to 2110) across the entire Lake Tahoe Basin landscape (see Maxwell et al. 2022*a*). These extensions interact through their combined effects on vegetation (mortality and regeneration), fuels, and surficial soils. As an example, although prescribed fire and thinning can have similar effects on vegetation, their effects on fine fuels will differ and will consequently effect wildfire spread.

Fig. 2. Decision model hierarchy to address the performance of management scenarios in achieving desired conditions across three focal areas: environmental quality, community values, and management operations. Each focal area is represented by 2 topic areas and each topic is represented by 2 to 4 attributes, for a total of 16 attributes. Parenthetical values indicate weighting derived by stakeholders (rounded to two decimals for display purposes), with assigned weights summing to one for each tier of the hierarchy. Attribute weights propagate up through each level of the hierarchy. Note: WUI = wildland urban interface.



The five unique management scenarios were run into the future using climate data from one global circulation model, i.e., Canadian Earth System Model (CanESM), at one relative concentration pathway (RCP 4.5, which represents a controlled emissions trajectory) then replicated 10 times to capture natural variation across the landscape in response to the scenarios. Replicates within the model are random, though bounded (e.g., when and where ignitions occur throughout the year). Climate projections were available through 2099 (year 89 in models presented) and so climate conditions for model years 90-100 replicated climate conditions from year 89. The results from each set of replicates for each management scenario were then averaged. LANDIS-II model output data are aggregated to annual timesteps, which were then further aggregated to decadal time steps for the purposes of analyses presented.

More details on the LANDIS-II modeling can be found in Maxwell et al. 2022*a*, *b* and the corresponding supplemental information, published in this special issue.

LANDIS-II model parameterization and validation

An array of modeling and field work informs the operation of the core model used in the analysis. Scheller et al. (2007) described early work in development and testing of the LANDIS-II modeling framework in general. Several previous applications of LANDIS-II in the Lake Tahoe Basin described the iterative work used to calibrate and validate the model for Lake Tahoe Basin forests (Loudermilk et al. 2013, 2014, 2017, Kretchun et al. 2016). In this instance, forest productivity was calibrated on remotely sensed data (MODIS 17a3) with net primary productivity for the study area reported as 393 g C/m² (SD = 129), while the modeled net primary productivity was 329 g C/m² (SD = 71). Disturbances were calibrated on recent historical disturbance events (e.g., fires from CalFire's Fire Resource and Perimeter dataset, bark beetle insect outbreaks from the USFS Aerial Detection Survey) and recent harvests within the Lake Tahoe Basin. Mean annual fire area from CalFire data (between 2000-2016) was 122 ha per year (SD = 210), while the model average using climate data from the same range of years was 117 ha per year (SD = 309). Scheller et al. (2019) described development and testing of the LANDIS-II fire module developed to better account for intentional and unintentional fire disturbances considered in this analysis.

Complementary work that informed assumptions in the analysis framework

Field studies within the Sierra Nevada Mountain Range broadly, and in the Lake Tahoe Basin specifically, have demonstrated the effectiveness of thinning and burning treatments in moderating impacts of wildfires through reductions in surface fuels, ladder fuels, and canopy contiguity (Safford et al. 2009, Winford et al. 2015). LANDIS-II modeling indicated that mechanical thinning would moderate fire behavior more effectively than hand thinning, which is limited to smaller trees; this finding was

Table 2. Attributes of the three focal areas evaluated using the ecosystem management decision support (EMDS) tool to determine the degree to which five different management scenarios met desired conditions for the Lake Tahoe West landscape. Note: WUI = wildland urban interface, WEPP = Water Erosion Prediction Project.

Attributes of focal areas	Modeling category description	Data source and derivation
Environmental quality:		
Functional fire	Measures how close to the historical fire regime are fires forecasted to burn at each of three severity classes: low, moderate, and high severity.	Decadal summaries of LANDIS-II fire outputs were used to derive three indicators: fire frequency, patch size of high-severity fire, and extent of fire by severity class. See Maxwell et al. 2022*a*, *b* for more details.
Upland vegetation health	Considers to what extent early, mid, and late seral forests are represented across the landscape compared to modern reference conditions.	Decadal summaries of LANDIS-II biomass by age class outputs were used to derive extent of each of three seral stage classes: early, mid, and late. See Maxwell et al. 2022*b*, White et al. 2022 in this issue for more details.
Wildlife conservation	Represents species richness, biodiversity across multiple functional groups, and the quality and connectivity of old-growth associated species habitat.	Decadal summaries of LANDIS-II biomass by age class outputs were used to derive estimates of suitable habitat for all vertebrates in the study area. Habitat defined by vegetation type, canopy cover, and average diameter (Mayer and Laudenslayer 1988; see White et al. 2022 and Slauson et al. 2022 in this issue for more details).
Quality water	Represents fine sediment and nutrient loading to streams and lakes compared to baseline conditions.	Decadal summaries of LANDIS-II ground disturbance by type were used to derive estimates of sediment and nutrient loading using Watershed Erosion Prediction Project (WEPP) models (Conroy et al. 2006) calibrated for the study area (see Dobre et al. 2022 in this issue for more details).
Water quantity and timing	A qualitative measure of increased water yield and delayed runoff to downstream water bodies and meadows.	Decadal summaries of LANDIS-II leaf area index outputs were used as an inverse proxy for water yield based upon hydrologic modeling by Krogh et al. 2020.
Community values:		
Fire risk to property	Measured by the value of properties threatened by predicted wildfires.	Decadal summaries of LANDIS-II fire severity outputs in the wildand urban interface (2.4 km from infrastructure) were used to derive values of threat to properties in the WUI (see Evans et al. 2022 in this issue for more details).
Wildland urban interface fire risk	The percent of forest in areas, near communities, at risk of burning at high severity.	Decadal summaries of LANDIS-II fire severity outputs in the wildland urban interface (2.4 km from infrastructure) were used to derive values of area burned.
Quality air	Smoke impact represented quantitatively by the number of days per decade sorted and weighted into high, very high, and extreme levels.	Decadal summaries of LANDIS-II daily emissions outputs sorted and weighted by high (60-200 Mg/day), very high (200-500 Mg/day), and extreme (> 500 Mg/day) emission levels (see Long et al. in press).
Carbon sequestration	Represents emissions with global warming implications including carbon stored in the entire system (in-forest and harvested wood products).	Decadal summaries of LANDIS-II net carbon sequestration values were used to represent carbon sequestration over time. Carbon sequestration rates from LANDIS-II based on live, dead, and soil carbon gains and losses. See Maxwell et al. 2022*b* in this issue for details.
Restoration byproduct	Indicates the predicted amount of biomass and wood product utilization resulting from a management scenario.	Decadal summaries of LANDIS-II woody material yield estimates were used to derive volumes of biomass and saw logs. See Evans et al. 2022 in this issue for details.
Cultural resource quality	Evaluated through a synthesis of indicators important to the Washoe Tribe, including predicted amounts of low-intensity fire, habitat for culturally important terrestrial species (e.g., deer, flicker, mountain quail, and aspen), and beneficial water flows to meadows and water bodies.	Decadal summaries of LANDIS-II wildlife habitat, fire, and water yield estimates used to derive indicators of cultural resource conditions (see information on individual resource derivations for more detail).
Recreation quality (summertime air quality)	Represented by summertime smoke impact (in terms of fine particulate matter or PM 2.5) sorted into high, very high, and extreme levels during the peak summer recreation season (June 1-September 15) because smoke episodes greatly limit outdoor activities.	Decadal summaries of LANDIS-II daily summertime emissions outputs sorted and high (60-200 Mg/day), very high (200-500 Mg/day), and extreme (> 500 Mg/day) emission levels (see Long et al. in press).
Management operations:		
Net treatment cost	Consists of cost of treatments (thinning and prescribed burning) less value of products removed.	Decadal summaries of LANDIS-II wood product outputs were used to derive yields for biomass and saw logs for which market values were estimated, along with removal costs, to derive net revenue estimates (see Holland et al. in press).
Suppression cost	All costs related to suppressing wildland fires.	Decadal summaries of LANDIS-II outputs of hectares of fires suppressed were used to derive suppression costs (see Holland et al. in press).
Staffing	Represents the number of agency personnel required to implement forest management projects.	Decadal summaries of LANDIS-II management activity outputs were used to estimate staffing needs by local managers.
Days of intentional burning	The number of days of prescribed fire or pile burning.	Decadal summaries of LANDIS-II prescribed fire burn days were used to derive burn day values.

consistent with findings from a study of the Angora Fire (located to the southeast of LTW; Safford et al. 2009). The Emerald Fire of 2016, 71 ha, was the largest fire for many decades within the LTW study area; a relative lack of historic wildfire and large prescribed burns within the basin provided limited historical data to validate some aspects of our fire models. However, a study conducted during (but completed after) our modeling by Low et al. (2021) found that treatments were associated with significantly lower coarse woody fuels and snag basal area even after 10 years; however, lower levels of fine fuels were not evidently maintained, which Low et al. suggested signals a need for prescribed understory burning. Effects of prescribed fire are not well defined for several reasons; first, they have not been studied as extensively as forest thinning treatments; second, many prescribed burns in the Lake Tahoe Basin have been managed as very low-severity "creep" away from piles rather than prescribed burns designed to restore reference tree densities by killing small-to-moderate sized trees; and third, the effects of repeated prescribed burns are likely to deviate from initial burns (Levine et al. 2020). Consequently, the long-term effects of restoring extensive, frequent prescribed burning regimes in similar vegetation types are understudied, with inferences drawn from systems such as the Illilouette Basin in Yosemite National Park where reduced suppression of wildfires has reestablished a more frequent fire regime (Boisramé et al. 2017, 2019). Those studies found that restoration of fire regimes decreased conifer area while increasing area of meadow and shrub areas (Boisramé et al. 2017) and likely increased downstream water availability (Boisramé et al. 2019). The effectiveness of treatments in moderating wildfires and resulting shifts in vegetation have been demonstrated in field studies (Manley et al. 2012) and non-LANDIS-based modeling efforts in the basin (Stevens et al. 2016) and in other nearby landscapes (Chiono et al. 2017). All of these effects were consistent with the results of the LANDIS-II modeling, although quantitative validation of model predictions will likely depend on long-term adaptive management that includes monitoring of landscape responses to treatments (Keitt and Abelson 2021).

Field research supported development of the hydrologic indicators examined in this modeling framework. A team of researchers evaluated effects of treatments to remove small trees on water quantity (Harpold et al. 2020, Harpold and Rajagopal 2020, Krogh et al. 2020), and their findings identified using leaf area index as a key indicator for the DST. For water quality, a recent study (Cao et al. 2021) determined that the Water Erosion Prediction Project (WEPP) model (USDA-ARS 2020), which was used in our analysis, performed well in simulating the actual sediment loads from the Emerald Fire. Meanwhile, additional field and modeling research within LTW found that mastication and prescribed burning were effective in reducing fuel loading while avoiding soil erosion, and that WEPP predictions were especially robust when erosion potential was high (Barnes and Harrison 1982, Harrison 2012, Harrison et al. 2016).

Environmental quality, community values, and operational dynamics

After forest conditions were modeled for each of the five management scenarios using LANDIS-II, resulting outputs were used by topic-area specialists to quantify the metrics used to represent each of the 16 attributes in our DST to evaluate scenario performance. Methods used, and related references, to inform each attribute are available in Table 2.

Decision support tool development

The DST we used was developed as detailed in Abelson et al. 2021. We substantively expanded the DST model presented in Abelson et al. 2021 beyond the environmental quality focal area to also include community values and operational focal areas (Fig. 2). Our DST was implemented using software components of the Ecosystem Management Decision Support tool (EMDS; Reynolds and Hessburg 2014). We used a multi-criteria decision model (MCDM; Kamenetsky 1982, Saaty 1994, Mendoza and Martins 2006, Murphy 2014) to evaluate the performance of 5 management scenarios (Table 1) in terms of desired condition outcomes established for the 16 attributes associated with the 3 focal areas (Fig. 2; Appendix 1). Data resulting from LANDIS-II modeling (Appendix 5) were either processed (e.g., calculating percent of landscape from hectares) and entered directly into the MCDM (Appendix 1) or were pre-processed by NetWeaver logic modeling software (Appendices 2-4; Miller and Saunders 2002, Saunders and Miller 2014) before inclusion in the MCDM (Abelson et al. 2021). We used the Criterium DecisionPlus software (CDP; Murphy 2014) to develop our MCDM and calculate scenario performance scores (Appendix 1; Abelson et al. 2021).

Criterion weights in the decision hierarchy were derived using Saaty's (1994) pairwise comparison methods in the Analytic Hierarchy Process (AHP) tool implemented in CDP. Using moderated discussion groups, we convened a group of 24 stakeholders to derive pairwise weighting of the 16 attributes (Fig. 2) in our DST (Abelson et al. 2021); ultimately, the weight of an observed value for each attribute indicates the degree to which that value contributes to the model's overall performance score (Fig. 2). Weights in the MCDM are calculated on a scale of 0 to 1, and sum to 1 at each level of the hierarchy, starting with the 16 attributes (Fig. 2). The Lake Tahoe West collaborative was established to guide watershed and forest restoration approaches on the west shore over the next two decades to increase social-ecological resilience (National Forest Foundation 2019). Although wildfire risk reduction to communities was an important goal, other socioeconomic factors were weighted less heavily by stakeholders than environmental quality. These priorities reflect the status of the Lake Tahoe Basin Management Unit as a "restoration forest" in which timber production and livestock grazing have been eliminated as management goals, the status of Lake Tahoe itself as an "outstanding natural resource water" under the Clean Water Act, and the fact that economic activities center on outdoor recreation. These priorities are reflected in the DST weightings with the environmental quality focal area being weighted most heavily at 59% of the evaluation. In contrast, community values carried 29% and operations carried 12% of the weight in the evaluation.

Scenario performance scores

Multi-criteria decision model performance scores were derived by evaluating conditions for the 16 attributes for each the 5 alternative scenarios at each of 10 time-steps; these results were then plotted and summarized. The overall performance score of each scenario was calculated in CDP as the sum of products of the attribute weights (range = 0 to 1) and their utility scores (range = 0 to 1), which then carried through each level of hierarchy such that performance can be evaluated at any level.

Performance scores range from 0 to 1; a score equal to 1 indicates optimal conditions that perfectly meet the target desired conditions, whereas a score of 0 indicates suboptimal conditions with the greatest deviation from target desired conditions. We divided the range of performance score values (i.e., 0 to 1) into five intervals of 0.2 to aid in the interpretation of differences in performance among scenarios (Table 3). We used both quantitative and qualitative approaches to compare the performance of scenarios with respect to maintaining or achieving desired conditions. Quantitative metrics included the mean, standard deviation, range (i.e., minimum and maximum values) in performance scores for any given level of the hierarchy, as well as the number of decades above a specified threshold (i.e., 0.8 or 0.6). Standard deviation and range can be informative to decision makers because predictability may be of utmost importance in some situations (e.g., it may be preferable to have a scenario that, on average, slightly underperforms over the full time horizon but does not have large year-to-year swings in forest condition). Qualitative metrics rank and compare scenarios regarding their relative performance compared to other management scenarios, both at any given time point and across a given time range.

Table 3. Decision model outputs (range from 0 to 1) interpreted in terms of performance scores and associated condition classes in the evaluation of management scenarios in the Lake Tahoe West landscape restoration project.

Performance score	Condition class
0.8 - 1.0	Optimal
0.6 - 0.8	Good
0.4 - 0.6	Marginal
0.2 - 0.4	Suboptimal
0.0 - 0.2	Poor

Sensitivity analysis

Criterium DecisionPlus models output sensitivity statistics (originally described for AHP models by Saaty 1994). In the case of our CDP modeling, the sensitivity analysis was repeated at each 10-year time step to assess model sensitivity over the 100-year period for each management scenario. The key metric produced by the sensitivity analysis is "criticality," which is the absolute percent change in a criterion weight that would cause the top-rated scenario in our analysis results to be replaced by another scenario. Criterium DecisionPlus output, like most commercial MCDMs that implement the AHP, provides a criticality score for all attributes. The criticality score is a measure of model sensitivity in that it is a metric describing how sensitive the model is to attribute weighting; low values of criticality indicate high model sensitivity to the associated attribute, and, conversely, high criticality values indicate relative model robustness (e.g., insensitivity). A simple way to assess model robustness is to examine the criticality value of the most sensitive attribute. The long-standing and well-accepted heuristic for judging robustness was proposed by Saaty (1994) as a criticality value of at least 10% for the most sensitive criterion. We follow this convention in assessing the robustness of our CDP models in the results.

RESULTS

Overall scenario performance

Relatively speaking, Scenario 5 (extensive fire-based approach; Table 1) outperformed all other scenarios, whereas Scenarios 1 and 2 consistently underperformed (Fig. 3; Appendix 6). Overall, the five scenarios formed three clusters: Scenario 1 (fire suppression only) and Scenario 2 (wildland-urban interface focus) had the lowest performance scores that trended together over time. Scenario 3 (thinning-based approach) and Scenario 4 (fire-based approach) trended together with moderate performance scores, whereas Scenario 5 consistently stood alone with the highest performance values.

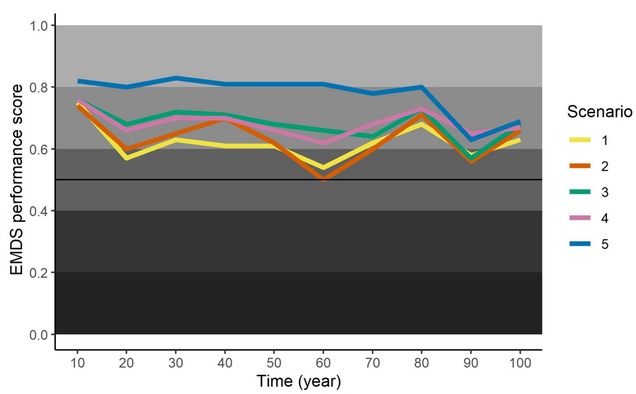
Mean performance of scenarios

Scenario 5 was the best performing scenario based on the mean performance score (mean = 0.78, SD = 0.07), indicating nearly optimal performance across the 100-year period (Fig. 3; Appendix 6). The remaining scenarios, in descending order of performance, were Scenario 3 and Scenario 4, both with mean performance scores of 0.68 (SD = 0.05, SD = 0.04, respectively), followed by Scenario 2 with a mean value of 0.63 (SD = 0.07) and Scenario 1 with a mean value of 0.62 (SD = 0.06). The standard deviation of these estimates indicates that Scenarios 1-4 were not well differentiated in their performance.

Year-to-year variation in scenario performance

In general, year-to-year variation within scenarios was low (Fig. 3), with standard deviations being ≤ 10% of mean values. Scenario 5 appeared to have the highest year-to-year variation (SD = 0.065) with this relatively high level of variation being driven by an

Fig. 3. Performance of 5 management scenarios (S1-S5) in terms of meeting overall desired conditions over a 100-year time period (2010-2110) on the west side of the Lake Tahoe Basin. Scenarios are arrayed from minimal management investment (S1) to landscape-wide management using thinning (S3) or fire (S4 and S5). Scenarios with performance scores closer to one indicate that optimal conditions resulted from management, whereas performance scores near zero indicate poor conditions resulted. Background shading corresponds with 0.2 intervals as outlined in Table 3 with the black horizontal line at 0.5. Note: EMDS = ecosystem management decision support tool.



observed decline in conditions the final decade of the 100-year modeling period; however, specific results at the end of multiple decades of modeling forest dynamics are less informative than trends over the course of time. Examining scenarios from years 0-80 would result in Scenario 5 having the lowest variability. Across the full century, Scenario 4 (SD = 0.039) shows a relatively minimal level of between decade variability. Scenarios 3 and 1 had intermediate standard deviation values of 0.053 and 0.059, respectively. Scenario 2 had the largest standard deviation value of 0.074.

Residency time in condition classes

Another facet of performance is the amount of time that conditions meet or approach desired target conditions, particularly when desired conditions are expected to be most resilient to disturbance. In general, residency times in good and optimal conditions were greater with increased management and increased use of fire (Fig. 3). Scenario 5 (extensive use of fire) had the greatest number of decades in optimal (n = 7) and good (n = 3) conditions over the 100-year period evaluated. Scenario 4 (use of fire) had the next highest residency times associated with desired conditions, with no decades in the optimal condition but all 10 decades in the good condition. Scenario 3 (primarily thinning) performed almost as well as Scenario 4, with all but one decade resulting in good conditions. Scenarios 1 and 2 performed the worst by this measure: Scenario 2 had eight decades in the good range and two in the marginal range, whereas Scenario 1 had seven decades in the good range and three in the marginal range.

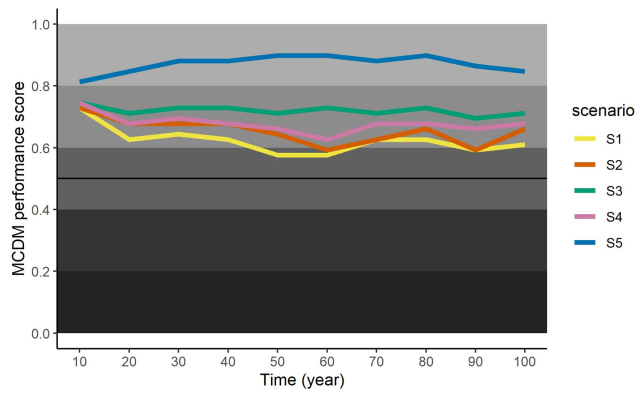
Focal area outcomes and contributions to scenario performance

Scenario performance was a function of the performance of the three focal areas (environmental quality, community values, and management operations) and their relative weights; understanding focal area performance can provide a deeper understanding of a system's response to perturbation. For example, the same mean performance score of "good" could result from two very different landscape conditions: (1) all three focal areas are in good condition or (2) one focal area is in poor condition and the other two are in optimal condition. We delve into how individual focal area conditions contributed to the observed overall performance of each scenario.

Environmental quality

Environmental quality was the primary objective of the Lake Tahoe West project, and consequently, it was weighted (and contributed) the most (59%) to overall scenario performance (Fig. 2). With regard to environmental quality, Scenario 5 (extensive fire) outperformed all other scenarios with little variation between decades (Fig. 4; Appendix 6). Environmental quality remained within an optimal range under management Scenario 5 over the entire century with nominal variation (mean = 0.87, SD = 0.028). Scenario 3 produced performance scores with a mean value of 0.72 (SD = 0.014), and Scenario 4 performed slightly worse with a mean value of 0.68 (SD = 0.030), reflecting their associated intermediate management inputs. Scenarios 1 and 2 (limited management) performed the worst but were still in the good range (mean = 0.65, SD = 0.042 and mean = 0.62, SD = 0.044, respectively), with higher between-decade variability (periodic drops into the marginal condition range).

Fig. 4. Performance of 5 management scenarios (S1-S5) in terms of meeting desired environmental quality outcomes over a 100-year time period (2010-2110) on the west side of the Lake Tahoe Basin. Scenarios are arrayed from minimal management investment (S1) to landscape-wide management using thinning (S3) or fire (S4 and S5). Scenarios with performance scores closer to one indicate that optimal conditions resulted from management, whereas performance scores near zero indicate poor conditions resulted. Background shading corresponds with 0.2 intervals as outlined in Table 3 with the black horizontal line at 0.5. Note: MCDM = multi-criteria decision model.



In terms of scenario performance, terrestrial conditions started and remained good to optimal over the course of the century (min = 0.69, max = 0.93), regardless of management scenario (min mean = 0.74, max mean = 0.89). Differences in terrestrial conditions were largely driven by functional fire, which was the only one of the three attributes that varied in condition class over time (min = 0.52, max = 0.93), and varied by management scenario (min mean = 0.66 for Scenario 1, max mean = 0.88 for Scenario 5). Aquatic conditions varied slightly more over the course of the century from mediocre to optimal (min = 0.45, max = 0.93), and similarly by management scenario (min mean = 0.53 for Scenario 1, max mean = 0.88 for Scenario 5). Within aquatic conditions, water quality was uniformly optimal, whereas water quantity was much more variable, ranging from poor to optimal (min = < 0.01, max = 1), and driven strongly by management scenario (mean = 0.13 for Scenario 1, max mean = 0.88 for Scenario 5).

Community values

Overall, the more management intensive scenarios (Scenarios 3, 4, and 5) performed well (Appendix 6), resulting in generally good conditions over most of the entire century (Fig. 5). Scenario 3 performed the best (mean = 0.69, SD = 0.10), followed closely by Scenario 5 (mean = 0.68, SD = 0.18) and Scenario 4 (mean = 0.67, SD = 0.07). The variation within scenarios was high, making the performance of these top three scenarios indistinguishable. Scenarios 1 and 2 were more variable, which resulted in mediocre overall performance (mean = 0.57, SD = 0.15, and mean = 0.53, SD = 0.11, respectively). Again, variation in performance within these two scenarios was high, obscuring differences in their performance.

Fig. 5. Performance of 5 management scenarios (S1-S5) in terms of meeting desired community values outcomes over a 100-year time period (2010-2110) on the west side of the Lake Tahoe Basin. Scenarios are arrayed from minimal management investment (S1) to landscape-wide management using thinning (S3) or fire (S4 and S5). Scenarios with performance scores closer to one indicate that optimal conditions resulted from management, whereas performance scores near zero indicate poor conditions resulted. Background shading corresponds with 0.2 intervals as outlined in Table 3 with the black horizontal line at 0.5. Note: MCDM = multi-criteria decision model.

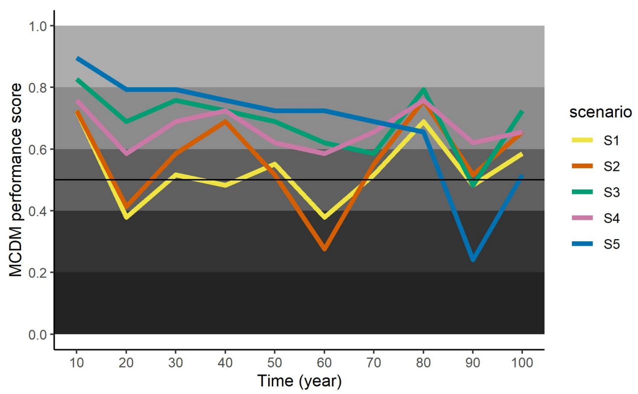
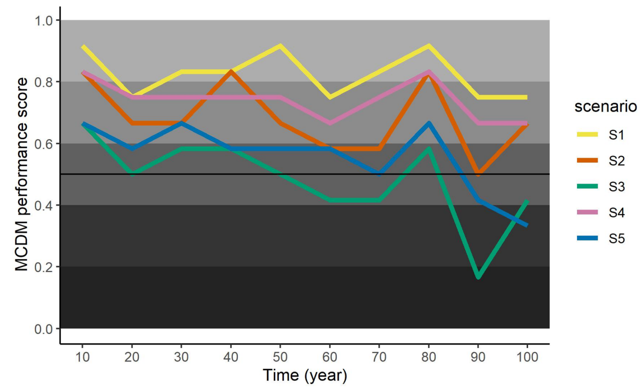


Fig. 6. Performance of 5 management scenarios (S1-S5) in terms of meeting desired management operations outcomes over a 100-year time period (2010-2110) on the west side of the Lake Tahoe Basin. Scenarios are arrayed from minimal management investment (S1) to landscape-wide management using thinning (S3) or fire (S4 and S5). Scenarios with performance scores closer to one indicate that optimal conditions resulted from management, whereas performance scores near zero indicate poor conditions resulted. Background shading corresponds with 0.2 intervals as outlined in Table 3 with the black horizontal line at 0.5. Note: MCDM = multi-criteria decision model.



Regarding cultural resource quality, Scenario 5 resulted in good performance (mean = 0.64) compared to poor to suboptimal performance for all the other scenarios. Wildland-urban interface (WUI) fire risk varied widely from poor (min = 0) to optimal (max = 0.97) over time and varied among scenarios although generally declined over time across all scenarios (min mean = 0.26 for Scenario 1, max mean = 0.55 for Scenario 5) indicating a strong influence of climate on fire risk in the WUI. Risks to property varied over time from suboptimal to optimal (min = 0.33, max = 1.0), but retained mean performance values of optimal across all scenarios (min mean = 0.87, max mean = 0.97), indicating that realized risk to property is episodic in the form of infrequent but high impact events.

Management operations

The focal area addressing operational aspects exhibited unique and somewhat opposing scenario performance relative to the other two focal areas (Fig. 6, Appendix 6). Generally, management operations focal area performance declined with greater management input, primarily reflecting the cost of management. Mean scenario performance in the operations focal area was led by Scenario 1 with an optimal performance score of 0.83 (SD = 0.07), in contrast to community values and environmental quality focal areas, whereas Scenario 1 performed the worst or second worst of all the scenarios. The remaining scenarios generally followed degree of management input: Scenarios 4 and 2 with good performance (mean = 0.74, SD = 0.06, mean = 0.68, SD = 0.12), followed by Scenario 5 with marginal performance and high variability (and mean = 0.56, SD = 0.11, respectively), and finally Scenario 3 with suboptimal performance and high variability (mean = 0.48, SD = 0.14).

The economic topic area performance varied widely from poor (min = 0) to optimal (max = 0.83) but varied less among scenarios from marginal to barely optimal (min mean = 0.53 for Scenario 3, max mean = 0.82 for Scenario 4). Suppression cost performance also varied widely over time (min = 0, max = 0.98) and by scenario from marginal to barely optimal (min mean = 0.62 for Scenario 2, max mean = 0.82 for Scenario 4). Interestingly, if net treatment costs (cost of removing material minus its market value) had been weighted more heavily, it would have been one of the few instances in which Scenario 3 performed poorly, and the lowest ranked among all the scenarios (other than no management) with a mean score of 0.19. The remaining three scenarios were rated as good and were nearly identical in their mean performance scores (Scenario 2 = 0.71, Scenario 4 = 0.76, Scenario 5 = 0.60). Finally, feasibility varied widely from suboptimal (min = 0.33) to optimal (max = 1) and among scenarios (min mean = 0.35 for Scenario 5, max mean = 1.0 for Scenario 1). Within feasibility, staffing varied to a degree over time, ranging from suboptimal (min = 0.29) to marginal (max = 0.69), and it ranged more widely among scenarios from suboptimal (min mean = 0.36 for Scenario 3) to good (max mean = 0.72 for Scenario 4), which is not surprising given that management investments were held fairly constant over time within scenarios.

Robustness of the decision model

We summarize the sensitivity analyses of the MCDM model results by the 10 time steps (Table 4). Consistent with earlier results (Fig. 3), Scenario 5 was the top-ranked scenario of the five management scenarios across all time steps except year 90, at which point Scenario 4 was the highest ranked scenario. Criticality values exceeded Saaty's (1994) 10% threshold heuristic for years

Table 4. Summary of sensitivity analyses calculated by Criterium DecisionPlus (CDP) for each of 10 decadal time steps of the 100-year period modeled.

Time step[†]	Top rated Scenario	Most sensitive focal area	Weight[‡]	Criticality[§]	Usurping scenario
10	5	Operations	0.12	16.78	1
20	5	Operations	0.12	40.62	4
30	5	Operations	0.12	40.26	1
40	5	Operations	0.12	26.89	2
50	5	Operations	0.12	32.83	1
60	5	Operations	0.12	50.25	1
70	5	Operations	0.12	27.47	4
80	5	Env quality	0.59	21.28	4
90	4	Env quality	0.59	1.15	5
100	5	Operations	0.12	1.21	4

[†]The CDP model was run at each time step, comparing performance of the five scenarios at each step.
[‡]Weight of the most sensitive criterion in the decision model.
[§]Criticality is the absolute percent change in weight on the most sensitive focal area in the decision model that would cause the top rated scenario to be replaced by an alternative (usurping) scenario.

10 through 80, indicating a high degree of confidence in identifying Scenario 5 as the best performing scenario up through year 80. At years 90 and 100, the criticality statistic dropped to nearly 1%, indicating that a change in weight of the most sensitive focal area could readily shift away from Scenario 5 being the best performing scenario later in the century, when conditions become more variable. Management operations was the most sensitive focal area for most of the century (Table 4), meaning a sufficiently large change in its weight would cause Scenario 5 to be replaced as the top ranked alternative in years 10 through 80 by another scenario for a given decade (Table 4); however, as already noted, the criticality results for years 10 through 80 indicate a robust model with Scenario 5 ranked highest in performance in this period. In contrast, in years 90 and 100, the criticality scores indicate that we could not practically distinguish between Scenarios 4 and 5 as the top ranked alternative.

DISCUSSION

Landscape-wide management is important

Our analysis showed that increasing the extent of management across the landscape maximized desired outcomes (Fig. 3). Despite a changing climate, modeled forest landscape conditions benefitted from management activities that reduce woody biomass through thinning and intentional fire. We found substantive differences among the five modeled management strategies in terms of their influence on landscape conditions and environmental quality over the course of the 21st century. Performance closely followed the extent of management across the landscape, i.e., the greater the number of hectares treated, the more positive the outcome for environmental quality.

In Lake Tahoe, as throughout California and the western U.S., the threat of wildfire to forests, property, and people has become a primary driver in forest management, with the primary objective being to reduce the probability that large, high-severity fires will occur (Hessburg et al. 2016). Our results showed that forest management treatments consisting of thinning and/or prescribed fire were effective at reducing the risk and probability of significant and destructive wildfires.

Scenarios 1 and 2 were more variable; perhaps because extreme wildfires in one period may inhibit the incidence of fire in the same area for many years; on the other hand, more dispersed treatments and moderate fires may encourage more moderate but more continuous disturbances over time (e.g., Scholl and Taylor 2010, Perry et al. 2011). The moderating effects of increased treatment are consistent with the expectations from previous synthesis work (e.g., Long et al. 2014) and from other landscape modeling in the region (e.g., Krofcheck et al. 2017). The finding that concentrating treatments in smaller areas, such as the WUI, could yield some benefits (such as the risk of property damage in developed areas), but risk losses (e.g., mortality of old trees) in untreated areas was consistent with previous research (Ager et al. 2010, 2013).

The two most aggressive treatment scenarios, Scenarios 3 and 5, treated roughly 50-70% of the forested landscape per decade (locations can be treated more than once per decade), which equates to a 20-year disturbance frequency. This is consistent with historic fire return intervals. Previous research has suggested that gains in performance in some metrics, such as fire and carbon outcomes, can be achieved by targeting treatments to the areas at greatest risk of high-severity fire (Krofcheck et al. 2017, Stevens et al. 2017). Prior research, focused predominantly on high-severity wildfire, has also found that treating large landscape areas mitigates impacts of severe wildfires (Moghaddas et al. 2010). Stevens et al. (2016) conducted a study in the northern portion of the LTW landscape, and although they used a different fire and vegetation modeling framework and did not incorporate climate change, they found that increased management treatment had beneficial effects by reducing the prevalence of high-severity wildfire.

Although we find substantive differences in overall performance (i.e., absolute value) between management scenarios, performance variability within any given scenario for environmental quality (Fig. 4) was low over the 100-year period. Performance in the community values focal area, unlike environmental quality, was such that there is considerably more year-to-year variation and performance was not synchronous among scenarios (Fig. 5; Appendix 6). The best performing scenario, regarding the community values focal area, in any given decade shifted frequently over time; this temporal variability in performance suggests that community values (as defined in this project) are more vulnerable to modeled conditions created by dynamic processes and stochastic events rather than purely management (as environmental quality performance indicates).

Performance of landscape fire as a management tool

One of the most important results of this analysis was that expanded use of managed fire to reduce forest biomass (i.e., Scenario 5) was consistently superior to other management approaches in achieving and maintaining optimal desired conditions (Fig. 3). In addition to reflecting the ecological benefits of fire, as reported by others (e.g., Agee and Skinner 2005, North et al. 2021), the strong performance of Scenario 5 was bolstered by the emphasis (i.e., weights) that was put on the importance of increasing functional fire and reducing the risk of large, high-severity fires (particularly in the WUI) while placing relatively low emphasis on the cost and logistics of treatments (e.g., restrictions on when burning is permitted; e.g., Kolden 2019). Stability did not explicitly alter performance scores of management strategies directly. However, some ecological processes (e.g., persistence of species at risk of local extirpation), and aspects of social well-being (e.g., consistent air quality versus periodic and significant periods of heavy smoke) may depend on maintaining relatively stable system conditions (Angeler and Allen 2016, sensu Johnstone et al. 2016). Variation over time reflects uncertainty in management outcomes, so lower year-to-year variation is most often preferable. We found that scenarios that treated smaller proportions of the landscape per year and treatments that limited management to areas concentrated around the WUI showed greater variability in landscape conditions over time. Consistent with other studies (e.g., Maxwell et al. 2020), this outcome appeared to be a function of the increased probability of large and high-severity wildfires that accompany limiting management to relatively small proportions of the landscape. Widespread frequent low- to moderate-severity fire is particularly effective in reducing the risk of future high-severity fires (Omi and Martinson 2004, Arkle et al. 2012); correspondingly, scenarios that extensively used prescribed burning (Scenario 5 in this study) performed well in terms of achieving desired conditions, as well as producing stable and reliable condition outcomes (i.e., low variability over time with more robust model performance) within the majority of the modeled century.

Fire as a management tool comes with trade-offs. Prescribed fire results in smoke emissions; although air pollution in the form of smoke is a serious social concern, it is often less impactful than severe wildfire. Our modeling also indicated that use of fire was less expensive than thinning. As a result, shifting toward intentional fire can result in net social benefits (Schweizer and Cisneros 2016, Long et al. 2018). Challenges with using prescribed fire include not having sufficient allowable burn days (based on suitable weather conditions and air quality) and adequate staffing to accomplish the work, both of which are commonly limiting factors in implementation (Ryan et al. 2013). These results suggest that with sufficient social license and commitment of resources, environmental outcomes can be optimized through the use of extensive fire as a management tool and these data may, in turn, help agencies and communities rally to overcome the social barriers to its implementation (McCaffrey et al. 2013).

End of century variability and uncertainty

Although ecological inertia, over long time horizons may result in vegetation changes not accounted for in our modeling, the value in longer-term modeling is to identify trends, thresholds, and trade-offs (Kim et al. 2017). Additionally, large timeframes are likely to be of great importance when considering landscape resilience. We modeled a 100-year period to explore trends and variability within and among management scenarios because many landscape-level dynamics emerge over long time horizons (e.g., carbon flux, effects of a changing climate). Although previous work in the LTW region focused on understanding forest composition and structure under the historical range of variation (Maxwell et al. 2014, McGarigal et al. 2018), we sought to expand upon past work by also considering disturbances under future climate conditions. That said, we acknowledge the substantial uncertainty in projecting future vegetation conditions and fire dynamics; it is certainly possible, as a result, for complex shifts in forest composition to occur (for example, we observe a modeled reduction in *Abies magnifica*). Further, the uncertainty in how climate will change over this timeframe makes observed dynamics in later decades less reliable (Scholes et al. 2014). Modeled dynamics accrue growing uncertainty as they reflect the cumulative effects of variability in climate, growth, fire, and beetle dynamic models. Further, although it is nearly certain that management will adjust to changing conditions over time (though predicting specific management adjustments is impossible), these feedbacks are not accounted for in our modeling. It is reasonable to expect that values to be observed in the near future will more closely conform to model predictions than those in the distant future; this is the result of, for example, interactions between natural variability, climate response uncertainty, and emission uncertainty. We believe one of the values of modeling results presented here lies in the relative performance of management scenarios over the course of the next century. However, longer-term dynamics and the potential for system thresholds multiple decades into the future is certainly an important area of research that merits further investigation.

Influence of topic area weighting on perceived management performance

In our DST, community values and operations (together comprising 41% of the total model) did not carry as much weight as ecological considerations (which alone comprised 59% of the model; Fig. 2). At the same time as environmental conditions over the course of the century showed a clear and consistent positive response to expanded treatment and expanded use of fire, variable (and sometimes compensatory) responses over time were observed in community values and operations (Figs. 5 and 6). A main finding was that management scenarios that did not reduce densities of small trees and associated fuels resulted in landscapes that were prone to more severe fire events, which then set in motion larger oscillations between poor and good community values and operational conditions.

Regarding ecological considerations, the aquatic topic area was weighted heavily by stakeholders, accounting for approximately 30% of the entire model. This likely reflects the exceptional importance of restoring and maintaining the ecological and hydrological quality of Lake Tahoe, although most efforts to date have focused on urban sources of impact rather than forest lands (Riverson et al. 2008). Although increased management activity modestly increased delivery of fine sediment particles and phosphorus to waterways, those increases generally offset loads from wildfires; as a result, the differences across scenarios were not substantial (Dobre et al. 2022). This finding is consistent with previous work suggesting that forest treatments mitigate wildfire impacts to water quality (Buckley et al. 2014). Availability of water is also an important consideration because it is important for recreation, and aquatic life depends on persistent summer stream flows. Our DST used LANDIS-II projections for leaf-area-index (LAI) as the proxy for water quantity based upon supporting research (Harpold et al. 2020, Harpold and Rajagopal 2020). This approach ignored complexity associated with elevations and topography found in those studies but was consistent with other approaches used in the Sierra Nevada Mountain Range based upon changes in water yield associated with basal area reductions (K. Podolak, D. Edelson, S. Kruse, B.

Aylward, M. Zimring, and N. Wobbrock, *unpublished manuscript*). Scenarios with increased thinning and burning treatments (both of which reduce LAI through removal of live biomass) accordingly performed well as a result of increased water availability. This finding is consistent with previous studies that have found that reductions in forest biomass can increase water yield (Roche et al. 2020). Further, results of hydrologic modeling conducted in the study area indicated that thinning small trees (up to 20 m tall) reduce LAI and also increase snow accumulation and melt volume (Krogh et al. 2020), further enhancing water quantity. Although our results predict minimal improvements in water quality resulting from forest management, they do contextualize water quality concerns with regard to larger restoration efforts. Results presented indicate that both water quality and quantity were likely to degrade in the future without broad-scale use of fire (Appendix 6); this provides compelling evidence to overcome near-term concerns about the impacts of forest treatments, fire in particular, on Lake Tahoe's water clarity. Our findings additionally add to the growing body of literature (e.g., Nair and Howlett 2016) that indicates that effective approaches to promoting long-term ecosystem resilience focus on longer timeframes, underscore the importance of adaptive management, and consider a wide range of interacting values, as opposed to a focus on near-term risk reduction and maintaining the status quo.

Attributes of community values and operations had high year-to-year variability; though, regarding overall scenario performance, gains in community values partially compensated for losses in operations. Although Scenario 1 generally performed poorly (and Scenario 5 generally performed very well) regarding community values because of the high risk of property damage, the opposite was true for the performance of management operations because the suppression-only scenario was less expensive in terms of implementation costs. Various studies have suggested that suppression-only strategies fail to account for the full social costs of future disturbances (Buckley et al. 2014, Bagdon and Huang 2016) and that restoration-based strategies can achieve social and ecological win-win outcomes (Bagdon et al. 2016, Spies et al. 2019).

In the DST, environmental outcomes were weighted more heavily compared to social and economic outcomes. As a result, management activity that benefited environmental conditions was prioritized over management costs and feasibility. For example, increasing treatments were needed to mitigate impacts from future devastating wildfires, but the type and extent of management were not substantially tempered by factors other than environmental outcomes. These choices were made intentionally to help ensure that strategies would promote ecological resilience without being unduly constrained by policies, regulations, and other institutional limitations (e.g., Stephens et al. 2013, Schoennagel et al. 2017). However, if community values and management operations had been given more weight, it is possible that Scenario 5 may not have been as much of a standout in terms of performance, perhaps Scenario 4 would have fared as well or better (as reflected in the sensitivity analysis; Table 4), and Scenario 3 may have performed more poorly, given the high cost of thinning.

Decision support for landscape resilience

The Ecosystem Management Decision Support tool, an environmentally focused DST, has been used since the late 1990s to provide decision support for numerous management issues related to environmental analysis and planning (Reynolds and Hessburg 2014 and work cited therein), but its application to the LTW resilience project is novel. Whereas previous applications have been point-in-time analyses based on the observed state of ecosystems (e.g., Hessburg et al. 2013, Cleland et al. 2017), the LTW DST considers ecosystem states over a 100-year timeframe based on the LANDIS-II process model. Examining a long time horizon provided a framework for an analysis of ecosystem resilience (Holling 1973, Walker and Salt 2010). Analyses and assessments in decision support have increasingly turned to knowledge-based methods to address contemporary management issues related to the sustainability, integrity, and resilience of ecosystems because these are large, complex, and abstract topics that are not easily modeled using traditional scientific analytical tools (Gunderson 1999, Swanson and Greene 1999, Reynolds 2001). A virtue of MCDMs, a component of our DST, in general is that they are rationale, transparent, and repeatable (Murphy 2014). That said, MCDM models typically operate at the interface between science and policy because they require judgments from decision makers as to the relative importance of the criteria (i.e., the focal areas and topics in our analysis). There is likely no such thing as a value-free decision in environmental management; DSTs work to make tacit valuations transparent. Deciding what topics matter and how much they matter are critical in the design of a MCDM and DSTs more broadly. The sensitivity analysis for the LTW model of scenario performance (Table 4) is helpful in balancing subjectivity on the one hand and a rational, transparent, and repeatable model on the other because it highlights those model weights that are most sensitive to determining the relative ordering of performance scores, and this is useful to focus discussion about choices that have been made in MCDM weights. Ultimately, the evaluation conducted in this DST reflects both integrity and resilience because model inputs were derived from process-based modeling that dynamically modeled the evolution of system states over time based on the simulation of processes (Scheller et al. 2019).

CONCLUSION

Use of interdisciplinary modeling has become an essential component of landscape restoration planning and implementation, especially as observed and projected climate change threaten the sustainability and resilience of ecological and social systems. Decision makers commonly evaluate projects based on short-term impacts to social values that have well-established regulatory frameworks (such as water quality, air quality, and endangered species). Such a framework may induce a bias against active management toward greater future resilience. Our decision-support modeling effort encourages the consideration of trade-offs among a wide range of social and ecological values over multiple decades. By evaluating the effects of climate change and different management activities on resilience over 100 years, we identified that there are substantive costs associated with management practices that do not proactively reduce forest biomass. Our work also addresses a key challenge for understanding the role of intentional fire, and mechanical biomass removal, on system dynamics and changes in climate.

The use of integrated modeling identifies trade-offs and responses of natural systems to perturbation caused by changing future conditions. Our work also establishes a suite of indicators and associated projections that can be used to evaluate the intersection of ecological processes, management activities, and climate change on landscape level forest resilience.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/13243

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Data Availability:

The data and code that support the findings of this study are openly available supplemental information associated with this publication.

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Appendix 1. Appendix 1: CriterionDecision Plus (CDP) model in CDPX format.

Please click here to download file 'appendix1.cdpx'.

Appendix 2. Appendix 2: NetWeaver (NW) model in NW2 format.

Please click here to download file 'appendix2.nw2'.

Appendix 3. Appendix 3: NetWeaver (NW) model in user readable format (HTML).

Please click here to download file 'appendix3.zip'.

Appendix 4. Appendix 4: NetWeaver (NW) model input specifying values used in NW fuzzy logic.

Please click here to download file 'appendix4.csv'.

Appendix 5. Appendix 5: Raw data inputs for the NetWeaver model (i.e. appendix 2) and CriterionDecison Plus (i.e. appendix 1)

Please click here to download file 'appendix5.csv'.

Appendix 6. Appendix 6: Multi-criteria decision model values and summary statistics for focal areas, topic areas, and attributes.

Please click here to download file ‘appendix6.xlsx’.