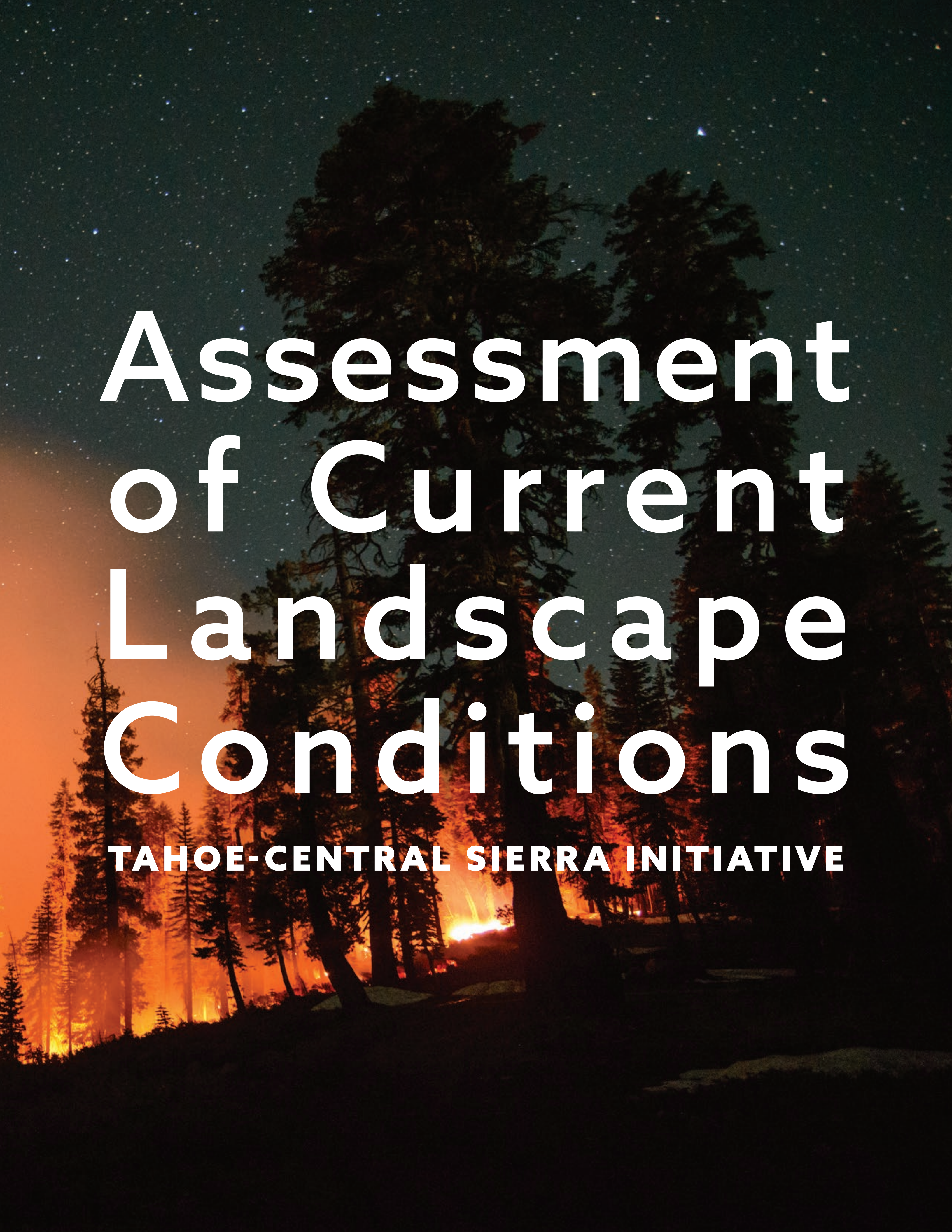

Assessment of Current Landscape Conditions

TAHOE-CENTRAL SIERRA INITIATIVE

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EXECUTIVE SUMMARY

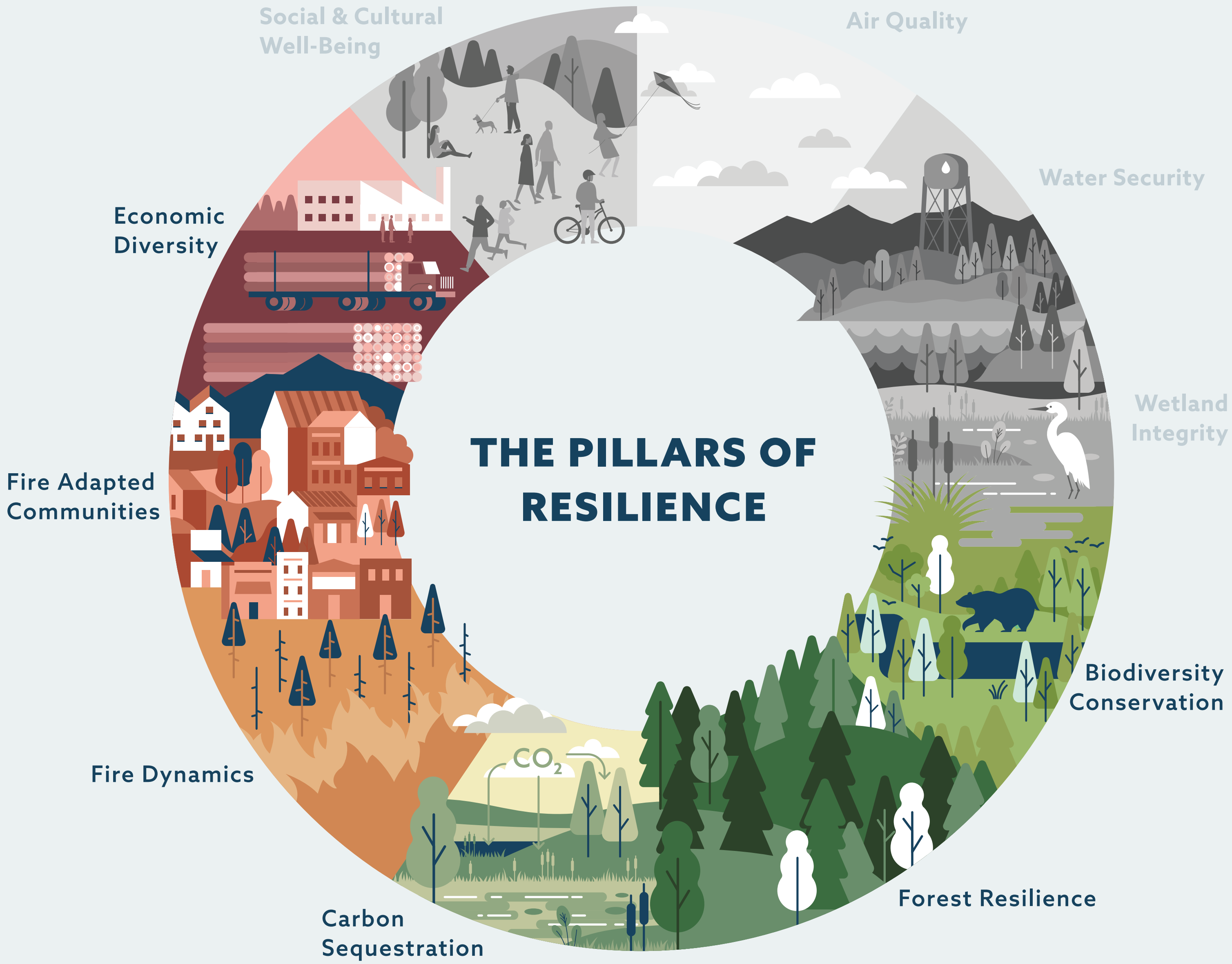
CLIMATE CHANGE, high-severity wildfire, and drought threaten the resilience of forests and communities in the Sierra Nevada. The area burned by high-severity wildfires annually is increasing, and prolonged droughts coupled with beetle outbreaks have the potential to result in massive tree mortality, leaving extremely large areas of dead trees. These factors, along with fire suppression and unsustainable logging practices, shaped the forests we know today, which are less resilient to wildfire and drought than pre-European settlement forests. Despite significant efforts since the early 1990s to improve forest health and resilience through the use of restoration thinning and prescribed fire, the current pace and scale of proactive forest management is not enough to reverse the increasing trend of large fires and widespread beetle-caused tree mortality tied to drought. There is a need to better understand how much and what kind of forest management is needed and where, and what co-benefits can be expected.

The Tahoe–Central Sierra Initiative (TCSI) is a partnership of state and federal agencies, non-governmental organizations (NGOs), the timber industry, and researchers that was established to improve forest and social resilience to climate change and other stressors across a 978,381-hectare (2.4 million-acre) landscape. Increasing forest heterogeneity and decreasing fuel loads through ecologically based forest management will likely improve the forest and human communities' ability to adapt to future wildfires and drought under a changing climate. To provide a foundation for achieving resilience, TCSI established a four-part Roadmap to Resilience:

1. *Framework for Resilience*
2. *Assessment of Current Landscape Conditions*
3. *Assessment of Future Landscape Conditions*
4. *Blueprint for Resilience*

The purpose of this initial assessment, part two of the Roadmap to Resilience, is to understand key aspects of current forest and landscape conditions, including fire and beetle/drought risk and biomass-processing capacity, across the TCSI area to establish the need and urgency for restoration based on a scientific foundation. We defined resilience in the *Framework for Resilience* based on ten pillars. Building on that, this assessment evaluates key features of the landscape in terms of resilience by assessing current conditions (2018–2020) across six of the ten pillars of resilience. The remaining four pillars and other factors will be addressed in the *Blueprint for Resilience*.

⇦ *Prescribed fire operations near French Meadows Reservoir in May 2021. Photograph by Jerry Dodrill.*



The assessment of potential future conditions is an essential step in shaping desired outcomes and the degree to which management approaches can improve landscape conditions across the pillars of resilience in the face of future climate conditions. The current and future conditions will be used to identify in the *Blueprint for Resilience* opportunities for restoration across the landscape using the Ecosystem Management Decision Support tool. This tool will identify opportunities to move toward desired target conditions across a wide array of metrics, resulting in the production of maps that identify where forest management could provide the greatest benefits based on a given set of priorities. Different pillars may be weighted to emphasize specific priorities. Underlying every spatial data layer will be is a logic model based on resilient or desirable conditions.

This assessment establishes a baseline of current conditions for key resources across the TCSI landscape. It provides a scientific foundation for the need to increase the pace and scale of restoration and identifies forested areas that are prime candidates for restoration treatments with the potential to achieve multiple benefits through forest treatments. For example, focusing restoration thinning and prescribed fire in places where there are high tree densities, drought vulnerability, high-intensity fire risk, and fire risk to communities can improve outcomes for multiple pillars.

We did not include biodiversity conservation, carbon sequestration, or economic-diversity pillars in this preliminary overlay example, as they are likely to require additional considerations in terms of appropriate and effective management treatments and the timing of associated benefits. For example, there may be short-term impacts of forest treatments on California spotted owl habitat and carbon storage but long-term protection of habitat and carbon from future high-severity wildfires. Prioritizing areas across the TCSI landscape to increase carbon or protect habitat for sensitive species will be integrated into the *Blueprint for Resilience* based on the assessment of future conditions.

Below are brief summaries of the current condition of six pillars: forest resilience, fire dynamics, fire-adapted communities, biodiversity conservation, carbon sequestration, and economic diversity.

PILLAR 1: FOREST RESILIENCE

Sierra forests evolved with a suite of frequent disturbances: wildfires, both from lightning and burning by indigenous people, bark beetle-caused mortality, drought-caused mortality, avalanches, landslides, and windthrow all of which created forest heterogeneity across the landscape. This heterogeneity included variations in surface and ladder fuels, which moderated fire behavior and spread, and variations in stand density and forest opening, which served as critical habitats. The forests, which represent 84% of the TCSI landscape, are now more homogeneous due to lack of disturbance. Over the past fifty years, only 24% of the TCSI landscape has been burned, thinned, or logged. The lack of disturbance is evident in the forest structure. Current tree density is 1.8 times as dense as reference areas with active-fire management and no timber management.

Current forest structure is dominated by areas with many small trees and few large trees. Forest types in the region vary by elevation and are primarily Sierran mixed conifer, Douglas-fir, white fir, and red fir on the west slope, with more Jeffrey pine on the east slope. In addition to tree density, species composition in the mixed conifer has shifted toward more shade-tolerant and in some cases fire-intolerant species (e.g., white fir), suggesting that forest treatments will need to address both density and composition.

New research on drought vulnerability informed where to prioritize forest management to decrease the risk of drought stress and beetle-caused tree mortality. By combining dry-season available water (the underground water that trees access) and maximum drawdown of that water in a dry year, we can better understand where forests are at risk from drought. Drought-vulnerable areas cover 38% of the forested landscape and are concentrated in the lower elevations of the American River and Yuba River watersheds, the lower-elevation east slope of the Sierra Nevada, and around portions of Lake Tahoe.

PILLAR 2: FIRE DYNAMICS

The potential risk of high-intensity fire is of great interest to agencies and the public. High-intensity fires can cause widespread tree mortality, they are difficult to suppress, and they can threaten lives and communities. Across the TCSI forested landscape, 57% is at risk of high-intensity fire. The risk is spread across most of the TCSI area, except in recently burned areas that may be at risk in the future.

PILLAR 3: FIRE-ADAPTED COMMUNITIES

We modeled the potential fire risk to communities based on the risk of four-foot or greater flames within the Defense (within 0.25 miles of development) and Threat (within 1.25 miles of development) zones. Defense and Threat zones define the Wildland-Urban Interface (WUI), which is the transitional area between the built environment and wildland ecosystems. Twenty-nine percent of the TCSI landscape is in the WUI, and 86% of the WUI is at risk of moderate- to high-intensity fire, posing a significant risk to communities and infrastructure.

PILLAR 4: BIODIVERSITY CONSERVATION

There are 195 terrestrial vertebrates with suitable reproductive habitat in the TCSI landscape, and species richness exceeds 85 species per hectare in some areas. The California spotted owl is a sensitive species that is the focus of Forest Service management guidelines and conservation strategies to protect and improve habitat. California spotted owl reproductive habitat likely covers 28% of the forested landscape. There are 429 known owl nesting sites that cover 6% of the forested landscape. Areas with high species richness and locations of California spotted owl nests need to be taken into consideration when planning forest treatments.

PILLAR 5: CARBON SEQUESTRATION

The net ecosystem exchange, which includes sequestration and respiration, and total carbon amount were calculated using the LANDIS-II model and data from a range of sources. The modeling results from a single year projected that in 2019, the TCSI landscape net sequestered carbon (i.e., it was a carbon sink, not a carbon source) at a rate of 3.1 million metric tons CO2e. This is equivalent to the emissions from ~700,000 passenger gas powered vehicles driven for one year. The total carbon pool consists of approximately 65% live carbon, 14% dead carbon, and 21% soil carbon. While the landscape operated as a carbon sink in 2019, the resilience of carbon sequestration is at risk in the future from anticipated increases in high-severity fire, droughts and beetle-related tree mortality, and vegetation shifts in response to climate change.

PILLAR 6: ECONOMIC DIVERSITY

Forest treatments can have a wide range of direct and indirect impacts on local economies, including recreation and jobs creation. We focused on the need for diverse, economically viable solutions to deal with the excess biomass from restoration treatments, because the costs of removing it is one barrier to increasing the pace and scale of forest treatments. Currently, there are no active sawmills or biomass facilities in the TCSI landscape. Sale of commercially valuable logs to sawmills outside of TCSI could be economically viable in some circumstances. However, transportation distances to nearby mills or biomass facilities for lower-value biomass and small-diameter logs are too great to be economically viable without subsidies or other economic-offset mechanisms.

Recently published supply-and-offtake modeling suggests that the cost to remove biomass across 8,000 ha/year (20,000 acres/year) at roughly the current rate can be reduced from an average cost of $15/bone dry ton to $2.80/bone dry ton if three biomass facilities are added within the TCSI area. The potential cost savings would be attributable to a substantial reduction in transportation costs, achieved by siting modern biomass-processing centers closer to the forest. This cost reduction could make it economically feasible to remove small trees, which are a primary contributor to wildfire risk but have low value.

We illustrated a simple approach to identify areas where multiple pillars depart from target conditions. The cross-pillar areas suggest important places to achieve multiple benefits through forest treatments and promote greater resilience to drought, fire, and bark beetle–caused tree mortality. The *Blueprint for Resilience*, the fourth element in the TCSI science enterprise, will use a more sophisticated decision support tool to combine the current conditions and future conditions under climate change to identify management options that can move the landscape into conditions expected to be more resilient to future disturbances. Combining this landscape-scale analysis with stand-based knowledge will be crucial to guide specific management prescriptions. By assessing current conditions and the potential for restoration thinning and prescribed fire to improve socio-ecological resilience, this work provides a foundation for forest management planning.

INTRODUCTION

Kristen Wilson and Patricia Manley

The goal of the Tahoe–Central Sierra Initiative (TCSI) is to increase the pace and scale of restoration thinning and prescribed fire across the watersheds of the central Sierra Nevada. The risks of large, high-severity fires, prolonged and severe drought periods, and widespread beetle-caused tree mortality threaten the resilience of forest landscapes and pose a high risk of catastrophic fire to communities. TCSI is a joint effort of The Nature Conservancy; Sierra Nevada Conservancy; California Tahoe Conservancy; National Forest Foundation; California Forestry Association; USDA Forest Service Pacific Southwest Research Station; University of California Natural Reserve System—Sagehen Creek Field Station; and USDA Forest Service Region 5, including the Tahoe National Forest, Eldorado National Forest, and Lake Tahoe Basin Management Unit. The eight groups signed a Memorandum of Understanding (MOU) in August 2017 that guides the project (USDA 2017). There are two additional National Forests that overlap the TCSI boundary, the Plumas National Forest and Humboldt-Toiyabe National Forest, but these forests each cover less than 3% of TCSI and were not signatories to the MOU.

TCSI established a *Roadmap to Resilience* co-led by the Forest Service Pacific Southwest Research Station and The Nature Conservancy to provide a foundation for achieving forest resilience across the landscape. The *Roadmap to Resilience* includes four components:

① *Framework for Resilience*

② *Assessment of Current Landscape Conditions*

③ *Assessment of Future Landscape Conditions*

④ *Blueprint for Resilience*

The *Framework for Resilience* defines resilience and describes the elements and metrics that can be measured to assess resilience and to monitor change over time. Resilience is the ability of the 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). We defined socioecological resilience based on eight pillars during a TCSI partnership workshop in 2018.

This document comprises an *Assessment of Current Landscape Conditions* for the pillars of socioecological resilience. We analyzed six of the ten pillars based on data for current forest and watershed conditions, outcomes of pertinent research, and modeling; those six pillars are 1. forest resilience, 2. fire dynamics, 3. fire-adapted communities, 4. biodiversity conservation, 5. carbon sequestration, and 6. economic diversity. Some of the pillars and metrics in the *Framework for Resilience* are not assessed in this report and/or will not be addressed in the future conditions modeling. Specifically, water security, air quality, wetland integrity, and social and cultural well-being are four pillars not addressed in this assessment because although they are pivotal to long-term resilience, the ability to address them quantitatively can be quite challenging. Data for some metrics were not available, were cost-prohibitive to develop, or were not prioritized by the TCSI leaders in the short term. The pillars, elements, and metrics in the *Framework for Resilience* represent a full-scope analysis of the landscape that TCSI was unable to achieve in the current iteration, and these data gaps indicate future goals for TCSI (Table 1). The pillars are numbered but are not ordered according to importance.

The *Framework for Resilience* identified core metrics for each element. In some cases, the metrics in this assessment overlap and others are different. The elements serve as a guide, while the metrics are suggestions. Individual regions within TCSI and other large-landscape assessments like that done for TCSI will need to choose metrics that are the most important to their area as well as metrics with data available or that are able to be compiled. Over time, more metrics can be incorporated as data become available or as additional funding and interest are raised. This assessment serves as a starting point.

The *Assessment of Future Landscape Conditions* is in progress. We will evaluate the degree to which forest management can improve landscape conditions and outcomes across the pillars in the context of future climate conditions over the next eighty years using a model called LANDIS-II. Current and future conditions will be used to identify opportunities for restoration across the landscape using the Ecosystem Management Decision Support tool in the *Blueprint for Resilience*.

The TCSI *Roadmap to Resilience* is similar to the approach used in the Lake Tahoe West (LTW) Restoration Partnership. First, LTW produced an assessment of current conditions compared to reference conditions for sixteen indicators (Gross et al. 2017). Next, LTW developed a restoration strategy based on the assessment plus modeling of different scenarios of forest management over the next eighty years of climate change using LANDIS-II, targeted modeling at finer scales, and field-based studies. The restoration strategy (Lake Tahoe West Landscape Restoration Partnership 2019) formed the rationale for a scoping notice for the project (Lake Tahoe West Restoration Project 2020). While the approach of assessing current conditions compared to desired conditions and modeling future conditions with management and climate change is similar, the two projects differ in scale, vegetation datasets, and indicators of resilience.

This assessment establishes a baseline for TCSI and is the first step in identifying priority areas for restoration thinning and prescribed fire. To this end, we overlaid spatial maps from the individual pillars of resilience to highlight areas in need of restoration thinning and prescribed fire based on current conditions only. Here we begin with a description of the TCSI landscape; we then describe the current condition of the aforementioned six pillars of resilience. We conclude by beginning to identify important areas for restoration thinning and prescribed fire. The spatial data from this assessment will be combined with spatial data from the future conditions modeling through the year 2100 to produce the fourth and final component of the Roadmap to Resilience, the *Blueprint for Resilience*.

■ **TABLE 1.** The pillars and elements defined in the *Framework for Resilience* compared to this assessment of current conditions and ongoing work to assess future conditions with climate change.

#	Pillar	Element	Metric	Source	Current conditions assessed	Future conditions assessed
1	Forest resilience	Structure	Tree density	SilviaTerra, contemporary reference polygons, climate classes, landscape management units	Y	Y
			Basal area			
		Composition	Diversity	SilviaTerra to CWHR types	Y	Y
		Disturbance	Fire, beetle, mgt.	USFS FACTS, FRAP, Aerial Survey Beetle Program R5, CAL FIRE NTMPs, THPs, Hanson et al. 2013 forest cover change	Y	Y
			Drought vulnerability	NDVI, PRISM, CA Data Exchange Center for full natural flows	Y	N
2	Fire dynamics	Severity	High-intensity fire, eight-foot flame lengths	FSim	Y	Y
		Functional fire	See Disturbance	See Disturbance	Y	Y
3	Fire-adapted communities	Hazard	Four-foot flame lengths within 1.25 miles of development	FSim, ICLUS	Y	Y
		Preparedness			N	N
4	Biodiversity conservation	Focal species	Habitat	SilviaTerra to CWHR types, stakeholder input	Y	Y
			Occurrence	Forest Service NRIS , CDFW Spotted Owl Observations, USFWS, and CNDDB		
		Species diversity	Number of species	SilviaTerra to CWHR types	Y	Y
		Community integrity			N	Y
5	Carbon sequestratio	Storage	Net ecosystem exchange	SilviaTerra, LANDIS-II	Y	Y
		Stability	Total forest carbon	SilviaTerra, LANDIS-II	Y	Y
6	Economic diversity	Wood product industry	Stumpage rate	Mason, Bruce, & Girard model	Y	Y
		Recreation Industry			N	N
		Water industry			N	N
		Economic health			N	N
7	Water security	Quantity			N	Y
		Quality			N	N
		Storage and timing			N	N
8	Air quality	Particulate matter			N	Y
		Visibility			N	Y
		Greenhouse gases			N	Y
9	Wetland integrity	Structure			N	N
		Composition			N	N
		Hydrologic function			N	N
10	Social and cultural well-being	Public health			N	N
		Engagement			N	N
		Recreation quality			N	N
		Equitable opportunity			N	N

TCSI LANDSCAPE

TCSI is a 978,381-hectare (2,417,632-acre) area in the central Sierra Nevada in the Sierran Steppe-Mixed Forest-Coniferous Forest-Alp ecoregion (Figure 1). The area spans California and Nevada and is defined to the north and south by watershed boundaries. TCSI encompasses six watersheds (USGS HUC8 level): Yuba, Truckee, Lake Tahoe Basin, Upper Bear, North Fork American, and South Fork American. The eastern boundary of TCSI is the watershed boundary for Lake Tahoe Basin but is an arbitrary watershed boundary at the California-Nevada state line for the Truckee River watershed. The western edge of TCSI skirts the boundary between the Sierra Nevada ecoregion and the Sierra Nevada foothills ecoregion and was hand-digitized uphill of the blue oak–foothill pine and blue oak woodland vegetation types.

The combination of existing projects and planned landscape-scale projects at a >80,000-hectare scale make TCSI a testing and demonstration geography of statewide significance. TCSI sets the stage for a regional approach to socioecological resilience guided by science. The TCSI area was selected for several reasons (USDA 2017):

- It contains high biodiversity
- It is an iconic landscape that people know and love
- To date, the area has not been impacted by the insect activity and disease that have extensively affected the southern Sierra
- Current large-landscape collaborative projects are underway or in the planning stages
- Some of these large-landscape projects are using innovative approaches that may serve as templates for increasing the pace and scale of forest restoration

We grouped the landscape into seven management zones which define forest management jurisdiction (Figure 2). National Forest was separated into three categories: Public Forest, Roadless, and Wilderness, based on administrative rules for timber harvest and wildfire management. Private land ownership was divided into Private Industrial and Private Non-industrial timber lands using the CAL FIRE Timber Management Dataset (2013). The CAL FIRE Timber Management Dataset only indicates if a landowner enrolled their property into the Timber Production Sone, it does not always mean the land is industrial or non-industrial. This was the best dataset available to distinguish between the two. Defense and Threat Zones were based on buffered distances from developed areas, 0.25 miles and 1.25 miles respectively. Developed areas were identified using the ICLUS v2.1 2020 SSP2 database (U.S. EPA 2017) and buffers away from developed areas were delineated as Defense or Threat Zones.

The two largest management zones are Public Forest and the Threat zone, which combined cover more than half of the TCSI forested landscape (Figure 3). Roadless and Wilderness areas represent 13% and 5%, respectively, while Private Industrial and Private Non-industrial represent 11% and 4%, respectively. Five National Forests overlap TCSI: Tahoe (44% of TCSI), Eldorado (23%), Lake Tahoe Basin Management Unit (9%), Plumas (3%), and Humboldt-Toiyabe (<1%).

FIGURE 1. TCSI is located in the central Sierra Nevada ecoregion encompassing six large watersheds, two biomass facilities outside the area, and three hypothetical new facilities. Inset maps shows primary and secondary biomass sources areas used in the Economic Diversity pillar.

TAHOE CENTRAL SIERRA INITIATIVE (TCSI) LANDSCAPE

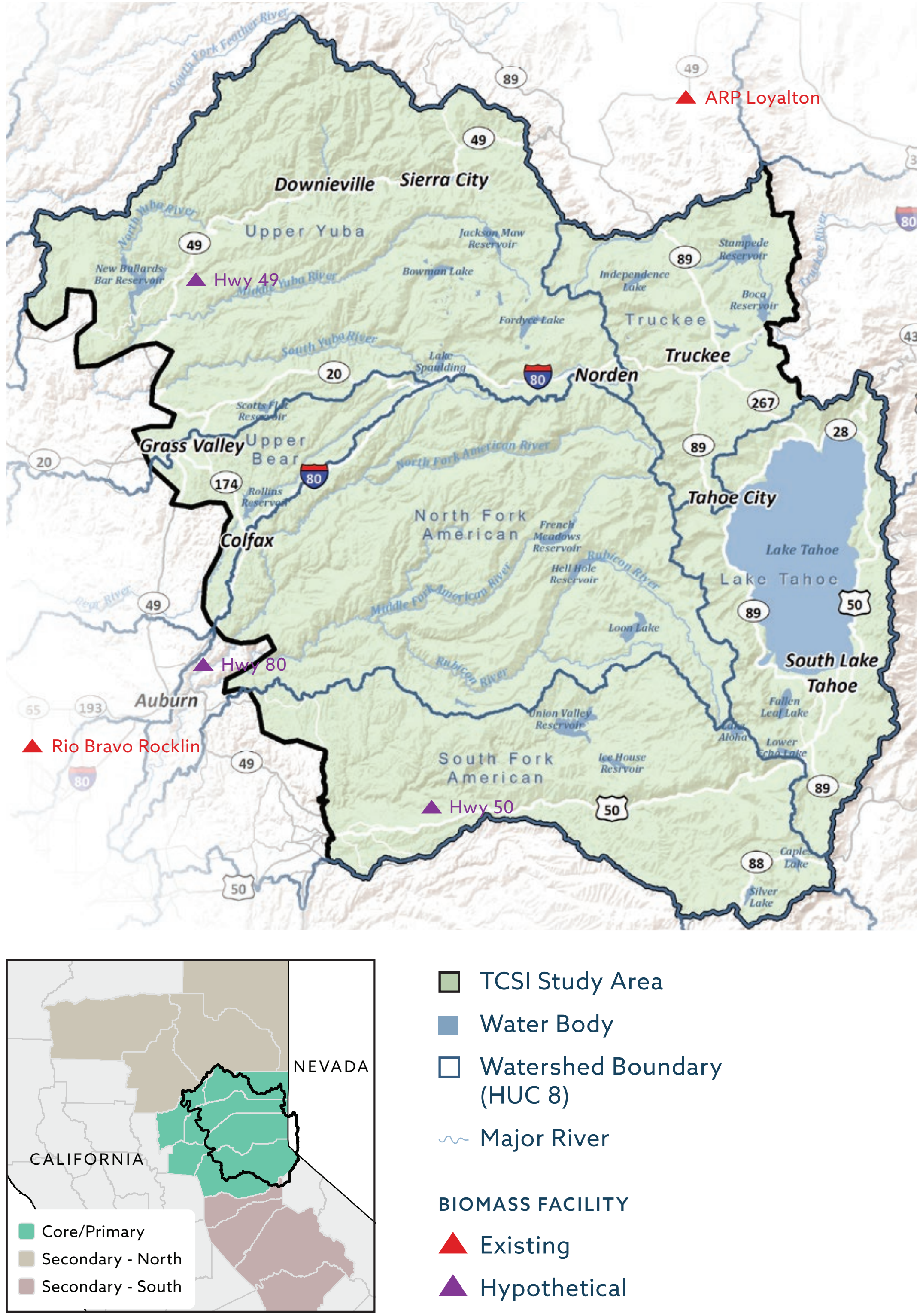


FIGURE 2. Management zones within TCSI defined byforest jurisdiction.

MANAGEMENT ZONES WITHIN TCSI

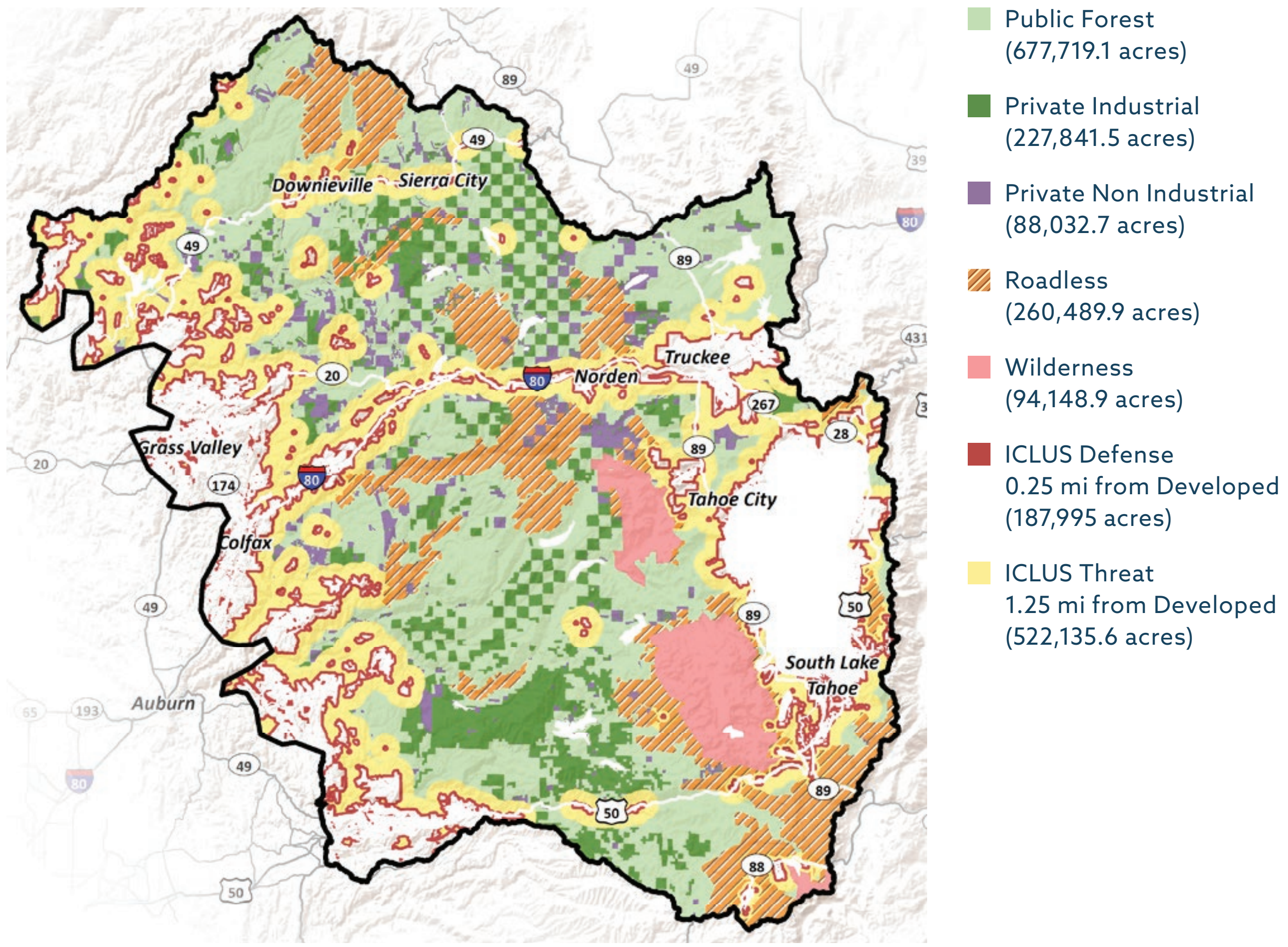
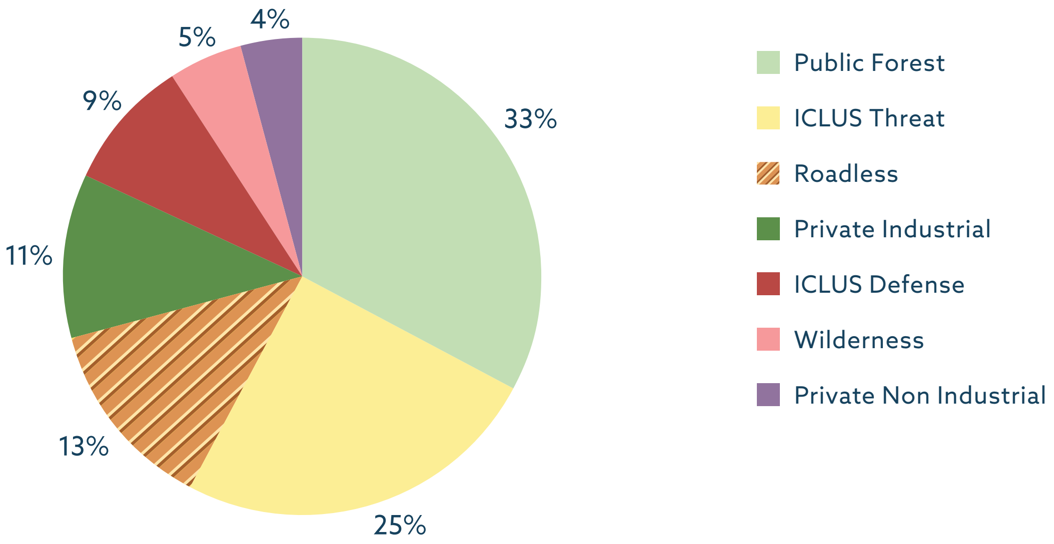


FIGURE 3. Public Forest and the Threat zone combined cover more than half the TCSI forested landscape.



PILLARS OF RESILIENCE

PILLAR 1: FOREST RESILIENCE

Kristen Wilson, Patricia Manley, Nick Povak, Charles Maxwell, Mark Tukman, Dylan Loudon, Angela White, Roger Bales, and Jim Roche

FOREST RESILIENCE: Vegetation composition and structure are in alignment with their biophysical setting and desired disturbance dynamics through time, considering climate change.

ELEMENT	METRIC	TARGET CONDITION
Structure	Tree density	Contemporary range of variability
Structure	Basal area	Contemporary range of variability
Composition	Diversity	Promote shade-intolerant, fire-tolerant species
Disturbance	Fire, Beetle, Mgmt	Historical fire return interval
Disturbance	Drought vulnerability	Forest water deficit <600 mm/year

Ecological resilience is the capacity for a system to recover characteristic processes, functions, and structures following a disturbance. Restoration thinning and prescribed fire attempt to increase forest resilience, in particular, by emulating natural disturbance patterns. Mimicking a forest structure and composition that would have been created by fire and other natural processes is the restoration goal. Prior to European settlement, forests in the Sierra Nevada were characterized by heterogeneous spatial patterns replete with individual large trees, gaps, and tree clumps of various sizes—patterns that were shaped by recurrent fire and other disturbances (Taylor et al. 2014, North 2012). After a century-plus of fire exclusion, timber harvesting, and other land-use practices, the predominant trend across Sierran forests is that they have become denser, with an ingrowth of small, shade-tolerant trees and less structural heterogeneity. As a result, fires that escape initial suppression efforts are often larger and of higher severity than they were historically, and they can threaten local communities and species interspersed throughout the landscape.

In overly dense patches of forest where the risk of high-severity fire is high, mechanical or hand-thinning of small trees is often an effective means of restoring forest structure and mitigating fire effects (Kelsey 2020). Reducing tree density through variable density-thinning treatments can allow for shade-intolerant species, such as Jeffrey pine and Ponderosa pine that are fire-resistant species, to persist and increase diversity. Restoration thinning and prescribed fire can reduce the extent and impacts of high-severity fire and the amount of drought-stress and beetle-caused tree mortality (Restaino et al. 2019, Fettig et al. 2013). Post-fire restoration is another important restoration tool to improve forest resilience (White and Long 2019, North et al. 2019). Forest-restoration principles suggest that topographic position at stand and landscape scales (North 2012) and protection of tall trees for California spotted owl habitat (North et al. 2017) should guide prescriptions. Additionally, areas of the forest with high vulnerability to drought can be treated proactively to try to prevent high rates of mortality (Hessburg et al. 2019).

We address each of the core elements associated with the forest resilience pillar—structure, vegetation composition, and disturbance—and describe their current and potential target conditions based on multiple metrics. We first describe forest structure today and how it compares to the contemporary range of variability. Second, we describe current forest and shrub composition to set a baseline for comparison of the relative change with future conditions based on projections from the LANDIS-II model. Third, we evaluate disturbance history to determine the degree to which areas may have compromised resilience.

1.1 FOREST STRUCTURE

We characterize two metrics of forest structure: tree density and basal area. The degree to which current forest structural conditions are resilient to disturbance and other environmental stressors requires a quantitative context for interpreting their vulnerability. As Taylor et al. (2014) wrote, "To guide and implement vegetation management, managers need quantitative estimates of reference forest characteristics, such as forest density and basal area." Historical and contemporary reference forest stands represent forest patterns that developed under disturbance regimes that are presumed to provide resilience to more frequent disturbance.

METHODS

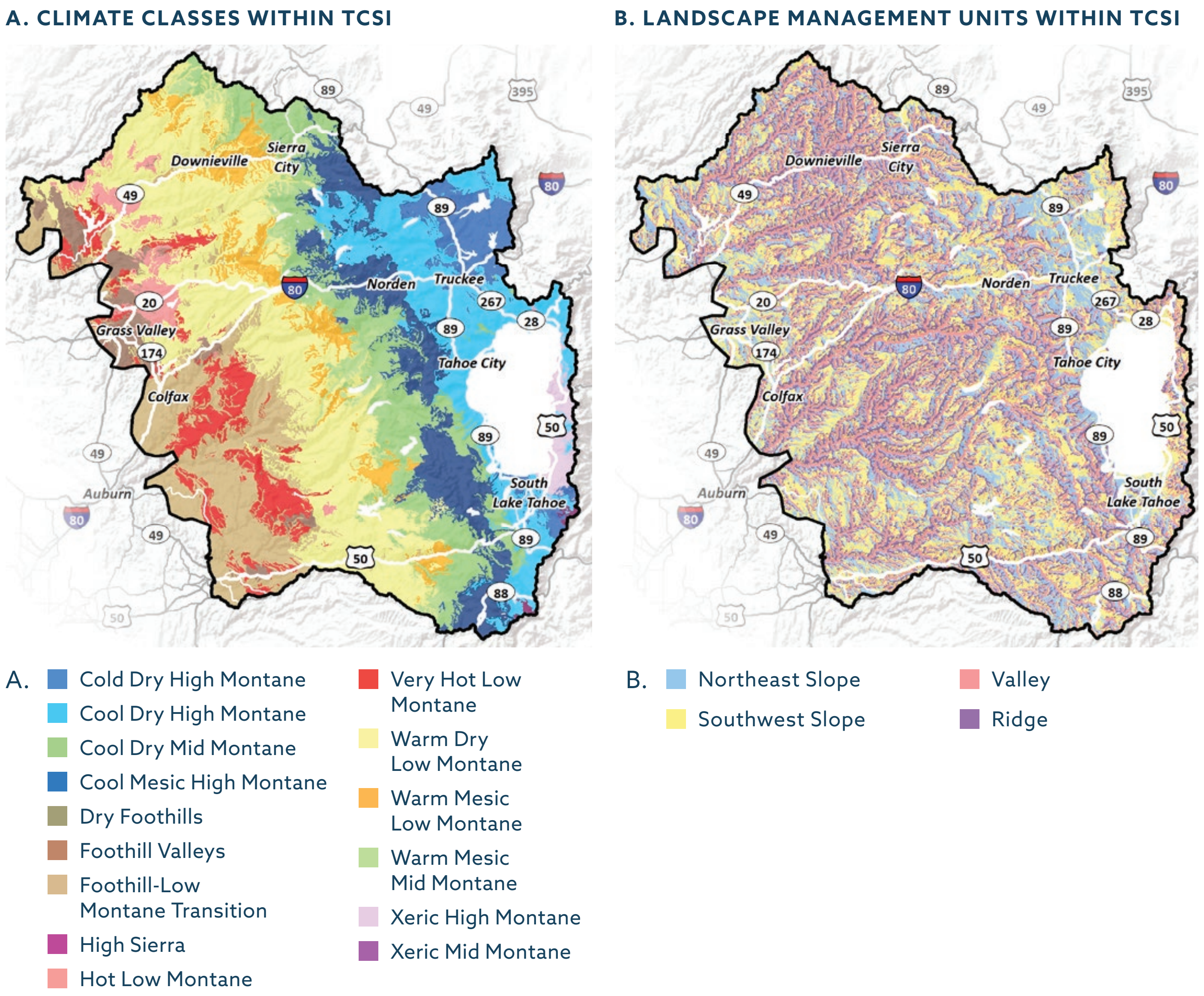
Vegetation data for this assessment were created by SilviaTerra, a firm that specializes in data-driven forestry. The dataset was created using Landsat satellite data and imputation based on Forest Inventory and Analysis (FIA) data. SilviaTerra provided vegetation data for the TCSI landscape, as well as across the Sierra Nevada, to enable comparisons with reference data. For this assessment, we used vegetation data provided at the 1-hectare cell size. The tree list included all trees >12.7 cm (>5 inches) diameter at breast height. We set thresholds for vegetation to be considered forested by visually reviewing cover types: >40 trees/ha and basal area >11 m2/ha excluded cells where shrubs were dominant, and <300 m2/ha was the upper limit to eliminate outliers (71 cells out of 960,192 total cells). Based on these thresholds, forested vegetation covered 84% (817,564 ha) of the TCSI landscape.

We used contemporary reference sites across the Sierra Nevada to establish target conditions for tree density and basal area (Jeronimo et al. 2019). The authors selected sites that had no timber harvest; burned at least twice in the past sixty years, with at least one fire in the last thirty years; and had high-severity fires on less than ten hectares and 10% of a reference polygon, similar to historical estimates of fire-severity proportion and size (Jeronimo et al. 2019). If an area had burned three or more times, then only low-severity patches were included in the reference sites. The sites may have been grazed or experienced other human impacts but are the best representation of forest structure with an active fire regime since 1957, the earliest record for fires with severity information. As Jeronimo et al. (2019) noted, "Contemporary reference sites are still recovering from decades of fire suppression so don't exactly match historical conditions." The contemporary reference areas covered 21,000 hectares across the Sierra Nevada, with a concentration in national parks in the southern end of the range.

Following the methods of Jeronimo et al. (2019), we stratified the landscape based on their biophysical setting, specifically the climate class and landscape management unit (LMU) classifications. Climate classes were based on climatic water deficit, January minimum temperature, and actual evapotranspiration (Figure 4). LMUs were four topographic positions: ridge-, valley-, northeast-, and southwest-facing slopes. We developed a simplified four-class version of the LMU layer (Landscape Management Tool v2 2012) that identified ridgetops, valley bottoms, northeast slopes, and southwest slopes. Each LMU was then attributed to a majority climate class. To make the sizes of the crossed units more realistic from a management perspective, we split LMUs larger than 500 hectares by watershed boundary (USGS HUC12 level) and joined LMUs smaller than four hectares with neighboring LMUs. We grouped climate classes into low and high elevation for comparison. Low elevation included: foothill valleys, foothill–low montane transition, very hot low montane, hot low montane, warm dry low montane, warm mesic low montane, and warm mesic mid montane. High elevation included: high Sierra, xeric high montane, cold dry high montane, cool dry high montane, cool mesic high montane, and cool dry mid montane (Table 2). These two classifications represent coarse-scale and fine-scale drivers of forest structure that can inform restoration prescriptions to improve forest resilience (Jeronimo et al. 2019).

We first characterized tree density and basal area for each 1-hectare pixel across the TCSI landscape and the contemporary reference sites based on 2018 SilviaTerra modeled vegetation. We defined the extrapolation of reference conditions based on climate class and LMU stratification—the contemporary range of variability (CRV). Statistical overlaps among the empirical distributions of tree density and basal area for CRV and TCSI were calculated. Overlap values ranged from 1, identical distributions, to 0, no similarity in the distributions. Distributions were compared for low-elevation climate classes only, high-elevation climate classes only, and both classes combined. CRV data did not exist for five of the fourteen climate classes within TCSI (135,856 hectares, 14% of TCSI). For these areas, we relied on adjacent climate class data. Northeast slopes and valleys in the cold dry high montane climate class and northeast slopes in the foothill–low montane transition climate class also lacked data. For these gaps, we used the maximum values from the other LMUs for each respective climate class, as north slopes typically have higher tree density. The areas with extrapolated CRV values are shown in the inset of Figure 6 and in Table 2 and are included as an attribute in the spatial data.

FIGURE 4. Figure 4. Climate classes (a) and landscape management units (b) used to segment forest structure.


A. CLIMATE CLASSES WITHIN TCSI

B. LANDSCAPE MANAGEMENT UNITS WITHIN TCSI

One-hectare cells with tree density or basal area values that were outside of the CRV were presumed to be more vulnerable and less resilient to disturbance than those that were consistent with CRV. We defined tree density and basal area values in TCSI as "within CRV" if the values fell within the 10th and 90th percentile of the range of conditions in corresponding climate class LMU categories. Tree density and basal area values outside this range were defined as either "below CRV" or "above CRV," and above values were further categorized into three levels of departure based on a quantile distribution: low, medium, and high departure.

We compared the CRV values to the natural range of variation (NRV) values compiled in a recent study for the Lake Tahoe West Project. The NRV included both historical and contemporary references from published and unpublished studies, ranging from pre-European settlement to 1968, and from across the Sierra Nevada and Mexico (Gross et al. 2017). We wanted to understand how CRV and NRV affected the total area considered departed or not resilient. Resilient and less-resilient conditions from Lake Tahoe West are like the "within CRV" conditions from this assessment, and non-resilient conditions are the same as "above CRV" conditions. We limited the comparison to the same four forest vegetation types: Jeffrey pine, mixed conifer, red fir, and subalpine. These types covered the majority of the TCSI forested landscape. We also compared departure across management zones and slopes ≥30% and slopes <30%, which is a cutoff commonly used for mechanical thinning equipment. Mechanical treatments can occur on slopes ≥30% in a cost-effective manner depending on the specific prescription.

CURRENT FOREST STRUCTURE

Forests in the TCSI landscape are 1.8 times as dense (mean 405±210 trees/ha vs. 219±123 trees/ha), have 1.5 times more basal area (41±20 m2/ha vs. 28±13 m2/ha), and have a higher maximum tree density compared to CRV (1,779 vs. 1,132 trees/ha, Figure 5). Higher tree density and basal area in TCSI reflect fire suppression compared to CRV. Forest structure in TCSI was close to the 90% CRV value, meaning current conditions are on the upper end of the range (Table 2). Overlap in the statistical distributions showed that forests within TCSI contain far more pixels with higher tree densities and higher basal area in TCSI compared to CRV (Figure 5). These trends were more pronounced for low-elevation climate classes (overlap <60%) compared to higher-elevation classes (overlap >70%).

Departure of tree density and basal area followed similar spatial patterns across TCSI (Figure 6). Fifty percent of the forested landscape (412,961 ha), including the areas where conditions were inferred, is within target conditions, whereas 38% (315,293 ha) is above target conditions and 11% (89,310 ha) is below target conditions. Applying the NRV thresholds for tree density to TCSI, we find the following: 42% of the forested landscape is within target conditions (combining 21% less resilient and 21% least resilient) and 58% is above target conditions, defined as not resilient in the Lake Tahoe West Project. Further, if we had set the threshold for above CRV as mean-plus-one standard deviation and combined climate classes by fire return interval, then about 60% instead of 38% of the forested landscape in 2018 is above target conditions. This is closer to the NRV area defined as not resilient and is an alternative approach to defining within reference conditions. The percent departure of the TCSI for basal area closely tracked results for tree density.

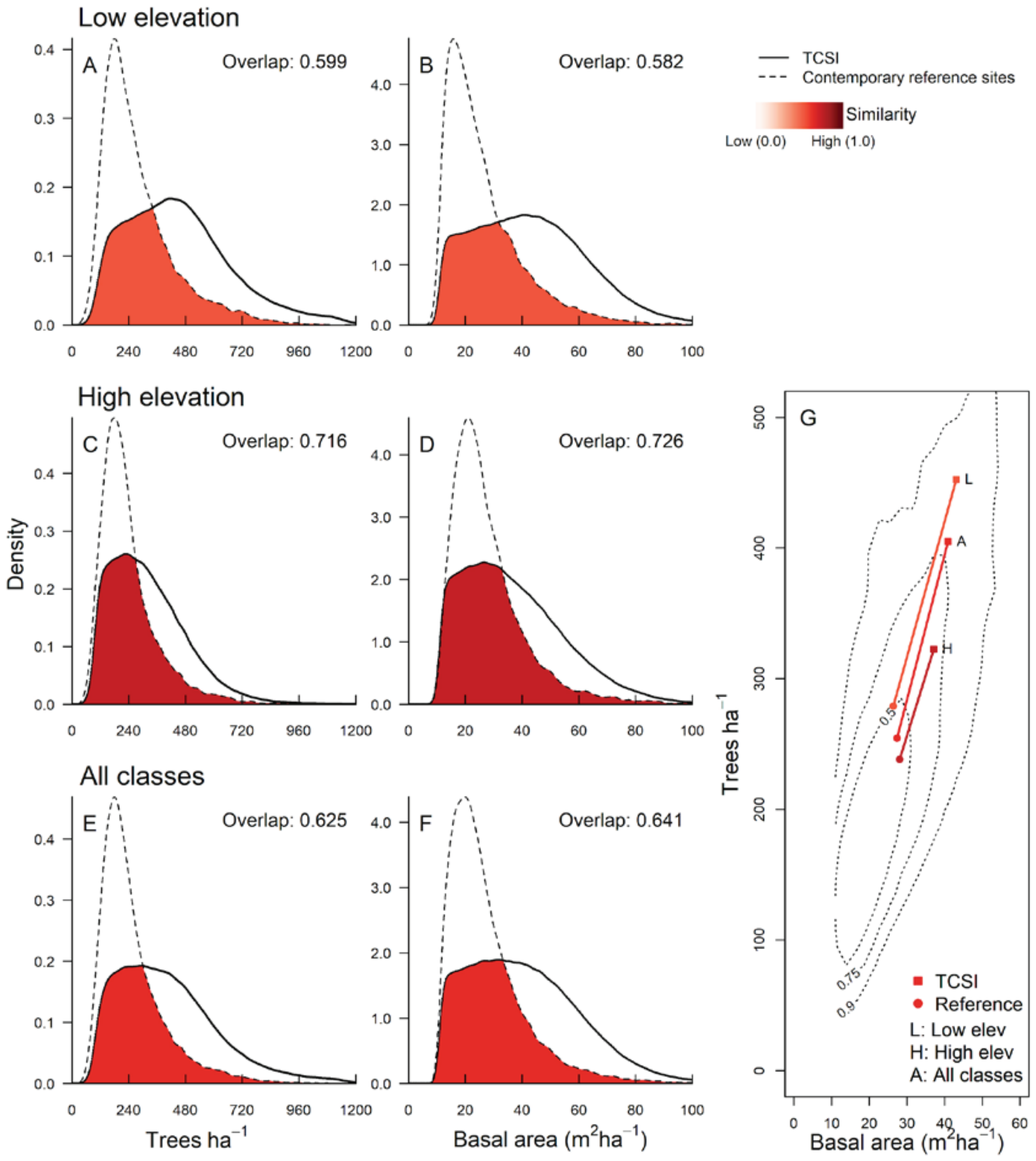
The prevalence of areas within and outside of CRV varied to some degree among the management zones, but not substantially (Table 3). In general, areas that were above CRV for both metrics were most prevalent on National Forest System lands, in the General Forest, Threat, and Roadless zones. Areas

■ **TABLE 2.** Contemporary range of variability in forest structure and thresholds used to define target conditions.

Climate Class	**Landscape Management Unit**	**Tree Density (Trees/hectare)**			**Basal Area (m^2/hectare)**			**No Reference, Inferred Values**	
		Current	Target		Current	Target			
		Mean±stdev	10%	90%	Mean±stdev	10%	90%		
Cold Dry High Montane	NE Slope	220±153	120	265	25±18	18	45	Yes	Max of all LMUs
	Ridge	256±174	120	265	29±20	18	45	No	
	SW Slope	190±139	81	256	22±16	16	36	No	
	Valley	264±168	120	265	32±22	18	45	Yes	Max of all LMUs
Cool Dry High Montane	NE Slope	270±171	63	247	32±21	12	36	No	
	Ridge	298±192	71	639	35±24	16	84	No	
	SW Slope	283±173	68	325	32±20	13	49	No	
	Valley	286±166	61	246	34±20	14	35	No	
Cool Dry Mid Montane	NE Slope	284±181	100	255	32±20	15	33	No	
	Ridge	322±226	97	382	36±26	15	44	No	
	SW Slope	309±192	92	383	35±21	16	44	No	
	Valley	320±197	106	413	35±21	15	46	No	
Cool Mesic High Montane	NE Slope	218±148	49	261	26±18	11	28	No	
	Ridge	243±188	58	261	29±24	13	27	No	
	SW Slope	276±180	60	254	32±21	11	23	No	
	Valley	264±168	45	179	30±19	11	18	No	
Dry Foothills, Foothill Valleys, Hot Low Montane, Very Hot Low Montane	NE Slope	418±233*	87	411	37±20*	12	54	Yes	Foothill-Low Montane Transition
	Ridge	526±263*	87	411	48±23*	12	54	Yes	
	SW Slope	409±219*	126	411	38±20*	19	45	Yes	
	Valley	447±215*	66	619	42±20*	13	66	Yes	
Foothill-Low Montane Transition	NE Slope	443±267	87	411	38±24	12	54	Yes	Max of all LMUs
	Ridge	477±276	87	411	42±25	12	54	No	
	SW Slope	362±222	126	411	32±20	19	45	No	
	Valley	441±234	66	619	40±21	13	66	No	
High Sierra	NE Slope	159±133	71	242	20±17	13	37	No	
	Ridge	100±95	117	710	15±20	12	80	No	
	SW Slope	200±138	180	564	27±19	29	79	No	
	Valley	150±132	74	400	19±17	13	51	No	
Warm Dry Low Montane	NE Slope	404±240	81	439	40±23	13	40	No	
	Ridge	454±266	75	450	45±25	13	49	No	
	SW Slope	373±225	76	598	37±21	13	54	No	
	Valley	433±229	104	588	43±22	14	49	No	
Warm Mesic Low Montane	NE Slope	420±246	65	323	43±24	12	35	No	
	Ridge	476±264	65	421	48±26	13	45	No	
	SW Slope	405±249	74	381	42±24	13	41	No	
	Valley	449±257	67	383	46±26	12	39	No	
Warm Mesic Mid Montane	NE Slope	311±173	65	323	36±20	12	35	Yes	Warm Mesic Low Montane
	Ridge	348±197	65	421	40±22	13	45	Yes	
	SW Slope	352±192	74	381	39±21	13	41	Yes	
	Valley	322±166	67	383	36±21	12	39	Yes	
Xeric High Montane	NE Slope	261±165	52	230	32±20	13	39	No	
	Ridge	295±167	62	325	35±22	13	43	No	
	SW Slope	264±171	79	365	32±21	15	45	No	
	Valley	276±165	60	325	33±22	15	43	No	

*Only Hot Low Montane for current conditions

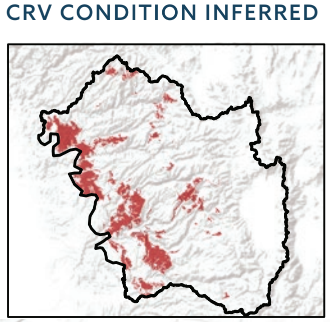
■ FIGURE 5. A comparison of the statistical distributions of forest density (A, C, E) and basal area (B, D, F) among the current TCSI landscape (solid lines) and contemporary reference sites (dashed lines) of Jeronimo et al. (2019). High overlap among distributions indicates a high level of similarity in forest structural attributes among the current and reference conditions. Analyses were conducted separately for low elevation (A, B), high elevation (C, D) and all sites combined (E, F). A separate analysis (G) shows the current levels of forest density and basal area deviating from away from 50th percentile reference conditions (middle dotted line) towards less probable conditions. Reference statistical densities (dotted lines) in panel G were constructed using all reference sites combined and represent 50th, 75th and 90th percentiles for forest density and basal area.

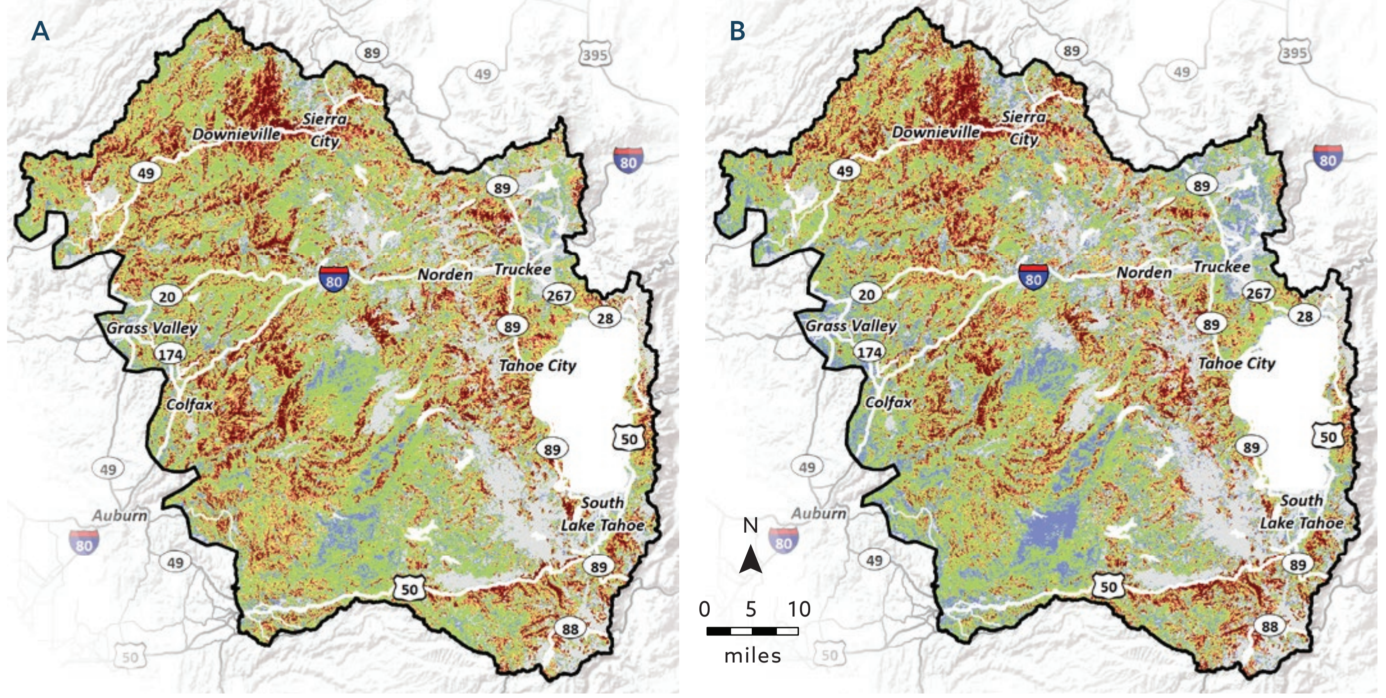


■ TABLE 3. Tree density departure area and percent of TCSI compared to contemporary conditions in different management zones and slope breaks.

Management Zone or Slope	Forest Area	%TCSI	Area (hectares) Above	Within	Below	Relative % of Forest Area Above	Within	Below
All Zones	817,564	84%	315,293	412,961	89,310	39%	51%	11%
Public Forest	251,920	26%	95,871	134,501	21,548	38%	53%	9%
Threat	182,728	19%	85,364	83,738	13,626	47%	46%	7%
Roadless	80,338	8%	35,446	35,465	9,427	44%	44%	12%
Defense	83,308	9%	30,846	42,231	10,231	37%	51%	12%
Private Industrial	84,509	9%	21,843	49,174	13,492	26%	58%	16%
Private Non Industrial	31,141	3%	12,019	16,483	2,639	39%	53%	8%
Wilderness	21,285	2%	9,432	7,845	4,008	44%	37%	19%
Slope								
<30%	454,462	46%	194,171	248,543	56,748	33%	55%	12%
>30%	280,767	29%	141,650	120,894	18,223	50%	43%	6%

■ FIGURE 6. Departure of current tree density (a) and basal area (b) from contemporary range of variability (CRV). Subset map shows areas where CRV data was missing and inferred from adjacent climate classes.





that were below CRV were most prevalent in Developed, Private Industrial, and Wilderness zones. Below-CRV conditions were concentrated along the edges of lakes, meadows, rock, development, and fire perimeters, where pixels were at the boundary of forest and another cover type. Sites below CRV were more prevalent on slopes <30%, while areas above CRV were most prevalent for slopes >30%, which can have important management implications as steeper slopes are generally inaccessible by traditional mechanical tree-harvest equipment.

Climate class and LMU categories were useful classifications to distinguish forest density and basal area across TCSI. Areas that exceed CRV for tree density or basal area and that are the farthest from target conditions highlight areas in need of restoration thinning and prescribed fire. CRV should not be viewed as a static target but as a range of conditions that can likely promote resilience to disturbances. CRV is a new type of target that differs from pre-European settlement or what is commonly referred to as "historical reference forest structure." Broad ranges of tree density bracket CRV, and forested areas that fall within CRV for tree density may still need treatment to reduce density to meet other objectives or to address surface-fuel loads that have increased with fire suppression. Additional metrics such as percent of shade-tolerant species or individual clumps and openings should also be considered when managing for forest resilience. Horizontal and vertical heterogeneity metrics would further identify stands that are resilient at a smaller stand level and within stand scales, even in areas identified as "within CRV" conditions for tree density that may need treatment.

1.2 VEGETATION COMPOSITION

A diversity of tree and shrub species can confer greater resilience to climate change and beetle outbreaks. The vegetation composition also affects fire dynamics, water reliability, carbon pools and sequestration, and economic diversity pillars. Since European settlement and fire suppression and logging, forests shifted to increased coverage of shade-tolerant and fire-intolerant species like white fir and red fir, incense cedar, Douglas fir, and tanoak (Safford and Stevens 2017). Other species that are more shade-intolerant and fire-tolerant declined in coverage: ponderosa pine, Jeffrey pine, sugar pine, and black oak (Safford and Stevens 2017). With recent increasingly large and high-severity fire patches, it is likely that shrub cover may be concentrated in these areas of significant forest-cover loss compared to the pre-European settlement period.

METHODS

We characterized each 1-hectare pixel across the TCSI landscape for modeling in LANDIS-II based on 2019 SilviaTerra data and on guidelines provided by Mayer and Laudenslayer (1988) for categorizing habitat into California Wildlife Habitat Relationship (CWHR) habitat types. Species-specific biomass estimates from LANDIS-II generated by crosswalks with SilviaTerra data were used to classify pixels into one of fifteen CWHR habitat types, based on the species with the greatest biomass in a pixel. The mean percent of the landscape comprising each type was calculated for comparison to future modeling outputs.

CURRENT VEGETATION COMPOSITION

There were twenty-five tree species in TCSI along with two shrub types that were added based on the National Land Cover Database 2018. At lower elevations on the west slope, ponderosa pine (*Pinus ponderosa*), gray pine (*Pinus sabiniana*), Douglas fir (*Pseudotsuga menziesii*), and hardwoods dominate. Hardwoods include tanoak (*Notholithocarpus densiflorus*), bay laurel (*Umbellularia californica*), canyon oak (*Quercus chrysolepis*), Pacific yew (*Taxus brevifolia*), and California nutmeg (*Torreya californica*), all mostly occurring along drainages, and big leaf maple (*Acer macrophyllum*) and interior live oak (*Quercus wislizeni*) spread more evenly throughout low elevations.

At middle elevations on the west slope, mixed-conifer forests consisting of white fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*), and sugar pine (*Pinus lambertiana*) are concentrated on the northern end. Jeffrey pine (*Pinus jeffreyi*) are found at mid-high elevations on the west and east slope. Red fir (*Abies magnifica*), western white pine (*Pinus monticola*), and lodgepole pine (*Pinus contorta*) occur at elevations higher than the mixed conifer and extend on both the west and east sides of the crest. White alder (*Alnus rhombifolia*) and Pacific madrone (*Arbutus menziesii*) are mostly found along drainages. Aspen (*Populus tremuloides*), Washoe pine (*Pinus washoensis*), western juniper (*Juniperus occidentalis*), and whitebark pine (*Pinus albicaulis*) are dispersed throughout TCSI. Mountain hemlock (*Tsuga mertensiana*) is concentrated in the high elevation and southeastern side of TCSI but is also dispersed throughout. Mixed chaparral is limited to lower elevations, and montane chaparral is present in mid and high elevations.

The most prevalent forest types based on CWHR classifications were Sierran mixed-conifer forest comprised of Jeffrey pine, white fir, incense cedar, and sugar pine that is not dominated by any particular species (44%); Douglas fir (19%); white fir (14%); and red fir (6%). Subalpine conifer (5%), Ponderosa pine (4%), Jeffrey pine (4%), and more shade-intolerant and fire-tolerant species covered smaller areas. Where species compositions in the mixed-conifer and pine types have shifted toward shade-tolerant and in some cases fire-intolerant species (e.g., white fir, incense cedar), forest treatments can focus on removing these species to shift species composition, though unless the disturbance regime is also restored, the shift in dominance will be temporary. Certain aspects and elevations, however, may consist of purely fir stands that represent natural conditions. Additional forest types included lodgepole pine, juniper, aspen, montane hardwood, and montane riparian, but all covered <1% of the TCSI area. Chaparral and non-forested areas also covered less than 1% of the area (Figure 8). The least common were mixed chaparral in lower elevations and montane chaparral in higher elevations, juniper, montane hardwood, aspen, and montane riparian habitat types, which were all <1.3% of total cover.

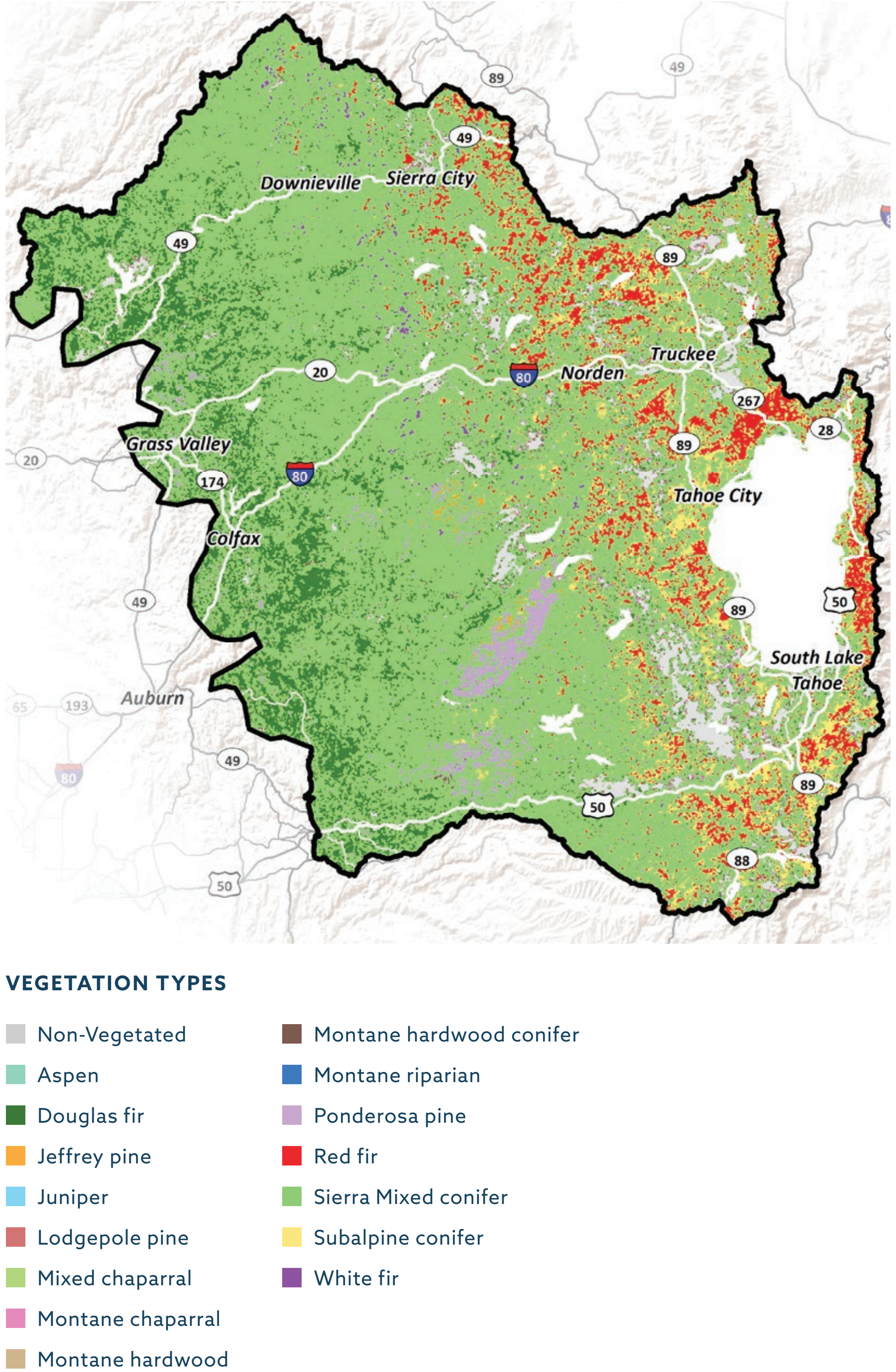


FIGURE 8. Vegetation types based on California Wildlife Habitat Relationship cover types and LANDIS model outputs, with cover type assigned based on dominant biomass, greater than 50%.

1.3 FOREST DISTURBANCE: FIRE, BEETLES, AND FOREST MANAGEMENT

Disturbance creates diversity, and fire served as an important feedback mechanism in disrupting succession and competition. The fire return interval, the time in between two successive fires, is a measure of the disturbance regime. The fire return interval departure—fire frequency pre-European settlement compared to recent fire history—is often used as an indication of the need to prioritize restoration-thinning and prescribed-fire treatments. When the fire return interval is frequent (mean ~11–29 years), as is the case for most of the mixed-conifer mid-elevation west slope area and the Defense zone around Lake Tahoe where fire suppression has been the predominant management principle, forests have missed multiple fire cycles. In contrast, in more alpine areas along the Pacific crest where the fire return interval is ~37–50 years, fewer fire cycles will have been missed as a result of fire-suppression policies, and less frequent management will be necessary to reduce the risk of large patches of high-severity fire. In the southeast corner of TCSI—subalpine areas and red fir forest—the fire return interval is the greatest, 133–200 years.

In practice, forests are managed using a variety of methods, including woody extraction, on-site processing, and/or fire. Disturbances affecting forest structure and composition consist of a range of disturbance types, and in the future, time-since-disturbance and disturbance-frequency calculations will need to include an array of disturbance types, given that thinning and beetle mortality are primary disturbance agents and will continue to be so for the foreseeable future. As such, we developed a composite measure of disturbance to represent current and future disturbance dynamics that combined the occurrence of fire, mechanical treatments (tree thinning and harvest), and intensive insect-caused mortality to evaluate the degree to which recent disturbance history deviated from historical regimes. We acknowledge that this combined representation of disturbance does not represent the varied ecological effects of different disturbances (Stephens et al. 2018). However, in combination with condition metrics, like live-tree density, they help reflect the multiple ecological aspects of disturbance and the degree to which forests are overdue for some type of disturbance.

Target conditions for disturbance frequency are selected with the expectation that a forest stand will adapt to future disturbance. When frequency is too high or too low, the character of the response will be altered to some degree, making the forest vulnerable to directional change or perhaps pushing a forest stand beyond a threshold of disturbance that could change its character and function. As such, target frequencies for disturbance represent conditions that are expected to enable stands to adapt and flex with future disturbance. By managing disturbance frequencies to the degree possible, it is expected that forests will continue to change over time in response to disturbance but that they will maintain their characteristic species, functions, and benefits over time. However, the types of disturbance, not just fire but a mix of fire and management, are novel in the context of historical disturbance regimes.

METHODS

We constructed a fifty-year disturbance history for fire and forest management by compiling all available datasets, plus a sixteen-year history for beetle-caused tree mortality, for 30-meter pixels across the TCSI landscape and compared them to estimated historical fire return intervals. The disturbance return interval (DRI) and measures of its departure were calculated as the difference between the pre-settlement median fire return interval (FRI, Safford and Van de Water 2014) and the current disturbance frequency, which included fire, mechanical thinning and harvest, mastication, and beetle-caused tree mortality. Fire-occurrence data (1970–2019) were provided by the Fire and Resource Assessment Program (FRAP) of the California Department of Forestry and Fire Protection. Aerial surveys of beetle-caused tree mortality were made from 2004 to 2019 (Forest Service Aerial Survey Program R5), as this was the longest dataset available for the entire TCSI landscape. Large, severe tree-mortality events due to bark-beetle outbreaks in the late 1980s and mid 1990s in TCSI were not included in this more recent aerial survey dataset. Harvest and treatment data were based on the Forest Service Activity Tracking System (FACTS) database (timber 1921–2019, hazardous fuels 1952–2019, and FACTS 1970–2019), which pertains to National Forest System (NFS) lands and non-federal lands where there were federal dollars funding the fuels reduction; the CAL FIRE non-industrial timber management plans (NTMPs 1993–2019); and the CAL FIRE timber harvesting plans (THPs 1997–2019). Additional forest-harvest and mortality data due to road building or other sources were inferred from the Hansen et al. (2013) database, which assesses global forest extent and change using Landsat imagery (2000–2019) across all lands. Fire and Resourse Assessment Program is in the process of developing a more comprehensive data source to track management treatments, which will be a valuable source of these data when it becomes available.

These data sources were used to calculate time since last disturbance, number of disturbances, percent disturbance return interval departure (PDRID), and disturbance delinquency for the years 1970–2019 at 30-meter resolution. PDRID was calculated following the percent fire return interval departure (PFRID) method of Safford and Van de Water (2014) but includes multiple types of disturbance:

Disturbance return interval (DRI) =

(# years of record)/(# disturbances + 1)

When current DRI > pre-settlement median FRI:

PDRID = (1-[pre-settlement median FRI/current DRI]) * 100

When current DRI < pre-settlement median FRI:

PDRID = (1-[current DRI/ pre-settlement median FRI]) * 100

The number of years of record used for this analysis was fifty for fire and management, with management databases beginning at different points in time, and sixteen for beetle-caused tree mortality. The results represent short-term departure when considering beetle disturbances. We also summarized the PFRID data for TCSI.

Additionally, a measure of disturbance delinquency (DD) was calculated to relate the time since last disturbance (TSLD) for a pixel compared to its fire return interval (FRI) as determined by Safford and Van de Water (2014). While a pixel may have missed one or more fire events in recent decades due to fire suppression and other management activities, it may have been disturbed recently and therefore would likely be a lower treatment priority compared to other pixels. Pixels that were disturbed within +/- 20% of their respective FRI were considered within their historical range and received an index of 0. Pixels disturbed more or less than +/- 20% FRI received a negative or positive number, respectively.

Disturbance delinquency (DD) =

TSLD > (FRI - [20% * FRI]) and TSLD < (FRI + [20% * FRI]): DD = 0

TSLD < (FRI - [20% * FRI]): DD = TSLD - (FRI - [20% * FRI])

TSLD > (FRI + [20% * FRI]): DD = TSLD - (FRI + [20% * FRI])

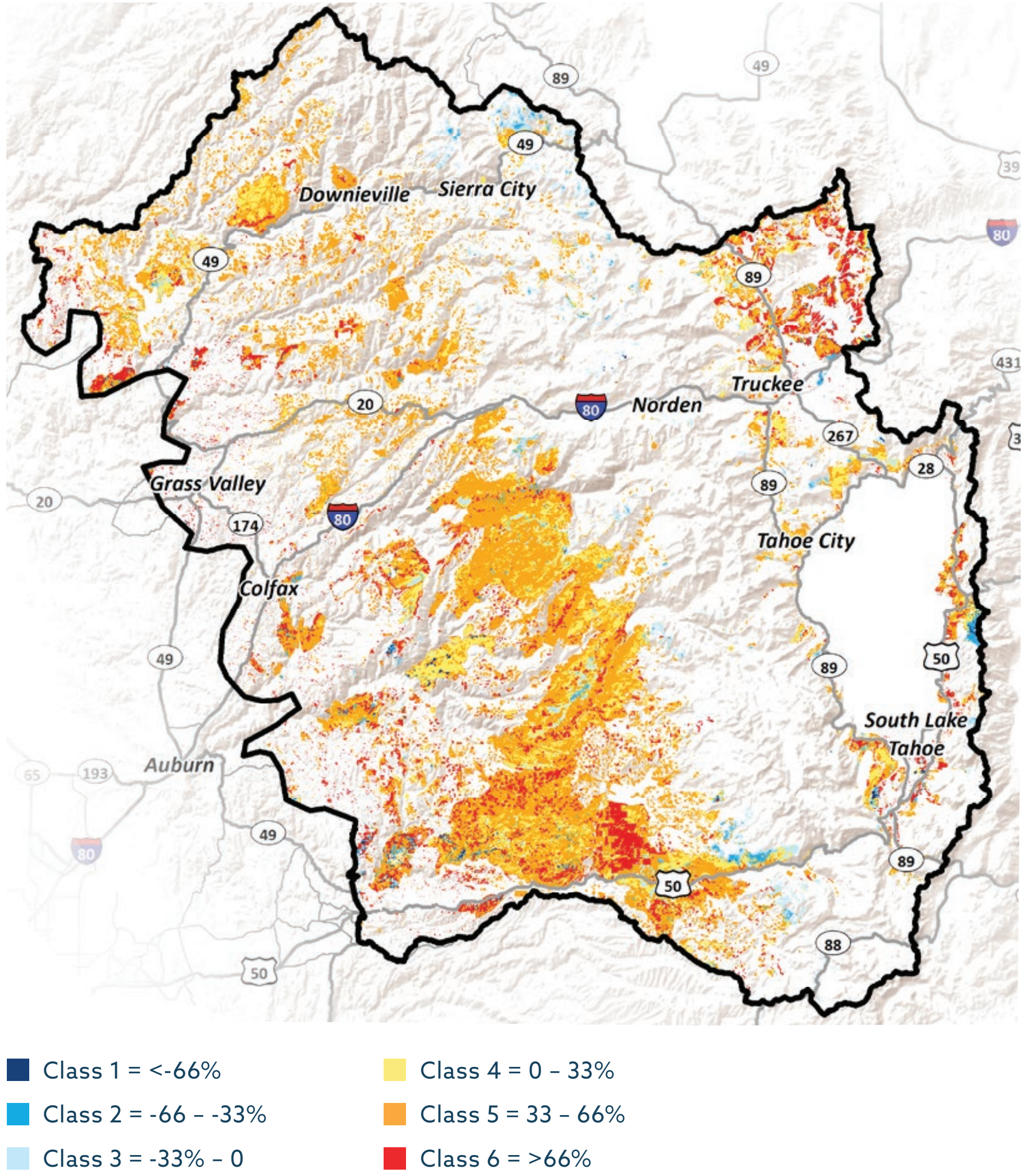
CURRENT DISTURBANCE FREQUENCIES, DEPARTURES, AND DELINQUENCIES

A total of 235,971 hectares, or 24% of the TCSI forested area, has burned, been treated or harvested, or died due to beetle infestation during the last fifty years (Figure 7). A total of 247 wildfires burned 120,363 hectares and accounted for more than half (52%) of the total disturbed area. More than one-third of the wildfire disturbance area was in a single fire, the 2014 King Fire, which burned a large high-severity patch that was 8,818 hectares in size (Jones et al. 2020, Kramer et al. 2021). Patch size and uniformity can impact forest regeneration, and a recent study of more than four hundred fires across California indicates that the King Fire burn patch was the most at risk to delayed or stunted natural forest regeneration of the fires evaluated (Stevens et al. 2017). Forest management accounted for 45% of the total disturbed area, and beetles 28%, which when combined with wildfire add up to 125%, as there were overlapping disturbances over the fifty-year period.

The PDRID showed positive percentages, or less frequent disturbances compared to the historical fire interval, for almost all of the disturbed area (90%, 211,361 hectares). Negative percentages, or places where the forest has been disturbed more than the historical fire return interval, covered only 18,802 hectares, or 8% of the disturbed area. The negative PDRID was mostly in clear-cut areas. Across TCSI, the PFRID based on 108 years of fire records beginning in 1908 is 66%±23% on average, indicating that most of the forest is highly

■ **FIGURE 7.** The last fifty years (1970–2019) of forest disturbances including forest harvest (clear cuts on Private Industrial land), restoration thinning and prescribed fire, fire, and beetle- and drought-caused tree mortality with the percent departure of these disturbances from the historical fire return interval. Positive values indicate where the forest has been disturbed but not as frequently as the historical fire return interval. Negative values indicate more frequent disturbance that the historical fire return interval, and values close to zero match the historical fire return interval.

OVERALL FOREST DISTURBANCE RETURN INDEX (1970–2019)



departed from historical fire return intervals (>67% means PFRID is classified as highly departed based on the interagency Fire Regime Condition Class). Approximately 17% (140,738 hectares) of the TCSI landscape has been disturbed, including all disturbances, within the time span of their respective fire return interval.

Some areas that have burned multiple times but are still forested, as well as recently treated forest areas, can serve as "safe zone" anchors for expanded use of fire as a management tool. In places like the Illilouette Creek Basin in Yosemite National Park, where managed wildfire reduced forest cover over the last forty years, past fires limited the spread and intensity of subsequent fires (Boisramé et al. 2017). Wildfire and prescribed-burn areas along with natural features such as rocky areas can provide anchors of low-density fuel where lower rates of spread and shorter flame lengths are expected under most conditions (Pollet and Omi 2002, Sneeuwjagt et al. 2013). These anchor areas can be used during active fire events to expand fire use as a management tool where fire suppression would otherwise be the primary objective. This is especially important considering limitations on mechanical thinning, including administrative restrictions such as Wilderness and Roadless zones as well as steep slopes or a lack of nearby roads that can make treatment prohibitively expensive.

This analysis is limited to the frequency of disturbance over the past fifty years, and we did not qualify uncharacteristic impacts—for example, those from large patches of high-severity fire. To more completely understand whether the landscape is out of sync with its historical disturbance regime, we would need to incorporate fire severity and patch size and uniformity (Stevens et al. 2017); define post-fire conditions as resilient or not; and isolate clear cutting. An additional limitation of PDRID is the fact that different disturbance agents likely affect tree density, biomass, and composition in different ways. Matching the historical fire return interval pre-European settlement with management and fire will not necessarily create more resilient conditions if the disturbance severity is outside of the historical disturbance regime. Additional interpretation of other components of the disturbance regime, especially severity, size, and spatial characteristics, should be considered when using PDRID and PFRID in planning restoration thinning and prescribed fire.

1.4 DISTURBANCE: DROUGHT VULNERABILITY

The analysis of drought vulnerability focused on precipitation (P), evapotranspiration (ET), and subsurface water use by trees. In forests with high tree densities, annual evaporative demand by the forest may routinely exceed annual precipitation. In these cases, trees rely on root-accessible groundwater. While over-year subsurface storage provides a buffer to sustain forest health during multiyear dry periods, root-accessible water storage is progressively depleted over time during extended periods of reduced precipitation, such as occurred in parts of the Sierra Nevada during the fall 2011 through fall 2015 dry period (Bales et al. 2018). In this case, depletion of subsurface storage combined with a typical dry-season demand from the vegetation was associated with the widespread drought stress and subsequent tree mortality observed across parts of the southern Sierra Nevada (Klos et al. 2018; Goulden and Bales 2019).

Forest disturbance by wildfire, drought, pests, disease, and management actions reduce tree density and basal area in forests, which can decrease evaporative demand and maintain ET at levels that can be met by precipitation plus withdrawal from subsurface storage (ΔS) (Roche et al. 2018). With climate change, increases in vegetation growth and ET are expected at higher elevations and latitudes, which are not currently water limited (i.e., annual P-ET>0) and will likely increase stress on these upper-elevation forests and reduce streamflow in watersheds in the Sierra Nevada.

Mapping P-ET provides estimates of water availability for both forest health and runoff for the TCSI landscape. Cumulative P-ET during a multiyear dry period has been shown to be correlated with metrics of drought stress, including change in NDMI (Normalized Difference Moisture Index) and the Forest Service's aerial surveys (dead trees per hectare) (Goulden and Bales 2019). Traditional drought metrics, developed for agriculture, are more poorly correlated with forest drought stress and tree mortality (e.g., Standardized Precipitation Index, Standardized Precipitation-Evapotranspiration Index, Palmer Drought Severity Index).

METHODS

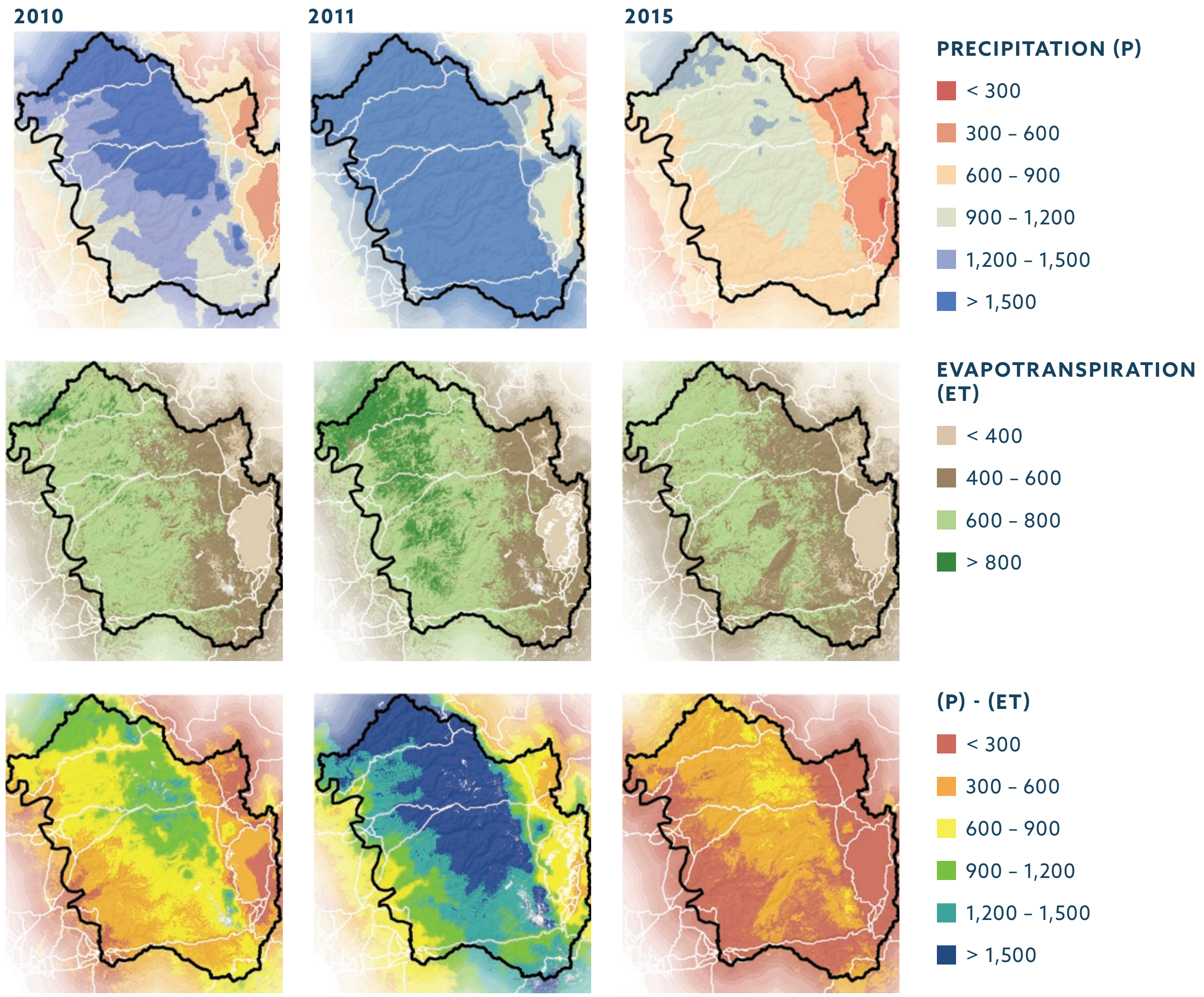
We first described precipitation and evapotranspiration average annual rates from 1985 to 2018 for the major watersheds in TCSI. Annual precipitation values were taken from the daily 800-meter-resolution PRISM dataset (PRISM 2018), with annual evapotranspiration scaled from measurements at eddy-covariance towers using Landsat data (Roche et al. 2020). Runoff (Q) is a function of precipitation (P), evapotranspiration (ET), and change in groundwater storage (ΔS), also called the water balance.

$Q = P - ET + \Delta S$

To check the water balance, we summed total annual runoff (P-ET) per basin for two basins and compared it to full natural streamflows from the California Department of Water Resources database—Yuba River at Smartville, ID=YRS, California Data Exchange Center, 2019, and American River at Folsom, ID=AMF, California Data Exchange Center, 2019 (Roche et al. 2020).

Next, we combined spatial data on the maximum cumulative P-ET deficit from 1985 to 2018 with the maximum seasonal withdrawal from storage in a single year. The maximum P-ET deficit is the maximum value of multi-year subsurface, plant-accessible water drawdown. This occurs when annual precipitation is less than evaporative demand, resulting in a net annual drawdown of stored subsurface water. The maximum seasonal withdrawal from storage is the amount of water withdrawn by trees to satisfy ET demand through the dry season. We added these two datasets to estimate the maximum amount of drawdown of subsurface water storage that would occur if the driest multi-year period was followed by the driest single year in the study period. High values represent greater vulnerability because there is a limit to the depth at which roots can access water.

■ **FIGURE 9.** Precipitation is highly variable compared to evapotranspiration in average (2010), wet (2011), and dry (2015) years. Precipitation minus evapotranspiration depicts the runoff in the third row. All figures are in mm.

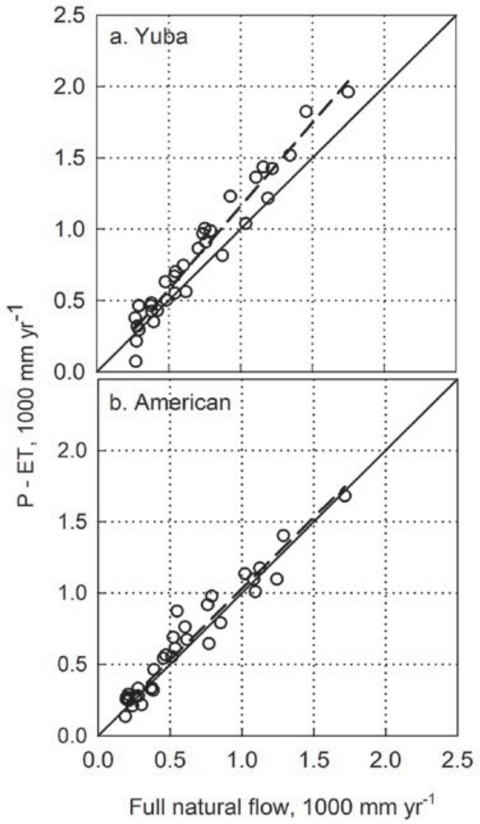


CURRENT P-ET CONDITIONS

Precipitation varies considerably from year to year, whereas evapotranspiration does not vary as much (Figure 9). Average precipitation (+stdev) is higher in the Yuba River watershed (1479+500 mm/yr) compared to the American River watershed (1228+430 mm/yr) and is much lower in the Truckee River watershed (883+340 mm/yr). Evapotranspiration varied little between wet versus dry years, averaging about 675+57 mm/yr across the Yuba River watershed, 619+54 mm/yr in the American River watershed, and 441+50 mm/yr in the Truckee River watershed. The large interannual differences in precipitation across TCSI, indicated by the coefficient of variation (CV), were amplified to give even larger relative interannual differences in P-ET. CV averaged 0.35 for precipitation and 0.63 for P-ET across the TCSI area, whereas ET is similar in wet versus dry years (CV=0.09).

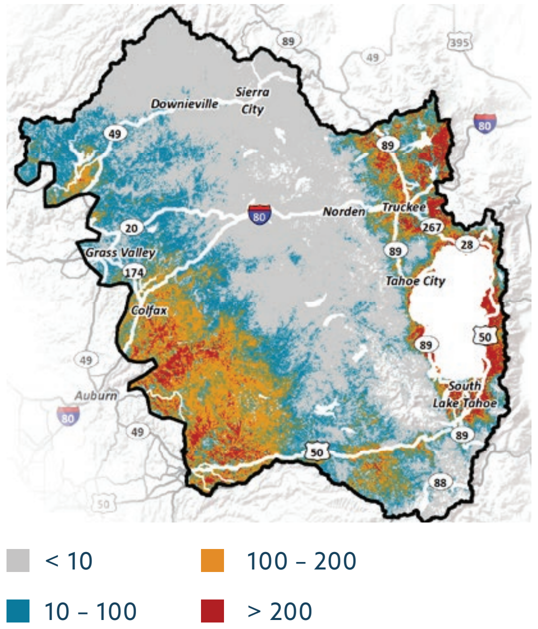
P-ET compared well with full natural flow values from the California Department of Water Resources (Figure 10). The P-ET values exhibit a median bias of about 130 mm for the Yuba River watershed and 40 mm for the American River watershed. These values, about 5% of precipitation or 10% of full natural flow, are within the expected uncertainty of the analysis, and indicate the modeled discharge, P-ET, matches the full natural flow. Note that annual values of P-ET do not account for ΔS, which is reflected in dry years having slightly higher runoff than would occur in the absence of multi-year storage to support ET. Conversely, in wet years some precipitation will go to replenishing over-year storage deficits, especially when following multi-year dry periods (Bales et al. 2018).

■ **FIGURE 10.** Runoff for two watersheds based on precipitation (P) minus evapotranspiration (ET) compared to full natural flow values shows good alignment.

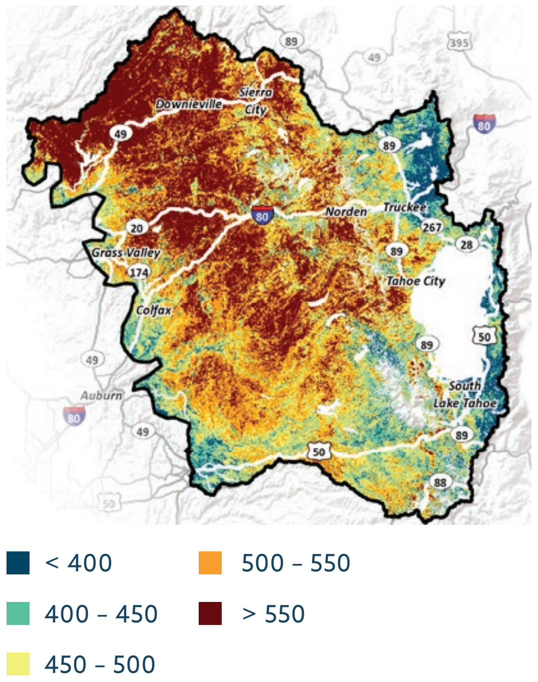


■ **FIGURE 11.** A drought vulnerability index identifying areas where tree roots may not be able to draw more water from the ground (c) calculated by adding the over-year drawdown of subsurface water storage (a) with the maximum seasonal withdrawal from storage in a single year (b).

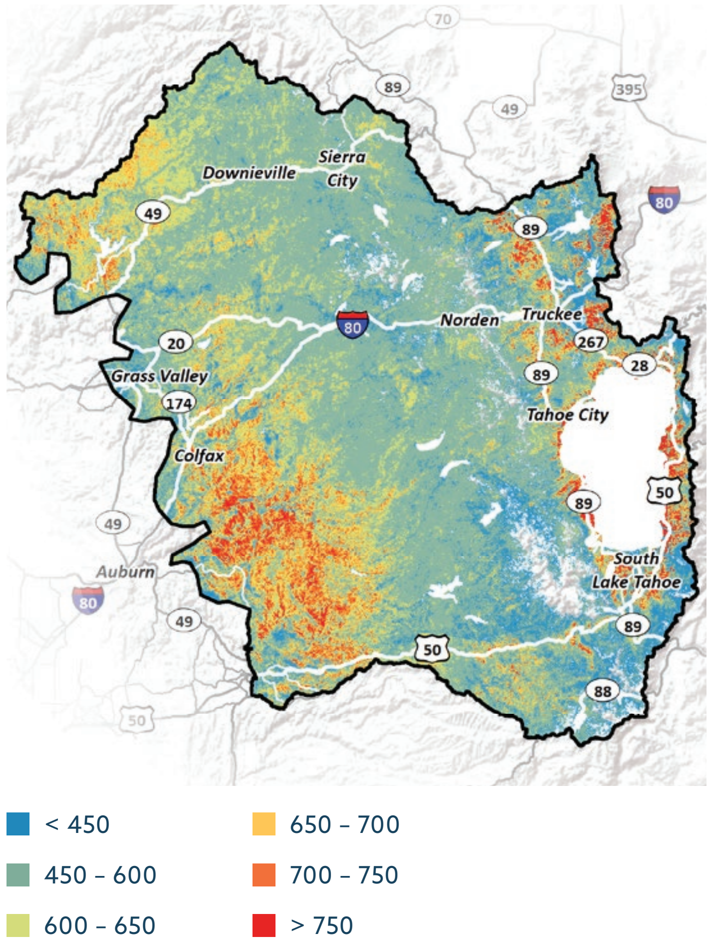
A. MAXIMUM CUMULATIVE 1985–2018 DRAWDOWN (mm)



B. MAXIMUM DRY SEASON WATER USE FROM STORAGE (mm)



C. DROUGHT VULNERABILITY INDEX



Maximum cumulative P-ET deficit was the highest in the dense forests of the lower American River basin (200–300 mm yr-1) and in the Truckee River basin (>300 mm yr-1). Note that most of these values are for the recent four-year drought and would be larger had the drought persisted longer. Maximum seasonal withdrawal from storage values, representing dry-season ET, are highest in the most productive forests, with broad areas more than 450 mm yr-1 and smaller areas more than 600 mm yr-1. After adding the maximum cumulative P-ET and the maximum seasonal withdrawal, we identified areas where tree roots may not be able to draw more water from the ground during a drought and would likely be susceptible to drought stress and beetle-kill (e.g., > 600 mm/year as suggested by Roche et al. 2020). This may be a conservative estimate of drought-vulnerable areas, as younger trees and trees unable to tap into deeper groundwater may be vulnerable outside of the areas identified. Further, climate change and shifts from snow to rain with earlier runoff periods will impact drought vulnerability.

The drought-vulnerable areas are concentrated in the lower-elevation American River watershed and Yuba River watershed, the marginal areas around Lake Tahoe, and small concentrated areas north and south of the city of Truckee (Figure 11). Areas with low vulnerability have either low annual evapotranspiration, high average annual precipitation, or both. Areas susceptible to drought stress (>600 mm/year) cover 38% of the forested landscape (766,000 hectares), indicating a large area at risk to tree mortality from drought stress and possible beetle outbreaks.

PILLAR 2: FIRE DYNAMICS

Edward Smith, Joe Scott, and Tanushree Biswas

FIRE DYNAMICS: Fire burns in an ecologically beneficial and socially acceptable way, perpetuating landscape heterogeneity and rarely threatening human safety or infrastructure.

ELEMENT	METRIC	TARGET CONDITION
Severity	High-intensity fire	Decrease risk

There is a growing concern about the resilience of fire-adapted, dry forests because of climate change, fire suppression, and the removal of the largest, most resilient trees. Combined, these drivers have led to overcrowding, mortality, and the accumulation of hazardous forest fuels. Such conditions contribute to the spread of high-intensity fire, resulting in an unprecedented increase in the size and severity of wildfires in forests of the Sierra Nevada, and more broadly across the western United States. The Sierra mixed-conifer forests that dominate the TCSI landscape evolved with frequent low- to moderate-severity fire with small proportions of high severity in the burned area prior to European settlement (Safford and Stevens 2017). A small percentage of the TCSI landscape contains forests that historically had longer fire return intervals, such as the red fir forest type. In these ecosystems, the incidence of high severity was a larger component of historic fire dynamics (Mallek et al. 2013).

There is an increasing awareness for the need to address fuels and the growing fire risk, but the size and extent of the affected area requires a strategic approach to treat areas with the highest restoration needs and in configurations that will confer the greatest benefit to neighboring untreated areas. The process of selecting areas for treatment is well supported in the literature through various means of spatial hazard quantification and risk assessment (Thompson et al. 2016). “Hazard,” here, is defined as the product of the calculated probability of a wildfire, derived through Monte Carlo simulation, and the potential intensity of fire, based on local weather and fuels and interpreted as flame length (Scott et al. 2013).

METHODS

We used fire-simulation modeling to quantify fire hazard across the TCSI area. The FSim large-fire simulator was used to quantify wildfire hazard across TCSI at a pixel size of 90 meters. FSim is a comprehensive fire occurrence, growth, behavior, and suppression simulation system. It uses locally relevant fuel, weather, topography, and historical fire occurrence information to make a spatially resolved estimate of the contemporary likelihood and intensity of wildfire across the landscape. The vegetation dataset was derived from LANDFIRE 2014 with modification to reflect fuel disturbances between 2015 and 2018. Fuel disturbances were incorporated based on wildfire datasets: Monitoring Trends in Burn Severity, Rapid Assessment of Vegetation Conditions after Wildfire, and Geospatial Multi-Agency Coordination fire perimeter data. Additional disturbances from forest harvest were based on Forest Service Activity Tracking System data and tree-mortality data from the Ecosystem Disturbance and Recovery Tracker (eDaRT). The fuelscape was created using the LANDFIRE Total Fuel Change Tool.

We classified flame lengths greater than eight feet as high-intensity fire, similar to what would result in high-severity fire effects on vegetation, which is measured post-burn. Eight-foot flames are considered high-intensity fires, while six-foot lengths are moderate intensity, and four-foot lengths are low intensity. Eight-foot flame lengths indicate fire that would be challenging to suppress even with air defense and in places where the fire would likely cause >75% tree mortality. To prioritize places in TCSI with the highest risk of high-intensity fire, we isolated eight-foot flame lengths with a greater than 60% burn probability (upper quartile of the data) and delineated continuous areas based on the four-neighbor rule for areas >100 hectares. These are not fire patches but continuous cells with high probability of high-intensity fire.

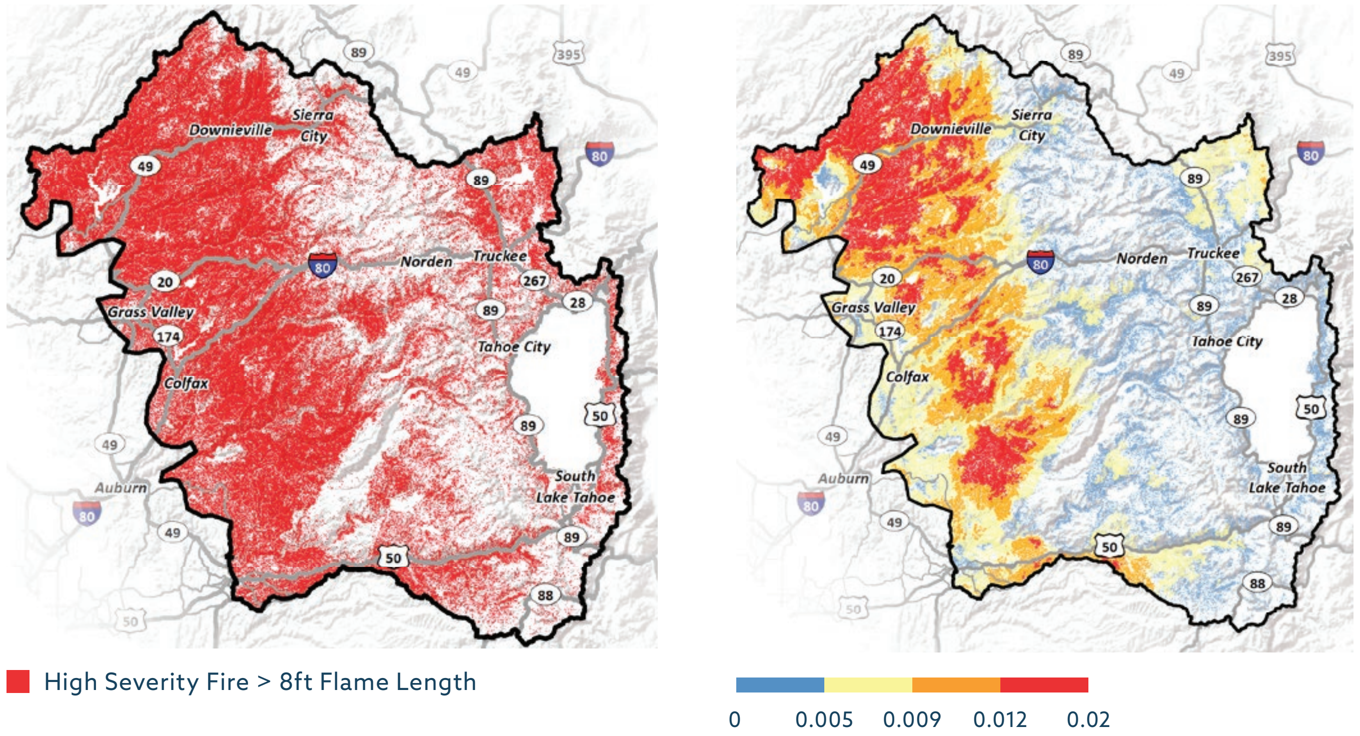
CURRENT RISK OF WILDFIRE AND SEVERITY CONDITION

Potential high-intensity fire covered 469,586 hectares, equivalent to 57% of the forested landscape in TCSI (Figure 12). High-intensity fire risk is prevalent across TCSI except in the highest-elevation Pacific crest and places that have burned recently at high severity, like the King Fire footprint. The extensive area of potential high-intensity fire indicates widespread risk across the landscape (Figure 12). The burn probability of high-intensity fire varies across TCSI, with higher probabilities

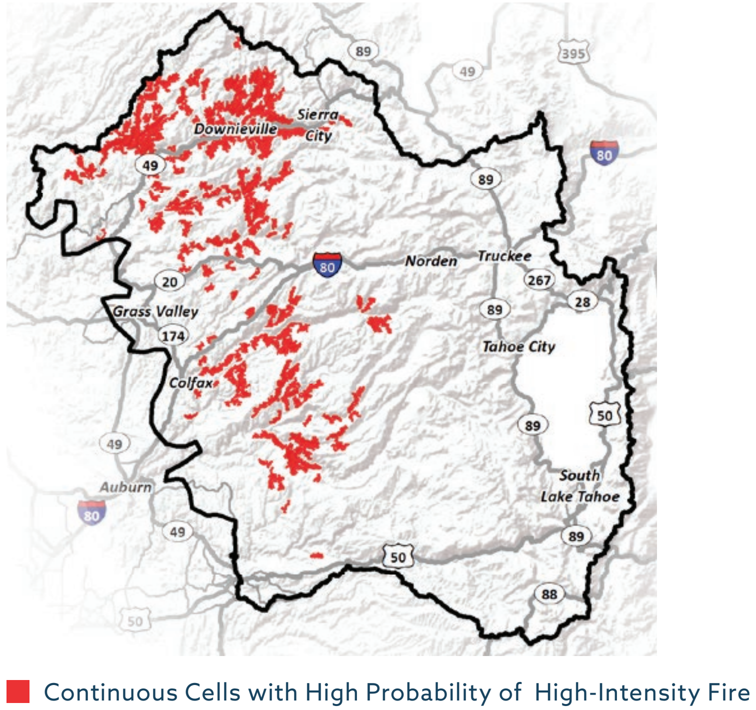
■ **FIGURE 12.** Potential high-intensity fire based on flame lengths greater than eight feet (a) burn probability of those areas (b), and isolated continuous cells with high probability of high-intensity fire (c).

A. HIGH INTENSITY FIRE

B. HIGH INTENSITY FIRE WITH BURN PROBABILITY SHOWN



C. CONTINUOUS CELLS WITH HIGH INTENSITY FIRE AND HIGH PROBABILITY



on the west slope and northwest portion of the landscape. These probabilities are relative, and even areas shown with low probability may still burn at high intensity. Finally, we identified 6% of the forested landscape (48,501 hectares) at risk of high-intensity fire, with continuous cells ranging from 100–5,000 hectares, indicating where there is elevated risk of large high-severity patches if fire were to burn these areas under conditions similar to those modeled.

PILLAR 3: FIRE-ADAPTED COMMUNITIES

Edward Smith, Joe Scott, and Tanushree Biswas

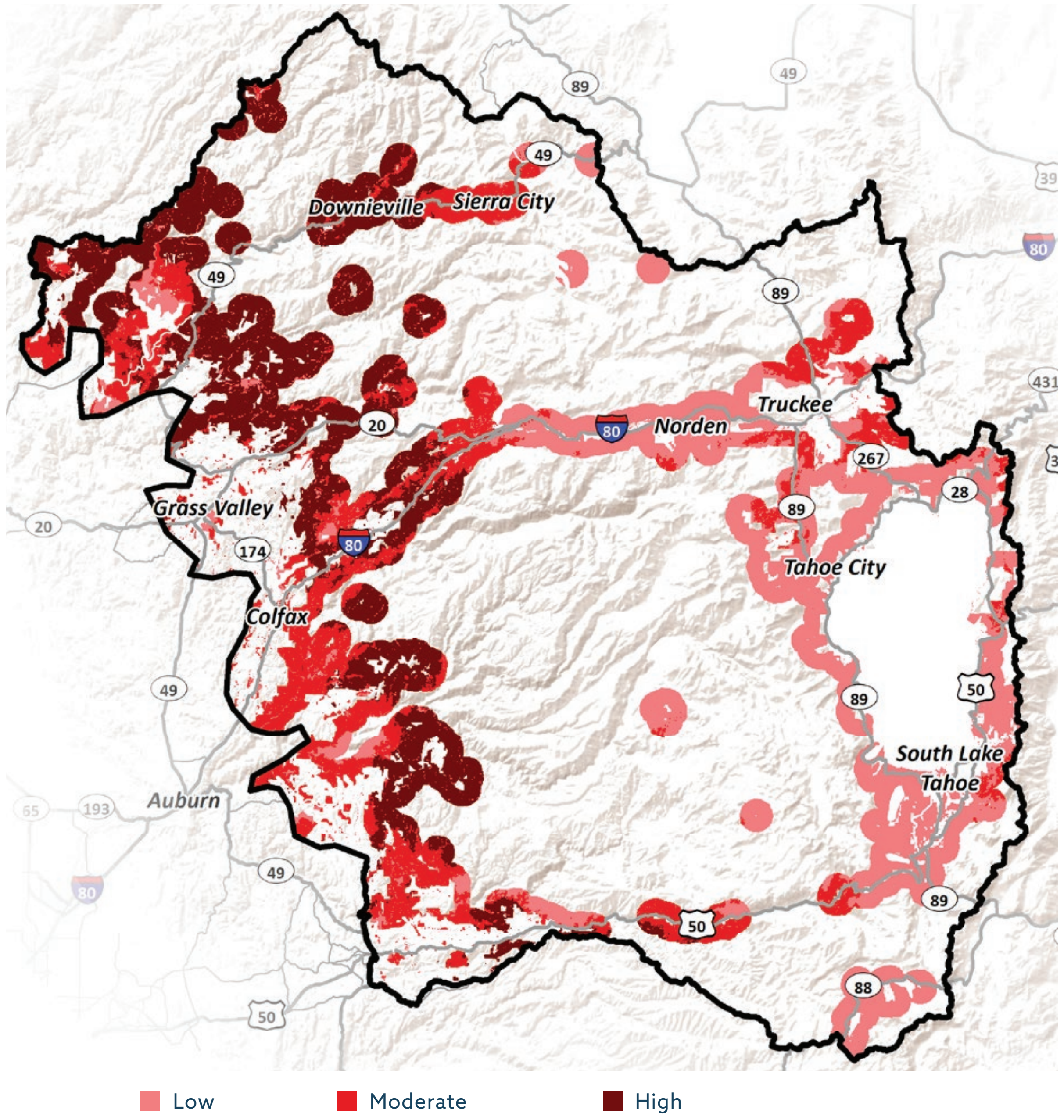
FIRE-ADAPTED COMMUNITIES: Communities live safely with wildfire and are accepting of management and natural ecological dynamics. Beneficial fire is encouraged, and unwanted fires are suppressed.

ELEMENT	METRIC	TARGET CONDITION
Hazard	Fire	Decrease fire risk

There are ten cities and four major highways within TCSI. The largest cities are located along Interstate 80 and Highway 50, which run laterally across the Sierra Nevada to the north and south of Lake Tahoe, respectively, and Highways 89 and 49, which run north to south through the landscape. There are more than 105,000 people living in the TCSI landscape. Along Interstate 80 are the cities of Colfax (population of ~2,000), Nevada City (~3,200), Grass Valley (~13,000), and Truckee (~16,500). At the north end of Lake Tahoe are Tahoe City (~2,100) and Incline Village (~8,800). Along Highway 50 are the cities of Camino and Pollock Pines (~8,600 collectively), South Lake Tahoe (~22,000), and Meyers (~29,000). Many smaller communities, such as Georgetown (~2,400) and Foresthill (~1,700), are intermixed within the wildlands across TCSI. In terms of water infrastructure, there are three major water agencies (Yuba, Placer County, and El Dorado County) with associated water systems and ten major reservoirs in the TCSI landscape. There are five large ski resorts (Heavenly, Kirkwood, Boreal Mountain, Squaw Valley, and Sierra-at-Tahoe) plus four smaller ski resorts (Homewood Mountain, Northstar California, Diamond Peak, Mt. Rose) located in this landscape.

The risk and threat of wildland fire to communities and infrastructure, such as roads and powerlines, can be reduced through a variety of forest management approaches that focus on the wildland-urban interface (WUI) and on communities and infrastructure. Community-based measures focus on community preparedness (e.g., ingress and egress routes, defensible space around structures, home hardening, fire-safe councils, and community protection plans). WUI-focused measures generally entail decreasing the risk of fire by reducing fuels and changing forest structure to support low-severity fire. Research indicates that fuels-reduction activities can lower fuel hazards and risk to human communities and that placement of treatments strategically (i.e., in close proximity to values at risk and in areas where hazard levels are highest) can improve chances of being successful

FIGURE 13. Relative fire risk to communities.



in reducing risk (Scheller et al. 2019, Ager et al. 2019). Of course, the threat of fire to communities is also reduced by managing for resilient forests and for a functional fire dynamic across the whole landscape (see Pillars 1 and 2). Wildfires can spread several miles in short periods and put communities that are miles from the ignition point at risk. The WUI is commonly defined by two zones: the Defense zone, which is typically the area within 804 meters (0.25 miles) of development, and the Threat zone, which is 2,012 meters (1.25 miles) from development (Healthy Forests Restoration Act of 2003, 16 U.S.C. §§108–148). In practice, the Defense zone depends on the topography, prevailing winds, and fuels and may expand in width where there are values at risk from fire.

METHODS

We identified WUI areas consistently across the TCSI landscape using the ICLUS v2.1 database for the Fourth National Climate Assessment, SSP2 (U.S. EPA 2017). ICLUS is a raster-based (1-km cell) growth model based on social, economic, and technological trends, called shared socioeconomic pathways (SSPs). The categories of development included urban, exurban, and suburban with a density from two dwelling units/40 hectares to ten dwelling units/0.4 hectares, along with commercial, industrial, institutional, transportation, and golf courses/parks. The Defense and Threat zones were identified as defined by the Healthy Forests Restoration Act of 2003 (16 U.S.C. §§108–148). The Defense and Threat zones differ from Forest Service and CAL FIRE definitions to make the WUI definition consistent across TCSI.

We analyzed the risk of high- and moderate-intensity fire based on four-foot flames in the Defense and Threat zones. The four-foot flame length was based on other precedent risk assessments in the Sierra Nevada as a threshold for when infrastructure would be significantly impacted. We categorized the relative risk to communities as low, moderate, or high based on burn probability of four-foot flames. Fire can present a hazard to communities in wildland areas, but the degree of risk varies with topography and fuels conditions. The relative risk highlights where there is a higher probability of fire while acknowledging that all communities are at some level of risk.

CURRENT STATUS OF FIRE-ADAPTED COMMUNITIES

The Defense and Threat zones covered 279,998 hectares, or 29% of the TCSI area. Within these two management zones the risk of high- and moderate-intensity fire covered 86% (247,970 hectares). The probability of flame lengths greater than four feet covers almost all community areas (Figure 13).

PILLAR 4: BIODIVERSITY CONSERVATION

Angela White and Kristen Wilson

BIODIVERSITY CONSERVATION: The network of native species and ecological communities is sufficiently abundant and distributed across the landscape to support and sustain their full suite of ecological and cultural roles.

ELEMENT	METRIC	TARGET CONDITION
Focal species	Habitat, Occurrence	Increase
Species diversity	Number of species	Maintain

Biodiversity metrics in this assessment were based on estimates of overall species richness and the number of California spotted owl territories supported in the TCSI landscape. Estimates of species richness were based on whether habitat that supported high-quality reproductive habitat for a given species existed. These metrics provide a strong foundation for interpreting current and future conditions based on LANDIS-II modeling. We based target conditions on the objective of no net loss.

4.1 SPECIES DIVERSITY

METHODS

We used the California Wildlife Habitat Relationship (CWHR) System (California Department of Fish and Wildlife 2019) to characterize habitat suitability for all terrestrial vertebrate species in the TCSI landscape, which in turn was used to make inferences about the degree to which the landscape supports native species richness. To attribute each 1-hectare cell with a CWHR habitat type, we compiled dominant vegetation type from LANDIS-II 2020 outputs (described above in section 1.2) and then used methods previously developed for the Lake Tahoe West Restoration Partnership (White et al. forthcoming) to derive seral stage: early (CWHR size classes 1–3), mid (size class 4), and late (size class 5). We also classified estimates of canopy cover into three broad classes based on tree density: S = sparse, M = moderate, D = dense. Habitat type, seral stage, and canopy cover were combined to generate a CWHR habitat type, which was then used to assess habitat suitability for each species in the landscape based on the CWHR database. The CWHR database provides habitat suitability values (low = <0.33, moderate = <0.66, and high = ≥ 0.66) for each species based on expert opinion and likelihood of use of each habitat type for breeding, foraging, and cover. For this assessment, we only included high-suitability reproductive habitat in our calculations of species richness and focal species habitat, values ≥ 0.66.

CURRENT SPECIES RICHNESS

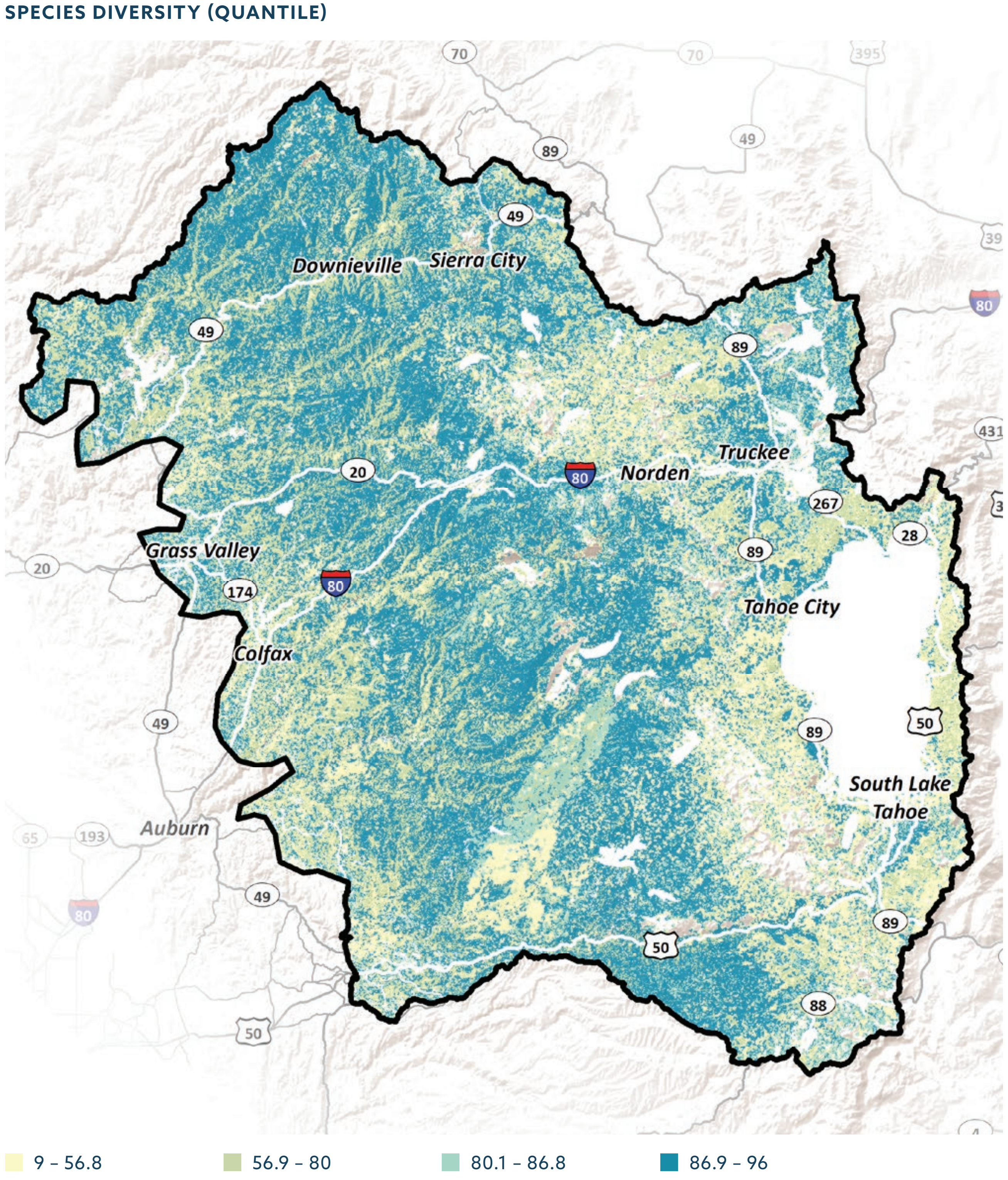
In total, we identified 195 species that used the habitat types modeled across the TCSI landscape for reproduction. Based on current conditions, high-suitability reproductive habitat in TCSI supports 148 species. Habitat supporting the greatest number of species occurred in mid-elevation areas classified as Sierran mixed conifer (Figure 14), where a large proportion of the landscape was estimated to be suitable for more than 5 species. Pockets of high-suitability reproductive habitat also occurred in the southeast and northwest corners of the Lake Tahoe watershed and the northeast corner of TCSI. Although river drainages and high-alpine areas tended to support habitat for a lower number of species, it is likely that these areas provide high-value reproductive habitat for many species that specialize in these habitats.

4.2 FOCAL SPECIES OCCURRENCE AND REPRODUCTIVE HABITAT

METHODS

We identified fourteen focal species based on their sensitivity to impacts from restoration thinning, prescribed fire, and wildfire. We used multiple sources to identify species: 1. expert interviews, 2. review of National Forest planning

■ **FIGURE 14.** Modeled terrestrial vertebrate diversity including birds, mammals, and reptiles based on habitat relationships.



documents, 3. review of forest restoration permitting documents for forest projects, and 4. input from the TCSI Steering Committee. We interviewed four wildlife biologists and two Sierra Nevada wildlife experts during fall 2018; the purpose was to understand what species would be informative for evaluating the impacts of restoration thinning and wildfire. The experts referred us to relevant planning and permitting documents. After reviewing these materials, we set the following criteria for identifying focal species: 1. included in forest restoration permitting documents for recent forest projects within TCSI and 2. listed as one of the following: Region 5 Sensitive Species; U.S. Fish and Wildlife Service listed, proposed, and candidate species; or Category 3 Management Indicator Species.

Fourteen focal species were identified: four species associated with late seral habitat (California spotted owl, northern goshawk, northern flying squirrel, Pacific marten), one species associated with burned areas (black-backed woodpecker), two amphibians (Sierra Nevada yellow-legged frog, foothill yellow-legged frog), three bat species (pallid bat, Townsend's big-eared bat, fringed myotis), three hunted species (mule deer, mountain quail, sooty grouse), and one species associated with shrubland (red fox sparrow) (Table 4). Two of these species, the California spotted owl and Sierra Nevada yellow-legged frog, are considered imperiled, based on their NatureServe status. One species, the foothill yellow-legged frog, is considered vulnerable. All three bat species and the Pacific marten are apparently secure, meaning not vulnerable or imperiled, and the other focal species are considered secure.

We mapped recent observations of nine focal species from 2008 to 2018 and critical habitat for Sierra Nevada yellow-legged frogs as presence or absence at the 1-hectare scale. Occurrence data were not available for the other four focal species: mule deer, mountain quail, sooty grouse, and red fox sparrow. Occurrence data were acquired from the Forest Service Natural Resource Information System database, the California Department of Fish and Wildlife Spotted Owl Observations Database, the U.S. Fish and Wildlife Service database, and the California Natural Diversity Database. The occurrence data especially for certain species are very incomplete; therefore, inferring places that need to be restored to protect focal species is limited by the lack of data.

We collected observation data on the California spotted owl and northern goshawk from the Forest Service Natural Resource Information System database and the California Department of Fish and Wildlife Spotted Owl Observations Database from 1981 to 2018, a longer time period than the other focal species occurrence data. Circle buffers were based on Protected Area Centers (PACs) for Threat, General Forest, Roadless, and Wilderness zones (121 hectares) and Protected Zones (PZs) on private land except in the Defense zone (40 hectares, Sierra Pacific Industries 2020), defined as active observations of pairs, nests, or young. We compared the total area and suitable habitat in the circle PACs to the Forest Service polygon PACs, which are used in planning and permitting project documents and are selections of the most suitable nesting and roosting habitat on National Forest land based on aerial photography and field verification. We mapped reproductive habitat for the California spotted owl across TCSI and within PACs and PZs following the method described in section 4.1. Finally, we overlaid the high-intensity fire risk from Pillar 2 with the California spotted owl PACs and PZs to understand how many nesting sites are at risk.

CURRENT FOCAL SPECIES HABITAT AND OCCURRENCE

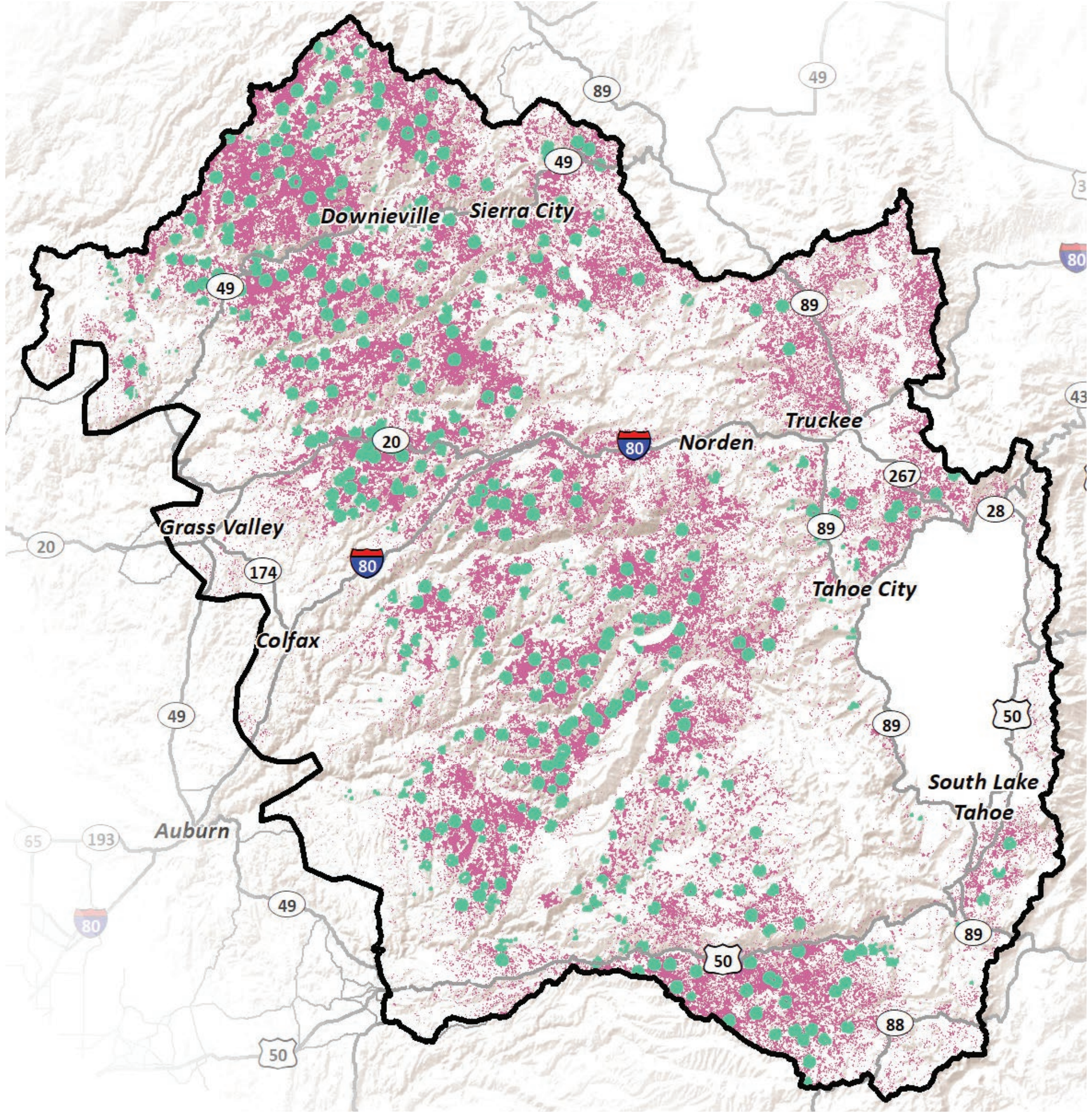
The California spotted owl had the greatest number of observations of any of the focal species covering 75,972 1-hectare cells (Figure 16). We mapped 429 California spotted owl PACs and PZs within TCSI. The majority of PACs fell in the Public National Forest (229), with an additional 27 in Roadless areas, and three in Wilderness areas. The majority of nesting sites on National Forests reflects where sites are commonly mapped compared to other management zones. There are 136 PACs or PZs depending on the land ownership within the Threat zone, or within 1.25 miles of developed areas. Finally, there are 29 PZs within the Private Industrial zone and 5 within the Private Non-industrial zone. All but one PAC and two PZs are at risk of high-intensity fire based on the fire modeling described in pillar two. These three owl nesting sites not at risk are within the footprint of the recent King Fire and may have been abandoned since the fire in 2014.

The U.S. Forest Service polygon PAC boundaries cover a slightly smaller total area (46,408 hectares) than the circle PACs and PZs, which reflects the fact that the polygons are based on the nesting and roosting habitat criteria and National Forest land. The reproductive habitat within the polygons is larger (23,748 hectares, 51% of the total area within PAC polygons) than for the circle buffers (22,600 hectares, 46% of the total area within PAC circles), as expected, because the polygons are drawn to encompass reproductive habitat. A five percent difference in reproductive habitat in the circle PACs compared to polygon PACs indicates that the circle buffers will work for National Forest and private land to delineate high value reproductive habitat. The difference between polygons on public land and circle buffers on private land would have made a synthesis across both management types challenging. Knowing that circles encompassed reproductive habitat similarly to polygons provided confidence that circle buffers can be used to approximate habitat suitability and distribution across all ownerships, a critical need for assessing an all-lands approach in TCSI.

The total area of reproductive habitat for California spotted owl across TCSI is 226,889 hectares (28% of the forested landscape) in 2018. Owl habitat was distributed across TCSI except in low-elevation west slope areas, recent fire scars, and alpine areas with rock cover. PACs and PZs cover 49,342 hectares (6% of the forested landscape, Figure 15). The Northern goshawk had the second largest number of observations, covering 53,500 1-hectare cells, and the foothill yellow-legged frog was third, with 11,383 cells (Figure 15). The three hunted species and the Pacific marten had few observations across TCSI. Only one species had critical habitat designated—the Sierra Nevada yellow-legged frog. The frog's critical habitat and observations covered 119,726 hectares in the high-elevation west slope of TCSI. Maintaining existing and increasing focal species habitat is a goal for TCSI to promote species persistence and resilience to multiple disturbances. This assessment provides a baseline for focal species habitat based on current conditions.

FIGURE 15. California spotted owl nests on National Forests and Private Land and suitable reproductive habitat.

CALIFORNIA SPOTTED OWL ACTIVE OR SUSPECTED NESTING SITES AND SUITABLE REPRODUCTIVE HABITAT

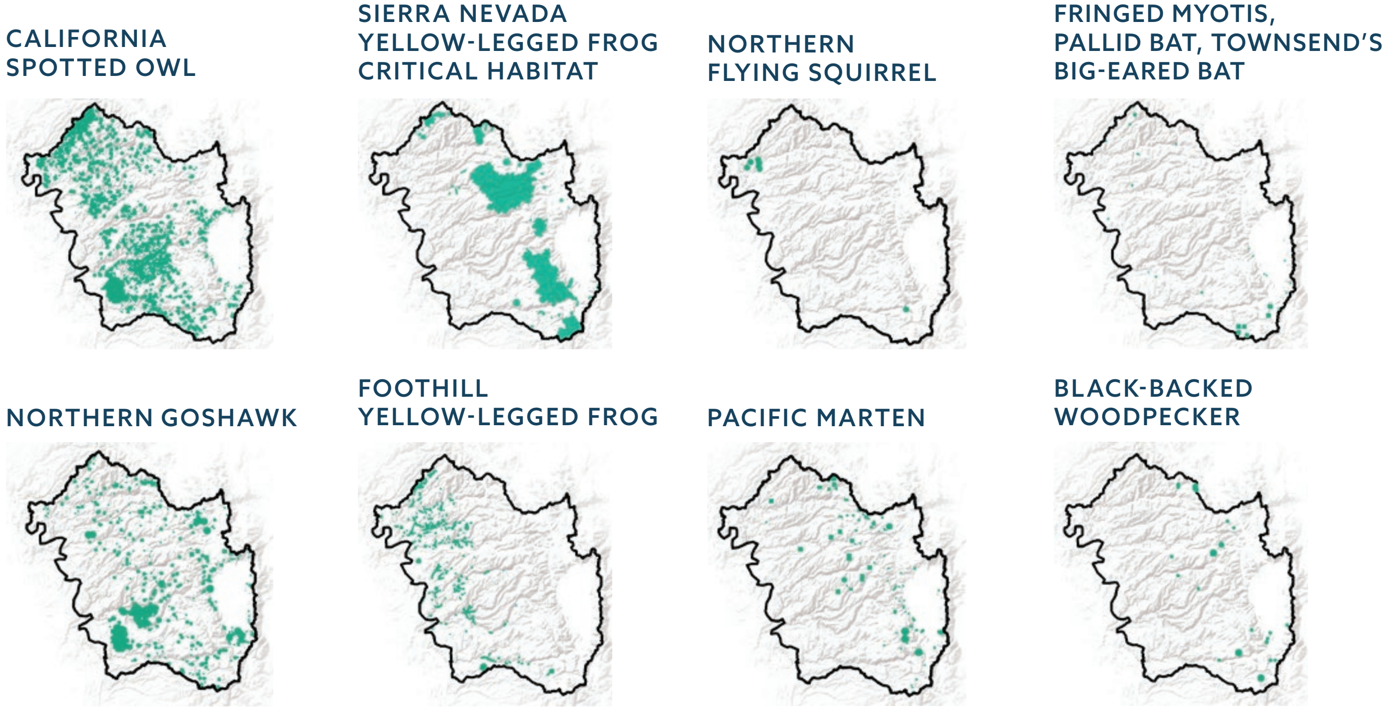


☐ California Spotted Owl PACs and PZs 🟪 California Spotted Owl Habitat

TABLE 4. Focal species for TCSI and their total reproductive habitat area in 2019.

#	Common Name	Scientific Name	Occurence Data	CWHR Habitat
1	California spotted owl	*Strix occidentalis occidentalis*	Y	Y
2	Northern goshawk	*Accipiter gentilis*	Y	Y
3	Northern flying squirrel	*Glaucomys sabrinus*	Y	Y
4	Pacific marten	*Martes caurina*	Y	Y
5	Black-backed woodpecker	*Picoides arcticus*	Y	Y
6	Sierra Nevada yellow-legged frog	*Rana sierrae*	Y	Y
7	Foothill yellow-legged frog	*Rana boylii*	Y	N
8	Fringed myotis	*Myotis thysanodes*	Y	N
9	Pallid bat	*Antrozous pallidus*	Y	Y
10	Townsend's big-eared bat	*Corynorhinus townsendii*	Y	N
11	Mountain quail	*Oreortyx picta*	N	Y
12	Mule Deer	*Odocoileus hemionus*	N	Y
13	Sooty grouse	*Dendragapus fuliginosus*	N	Y
14	Red fox sparrow	*Passerella iliaca*	N	Y

FIGURE 16. Focal species occurrence data highlights a few species with abundant observations. The Sierra Nevada yellow-legged frog is the only species with a Critical Habitat designation.


CALIFORNIA SPOTTED OWL

SIERRA NEVADA YELLOW-LEGGED FROG CRITICAL HABITAT

NORTHERN FLYING SQUIRREL

FRINGED MYOTIS, PALLID BAT, TOWNSEND'S BIG-EARED BAT

NORTHERN GOSHAWK

FOOTHILL YELLOW-LEGGED FROG

PACIFIC MARTEN

BLACK-BACKED WOODPECKER

PILLAR 5: CARBON SEQUESTRATION

Charles Maxwell and Rob Scheller

CARBON SEQUESTRATION: Carbon is sequestered and stored sustainably.

ELEMENT	METRIC	TARGET CONDITION
Storage	NEE	Sequestering
Stability	Total forest carbon	Maintained or increased

Forests play an important role in mitigating climate change; they sequester and store large amounts of carbon. However, forests are at risk of losing carbon because of rates of decay and disturbance, especially with high-severity wildfire. Forest management can reduce the potential for high-severity fire by reducing forest density. There is a trade-off: Management incurs a short-term carbon cost to avoid substantial carbon losses from high-severity fires over longer times. While there is a short-term carbon cost, the treatments can shift carbon stock growth to larger and more resilient trees. In Assembly Bill 32 the state of California set a goal to reduce fossil fuel carbon emissions to 116 Tg and recognized the need to offset emissions through land management, including forest management. Further, California executive order B-55-18 mandates that the state achieve carbon neutrality by 2045 and maintain net negative emissions thereafter.

Natural and working lands have been identified as essential to reaching this goal, with forests targeted to contribute approximately 20.5 million metric tons (MMT) per year toward the goal of an additional 125 MMT of CO2 captured and sequestered (i.e., negative emissions) statewide (Baker et al. 2020). While emissions from wildfires are not currently included in the emissions inventory, unhealthy forests have contributed significant emissions to the atmosphere in recent years. Preliminary estimates from the 2020 wildfire year for California indicate that wildfires burning in California forests emitted more than 80 MMT of CO2 (California Air Resources Board 2020), suggesting that forests were a net source of carbon to the atmosphere in 2020. The target condition for forests in TCSI is to maintain carbon sequestration.

METHODS

We characterized total ecosystem carbon and the net ecosystem exchange for 2019 using the LANDIS-II model in conjunction with a 2019 SilviaTerra base map. Model inputs include soil carbon pools based on the 2017 gridded USDA SSURGO data for California and dead carbon pools from an interpolation of FIA data of fine and coarse woody debris, following Wilson et al. (2013). To quantify total ecosystem carbon for 2019, we summed the live carbon pool (leaves, roots, and wood), dead carbon pool (litter, duff, and down woody debris), and soil organic carbon pools. The model estimates live carbon pools via internal growth and allocation among the various pools for each species per cell. We mapped total forest carbon, net ecosystem exchange (NEE), and total soil carbon across TCSI for 2019 to identify where carbon was concentrated.

Net ecosystem exchange (NEE) is primary productivity—the amount of carbon the forest acquires as it grows—minus the ecosystem respiration (e.g., decomposition). NEE includes sequestration and respiration but does not include emissions from fires. A negative NEE indicates a carbon sink (subtracting carbon from the atmosphere) and positive values a carbon source (adding carbon to the atmosphere). LANDIS-II calculates NEE internally, with growth and decomposition based on climatic conditions in the Net Ecosystem Carbon & Nitrogen (NECN) extension (v. 6.5). The soil model is based on the CENTURY model, in which different soil pools have different decomposition rates that are a function of the type of material (structural or metabolic), soil temperature, soil moisture, and soil type. Carbon and nitrogen are tracked through multiple live and dead pools, as well as tree growth and landscape carbon sequestration. Soil moisture, as well as movement across the dead pools—wood and litter deposition and decomposition, soil accretion and decomposition. We calibrated net primary productivity based on the average annual net primary productivity from 2000 to 2015 from the MODIS 17A3 satellite product. We validated NEE measures against mean annual NEE from the Sagehen AmeriFlux tower site for the years 2015–2019. We calculated the carbon dioxide equivalency (CO2e) of the annual sequestration rate by multiplying tons of carbon by 3.67, and also multiplying by the area with vegetative cover in 2019 in the LANDIS-II model (892,341 hectares). Finally, we compared 2019 annual NEE in TCSI based on the LANDIS-II model to the 2019 annual net forest carbon change values from the Board of Forestry and Fire Protection report (2020), which are an annual averages calculated over a decade for the entire Sierra Nevada and Cascades (Christensen et al. 2020).

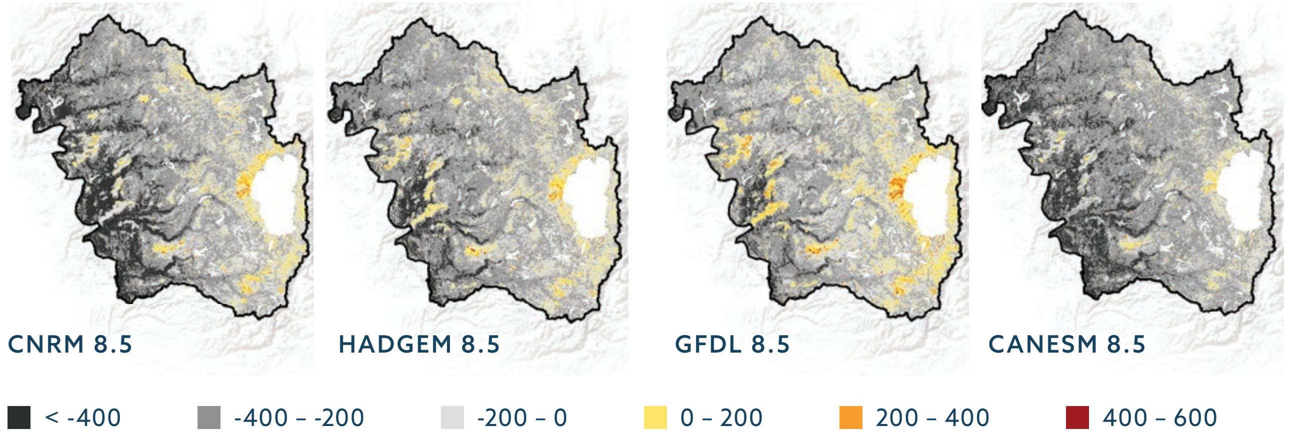
CURRENT CARBON

Net ecosystem exchange in 2019 was 3.1 MMT CO2e. Regardless of climate model projection, carbon was sequestered and the landscape was a net sink for carbon, with the rate varying based on different climate inputs (Figure 17a). This sequestration rate across TCSI in 2019 is slightly below the landscape's area weighted contribution to statewide carbon neutrality (3.3 MMT/year). To put this in context, the sequestration rate is equal to the emissions from ~700,000 gas powered passenger vehicles driven for one year or one coal-fired power plant operating for one year, based on the EPA Greenhouse Gas Equivalencies Calculator. The modeled mean NEE over the years 2015–2019 was close to observed values from the AmeriFlux tower at Sagehen over that same time period, serving as validation of the modeling results (modeled -60±140 g C M-2 compared to observed -66±72 g C M-2).

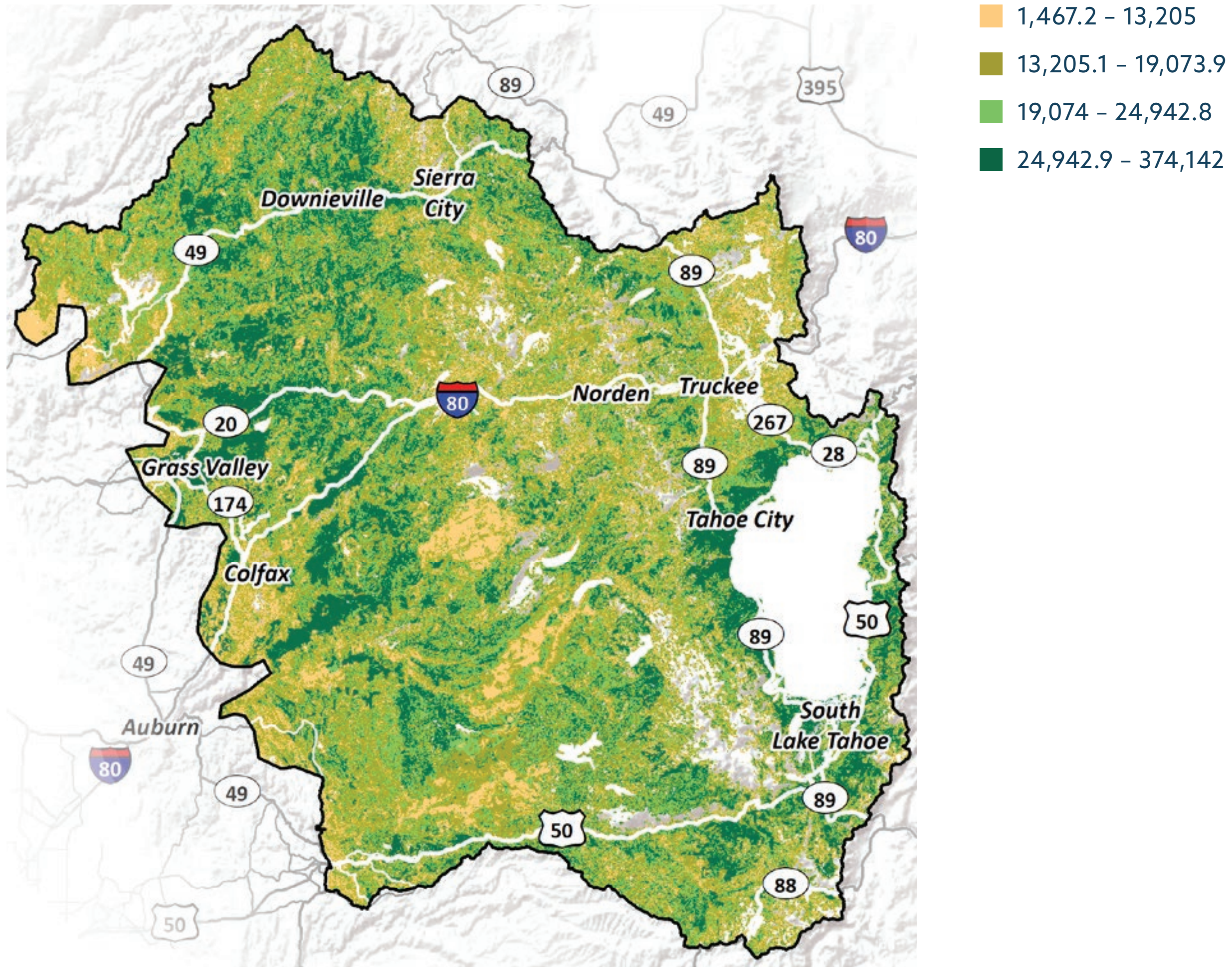
Compared to annual net forest carbon change values measured for the entire Sierra Nevada and Cascades area for the 2019 reporting period (2.0±2.4 MMT CO2e per year, Board of Forestry 2020), the TCSI modeled rate appears high given that TCSI represents only 15% of the entire Sierra Nevada and Cascades

■ **FIGURE 17.** Net ecosystem exchange in 2020 shows areas that are sources of carbon with positive values and areas that are sinks for carbon, negative values (a) and the total forest carbon pool (b).

A. CARBON SOURCES (POSITIVE VALUES) AND CARBON SINKS (NEGATIVE VALUES) (g/cm^2)



B. TOTAL FOREST CARBON POOL (g/cm^2)



area (6,086,472 hectares forested, Board of Forestry 2020). The higher NEE rate modeled in TCSI may be due to different methods (LANDIS-II vs. GRM [growth, removal, mortality]), soil data (SSURGO vs. STATSGO2), vegetation data (SilviaTerra vs. FIA), or acquisition dates of the vegetation datasets. The Board of Forestry measurements for 2019 include several drought years, whereas the 2019 TCSI modeled value is for a wet year. Another explanation may be that carbon sequestration is not even across the Sierra Nevada and Cascades area and comparing the two rates needs to take into account spatial variation in sequestration rates.

The live pool of carbon in 2019 was 242±16 Mg, the dead pool was 52±9 Mg, and the soil pool was 77±24 Mg (Figure 17b), translating to 65% live carbon, 14% dead carbon, and 21% soil carbon.

PILLAR 6: ECONOMIC DIVERSITY

Daniel Porter, Tom Baribalt, and Tanushree Biswas

ECONOMIC DIVERSITY: Restoration and recreation, among other activities, support a diverse economy.

ELEMENT	METRIC	TARGET CONDITION
Wood products	Stumpage rate	Reduced cost

Note: For methodological and practical reasons, a companion study, *Tahoe–Central Sierra Initiative: Phase 1 Restoration Wood Supply Assessment*, was completed in parallel to the larger and separate LANDIS-II analysis presented in this report. Summary findings from this assessment are provided below, and the full report can be found here: https:/www.scienceforconservation.org/products/TCSI-phase-1

For the purposes of this study, we limited our analysis to harvested forest products because that sector is directly relevant to forest restoration. Forest products are harvested for restoration purposes and used for their highest and best use and, in doing so, partially offset project costs, promote community workforce development, and sustain professional capacities needed for long-term forest restoration and hazardous-fuels-reduction activities. Evaluating the contributions of recreation and associated tourism was beyond the scope of this study. To the degree stakeholders are interested, we would support further study on other elements of economic diversity such as the contribution of water capture and water storage, as well as the need to develop/redevelop a skilled workforce.

The TCSI region has no active sawmills or biomass facilities within its boundary. Facilities do exist to the west, north, and south but may not be able to process the wood volumes associated with increased restoration or do so with positive, or at least not significantly negative, project-level cash flow. In most cases, transportation distances are simply too far and/or the biomass monetary value is too low to justify its removal.

METHODS

Using the SilviaTerra base map, for four management scenarios we modeled approximate quantities of biomass (i.e., material <10 inches diameter) and timber (i.e., small-end diameter ≥10 inches) expected as by-products of forest restoration treatments across the TCSI area. Where biomass volumes could be feasibly processed by existing biomass plants, those fractions of volumes were routed to the closest facility with available processing capacity. For more ambitious restoration scenarios in which wood volumes exceeded regional processing capacity, we identified generalized, hypothetical locations for biomass electricity facilities within the TCSI area, sited and sized to process the projected additional supply while minimizing transportation distances. Producing biomass electricity is currently the most common end use for forest-derived biomass, and it was used for this study because the associated pricing and key utilization metrics are well understood. Our biomass supply estimates could, with additional analysis, be fit to other end uses such as cellulosic ethanol, mass timber, oriented strand board, etc.

Based on the new bioelectricity plant locations along the Highway 49, Highway 50, and Interstate 80 transportation corridors (Figure 1) and using a detailed transportation routing algorithm, we evaluated the effects of reducing transportation distances (relative to the business-as-usual scenario) on biomass stumpage (defined as delivered price less logging, chipping, and haul costs). Stumpage is the value (i.e., $/bone dry ton or $/thousand board feet of timber) to the landowner at the beginning of a timber and/or biomass removal "sale" or project. It is the value paid for the timber on the stump after considerations are made for all other costs associated with its removal. In some contracting arrangements, this value can be used to partially offset treatment costs.

All operable forestlands (i.e., private, state, federal) were evaluated. For this analysis, "operable" areas were defined as having a high feasibility for machine-based thinning. For the TCSI area, 273,972 hectares (28%) were classified as industrial timberland and considered operable. An additional 300,681 hectares of National Forest Service land (31% of the TCSI area) were classified as operable based on Sierra Nevada–wide operability study (North et al. 2015, Case C). Prior to modeling mechanical thinning treatments, an unsupervised vegetation classification system was used to aggregate similar groups of trees into "stands," to which the SilviaTerra tree list (i.e., an accompanying list of tree species and diameters) was attached. Stands were then selected by the harvest simulation software based on their operability and Stand Density Index (SDI), among other factors, with an overarching model goal of reducing tree densities in the most dense and operable stands. With the exception of the business-as-usual (BAU) scenario and industrial timberland harvests, none of the simulated forest scenarios or treatments included a biomass or timber volumetric goal as commonly used in commercial forest management models. Harvests were simulated for twenty years, starting in 2019; each stand received a maximum of one "entry" during the modeling period. Biomass and timber volumes were tallied for the purposes of the stumpage analysis.

■ **TABLE 5.** Forest management scenarios used for the Economic Diversity pillar. Includes mechanically treated areas only, not hand thinning or prescribed fire, and ~87,000 ha of mechanical treatment on private timberlands over 20 years.

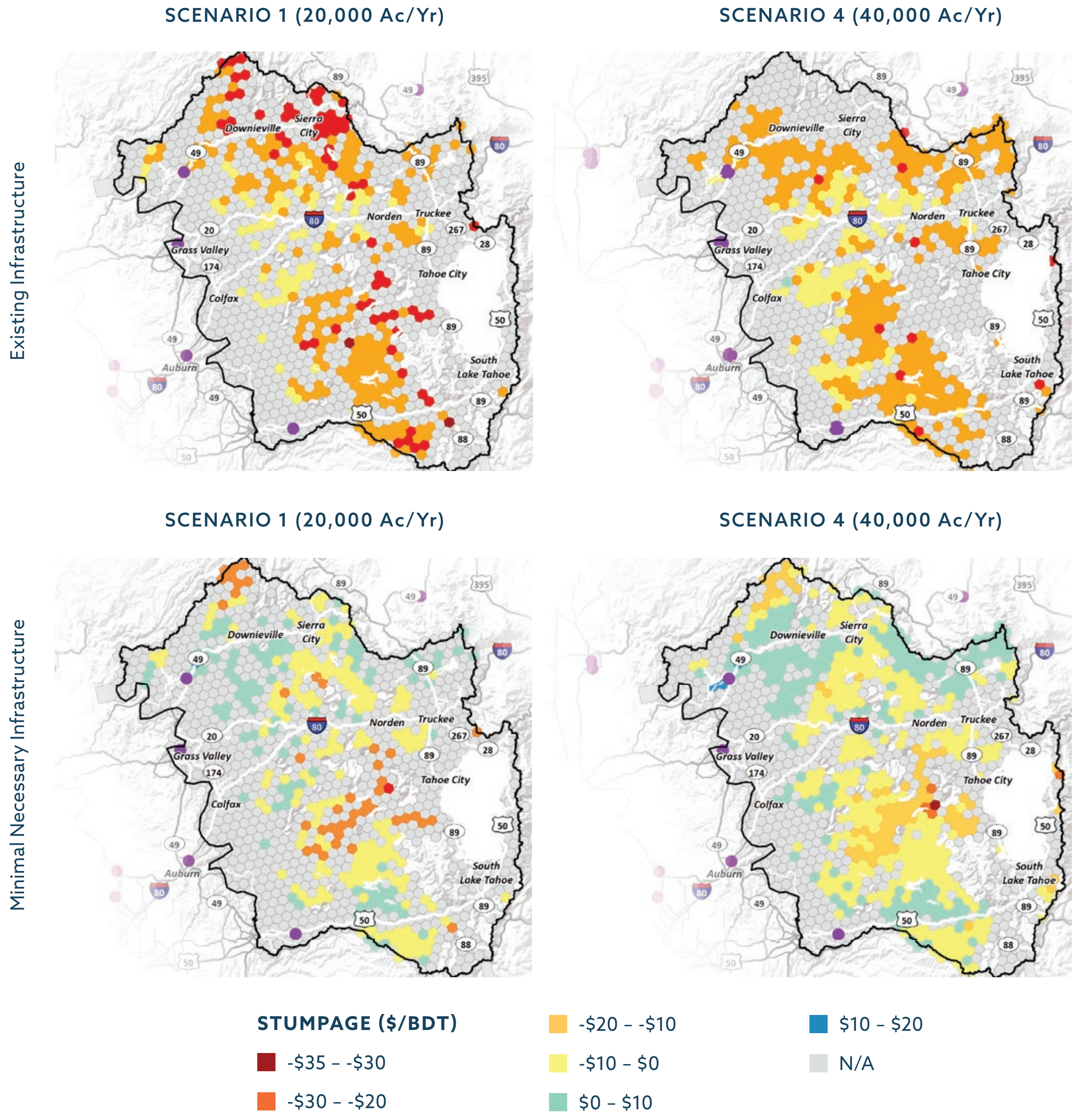
Scenario	**Area Treated (ha/year)**	**Area Treated Over 20 years (ha)**
BUSINESS AS USUAL Reflects recent (5-year) harvest levels at county level (private and public lands), adjusted for proportion of county that lies within the TCSI area.	8,296	165,921
CLIMATE CHANGE RESILIENCE All operable area in the General Forest zone on National Forest Service lands are treated, and prescribed burning is employed to a greater extent on some non-operable areas.	20,638	246,858

■ **TABLE 6.** Forest prescriptions modeled for the economic diversity pillar. Rx burn = prescribed fire, PCT = pre-commercial thin, SG = skips and gaps, REG = regeneration, stand-replacing mechanical treatment.

Allocation				Rx			
Zone	Own	Ops	Seral stage	Rx Burn	PCT	SG	REG
Defense	**USFS**	**Manual; Mech**	**Early/Mid/Late**	Y	Y	Y	**N**
	Private[†]	**Manual; Mech**	**Early/Mid/Late**	**N**	Y	Y	Y
Threat	**USFS**	**Manual; Mech**	**Early/Mid/Late**	Y	Y	Y	**N**
	Private	**Manual; Mech**	**Early/Mid/Late**	Y	Y	Y	Y
General	**USFS**	**Ground-based**	**Early**	Y	Y	**N**	**N**
	USFS	**Ground-based**	**Mid**	Y	**N**	Y	**N**
	USFS	**Ground-based**	**Late**	Y	**N**	Y	**N**
	USFS	**Cable**	**Early**	Y	Y	**N**	**N**
	USFS	**Cable**	**Mid**	**N**[†]	**N**[‡]	Y	**N**
	USFS	**Cable**	**Late**	**N**[†]	**N**[‡]	Y	**N**
	USFS	**NonOperable**	**Early/Mid/Late**	Y	**N**	**N**	**N**
General	**Private**	**Ground-based**	**Early**	Y	Y	**N**	**N**
	Private	**Ground-based**	**Mid**	Y	**N**	Y	Y
	Private	**Ground-based**	**Late**	Y	**N**	Y	Y
	Private	**Cable**	**Early**	Y	Y	**N**	**N**
	Private	**Cable**	**Mid**	**N**	**N**	Y	Y
	Private	**Cable**	**Late**	**N**	**N**	Y	Y
	Private	**NonOperable**	**Early**	Y	**N**	**N**	**N**
Wilderness	**USFS**	**Off limits**	**Early/Mid/Late**	**N**	**N**	**N**	**N**

[†] Includes other non-USFS Ownership limited to a few percent of land base

■ FIGURE 18. Biomass stumpage costs for two scenarios and two infrastructure cases suggests that adding three new biomass facilities will decrease costs of treatment more than increasing the scale or work.



The analysis of stumpage prices was completed for four management scenarios (Table 5), each using various combinations of treatments (e.g., thinning or prescribed fire, Table 6) depending on management zone, ownership type, and seral stage (e.g., young or middle-aged forest). Each successive scenario incorporates the dynamics of all preceding scenarios. We present only the results of period 4, 15–20 years from current conditions, and two scenarios in this assessment.

CURRENT CONDITIONS AND EXPANDED PROCESSING INFRASTRUCTURE

In Scenario 1—the business-as-usual (BAU) or baseline management scenario—approximately 165,921 hectares of forest would be treated over twenty years (average of 8,296 ha/year) using a combination of commercial timber harvests on private timberlands, commercial timber harvests on National Forest Service lands, and some nominal quantity of restoration treatments on federal and state lands (i.e., not reflecting restoration treatments attributable to the very recent uptick in forest health funding). We estimate that Scenario 1 would produce 80,000 bone dry tons (BDT) of biomass and 191,188 board feet (Mbf) of sawtimber per year.

With current electricity-generating infrastructure, biomass produced from forest restoration would have a substantially negative value, averaging -$15/BDT if dispatched to the sole operating bioelectricity plant in Rocklin, California (Figure 18). The Rocklin plant has the capacity to consume approximately 100,000 BDT/year of forest biomass but sources raw material from both inside and outside the TCSI landscape. With three additional infrastructure facilities, the biomass removal average is -$2/BDT, which while still negative is an improvement in the cost.

In Scenario 4—the climate change resilience scenario—approximately 246,858 hectares of forest restoration treatments would be added to the 165,921 hectares of BAU treatment over twenty years described previously for an average of 20,638 hectares per year (Figure 18). Increasing the scale of work has less of an impact on the average cost, from -$15/BDT in business as usual to -$12/BDT for the climate change resilience scenario, both with existing infrastructure. The same is true if you increase the biomass facilities by adding three new facilities. The cost is nearly cost neutral, -$2.8/BDT on average for BAU treatment to -$2.9/BDT for the climate change resilience scenario.

Increasing infrastructure by adding three new biomass facilities has a bigger effect on biomass removal cost than increasing the scale of treatment. The cost surfaces also highlight how operability, specifically less-steep slopes and close proximity to existing roads, limits the potential area for treatment. Opening up the operability to steeper slopes and locations farther from roads—through the use of hand-thinning, cable logging, or other removal techniques—would increase options for increasing the supply of woody material.

CROSS-PILLAR BENEFIT ANALYSIS

Tanushree Biswas, Kristen Wilson, Patricia Manley, Nicholas Povak, Dick Cameron, Dan Porter, and Edward Smith

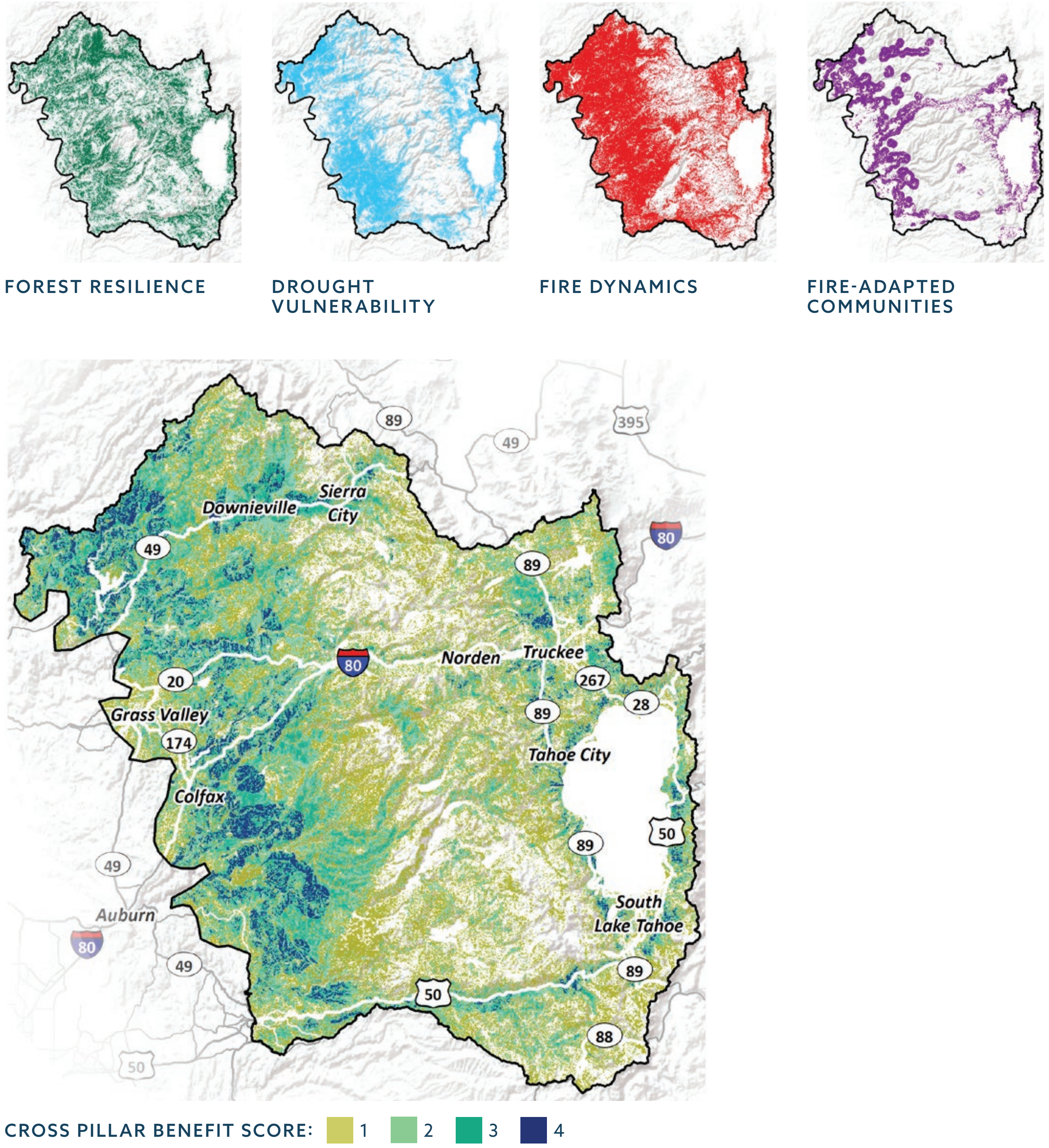
This assessment establishes a baseline of current conditions for key resources across the TCSI landscape, and it provides a solid scientific foundation for the need to increase the pace and scale of restoration, as well as to identify forested areas that are prime candidates for restoration treatments. As a demonstration of how to apply these (and other) data to identify areas for treatment that would yield multiple benefits, we overlaid spatial data from the first three pillars, with two metrics from the forest resilience pillar, and one metric each from the fire dynamics pillar and fire-adapted communities pillar. Areas where multiple pillars departed from target conditions indicate areas with an opportunity to achieve multiple benefits through forest treatments and promote greater resilience to drought, fire, and bark beetle–caused tree mortality.

We did not include biodiversity conservation, carbon sequestration, or economic diversity pillars in this preliminary overlay example, as they are likely to require additional considerations in terms of appropriate and effective management treatments and the timing of associated benefits. Managers will need to make local decisions with additional consideration to balance potential short-term impacts to California spotted owl habitat or loss of carbon with long-term protection of habitat and carbon from future high-severity wildfires. Both owl nesting sites and carbon are distributed throughout the landscape across areas of pillar alignment and divergence.

We analyzed the economic diversity pillar by using the overlay of the three-pillar map divided by the spatially explicit cost surface. This return-on-investment index illustrates how multiple pillar benefits and economics can be considered in project planning given existing biomass infrastructure or the minimum additional biomass infrastructure needed to reduce biomass removal costs.

Development is underway on a spatially explicit decision-support tool for targeting treatments and weighting of pillars, termed the Blueprint for Resilience, which is the fourth element in the TCSI science enterprise. The Blueprint for Resilience will incorporate a more sophisticated approach to combining the pillar spatial data from this assessment of current conditions along with LANDIS-II model spatial outputs of future conditions under climate change to identify management options that will effectively move the landscape into conditions that are expected to be more resilient to future environmental disturbances, including climate change. Here we illustrate a simple approach to how current conditions across multiple pillars might be evaluated.

■ **FIGURE 19.** Overlay of three pillars highlighting places at risk of large high severity fire patches, greatest drought vulnerability of trees (upper quartile), fire risk to communities, and tree density above the contemporary range of variability. All maps are scored zero or one and there was no weighting of the pillars.


FOREST RESILIENCE

DROUGHT VULNERABILITY

FIRE DYNAMICS

FIRE-ADAPTED COMMUNITIES

METHODS

In the current assessment, we produced two synthesis maps. The first map is a spatial overlay of the first three pillars, resulting in an opportunity score from 0, low opportunity for restoration thinning and prescribed fire, to 4, high opportunity. To calculate a four-pillar score, we first normalized the pillar spatial data into zero or one values based on the specific thresholds listed below. We did not weight any of the zero or one values; we summed them. The highest possible score was 4.

1 FOREST RESILIENCE PILLAR

a. Forest departure: above target tree density = 1
b. Drought vulnerability: >600 mm drought vulnerability index = 1

2 FIRE DYNAMICS PILLAR

a. Large high-severity fire patches defined by flame length exceedance probability >8 feet, >60% probability, >100-hectare patch = 1

3 FIRE-ADAPTED COMMUNITIES PILLAR

a. Flame length exceedance probability >4 feet, >50% probability, and within Defense and Threat zones = 1

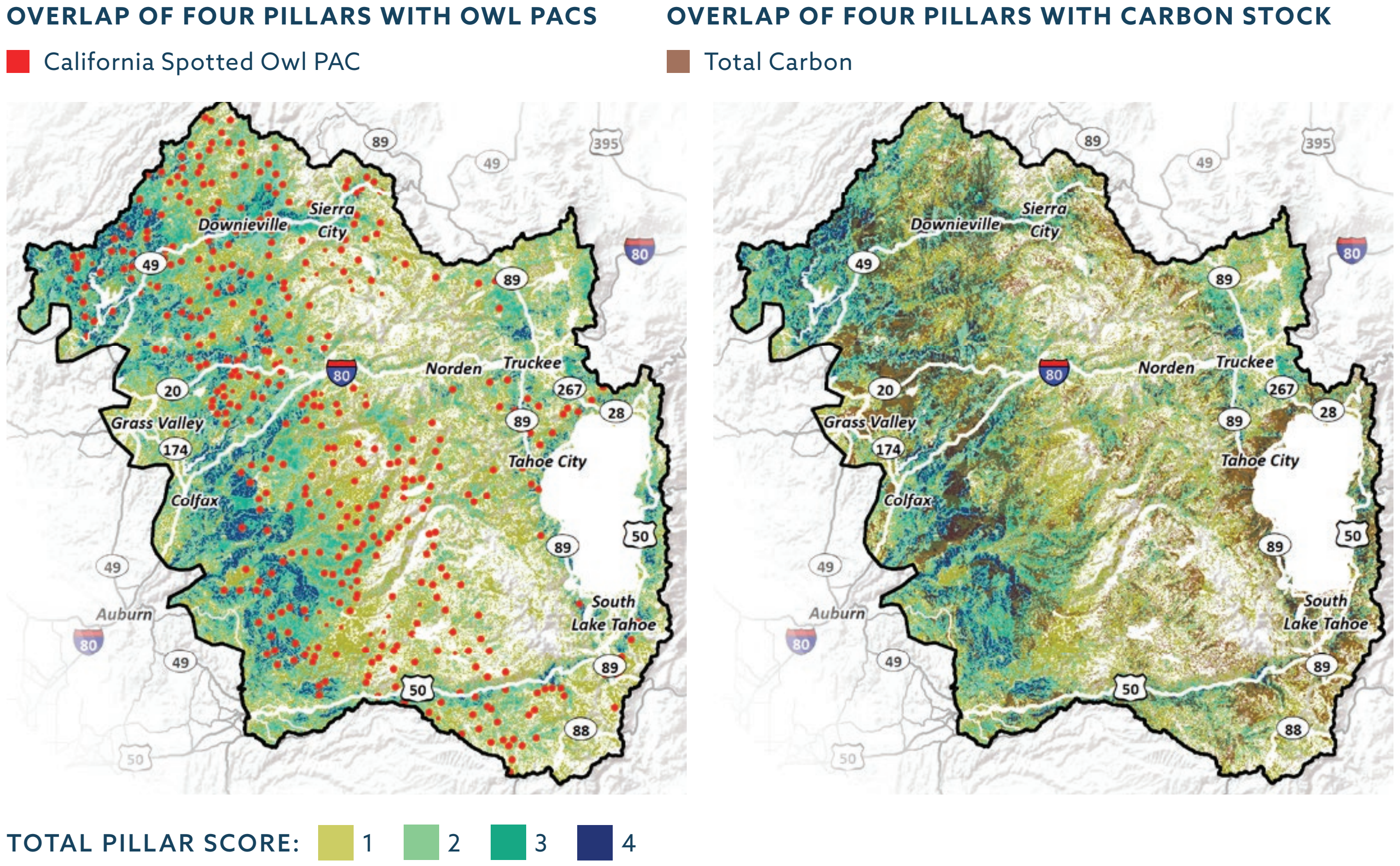
To incorporate the sixth pillar, economic diversity, we produced a second map, where we overlaid the pillar score map with the cost surface and only calculated a return-on-investment index for areas with cost data. We normalized the total pillar score by dividing the area with pillar score values by the total area in a hexagon. The return-on-investment index was calculated by dividing the pillar score by the costs of removing biomass from a given hexagon. We displayed the return-on-investment index as ROI (-), ROI (<0) for values closer to zero but still negative, and ROI (+). We calculated the ROI for two scenarios of treatment and two infrastructure cases.

CURRENT CONDITIONS SYNTHESIS

The pillar score map highlights the greatest alignment of departed conditions across the pillars in low- to mid-elevation west slope areas of TCSI, especially in the American River watershed and the upper Yuba watershed (Figure 19). Areas around Lake Tahoe and the city of Truckee also stand out with high scores. The spatial pattern of high pillar scores is due to the distribution of large high-severity fire risk, the location of human communities at risk from fire, and the highest drought vulnerability of the forest across TCSI. Both the California spotted owl PACs/PZs and the total carbon, which represent potential co-benefits or trade-offs from restoration thinning and prescribed fire, overlap the pillar score map in the low-mid elevation west slope and surrounding Lake Tahoe (Figure 20).

Across TCSI, areas departed for all three pillars cover 79% of the forested landscape, with the pillars overlapping spatially on 6% of the forested landscape (47,985 hectares). These areas with pillar overlap highlight places that are likely to be the most vulnerable to climate change. The pillars align across low-mid elevations on the west slope, around Lake Tahoe and the city of Truckee, and along the Highway 50 corridor. By mapping the return-on-investment index, areas with either a high pillar score and low cost or areas with a low pillar score and low cost both stand out as positive values. This can help identify treatment locations that account for spatial variation in cost and pillar alignment. Given existing biomass facilities, the ROI index is greater at higher elevation on the west slope than lower-elevation areas (Figure 21). If three new additional biomass facilities were added within TCSI, the ROI index becomes positive, with the highest ROI in the northern and southern ends of TCSI and a small area in the central western section of TCSI. However, cost is not the only driver in determining treatment priorities and additional stakeholder input is needed to shape management priorities.

FIGURE 20. Owl nesting sites and high carbon stocks overlaid on the four pillar map showing places where forest management can account for possible co-benefits or tradeoffs.



OVERLAP OF FOUR PILLARS WITH OWL PACS

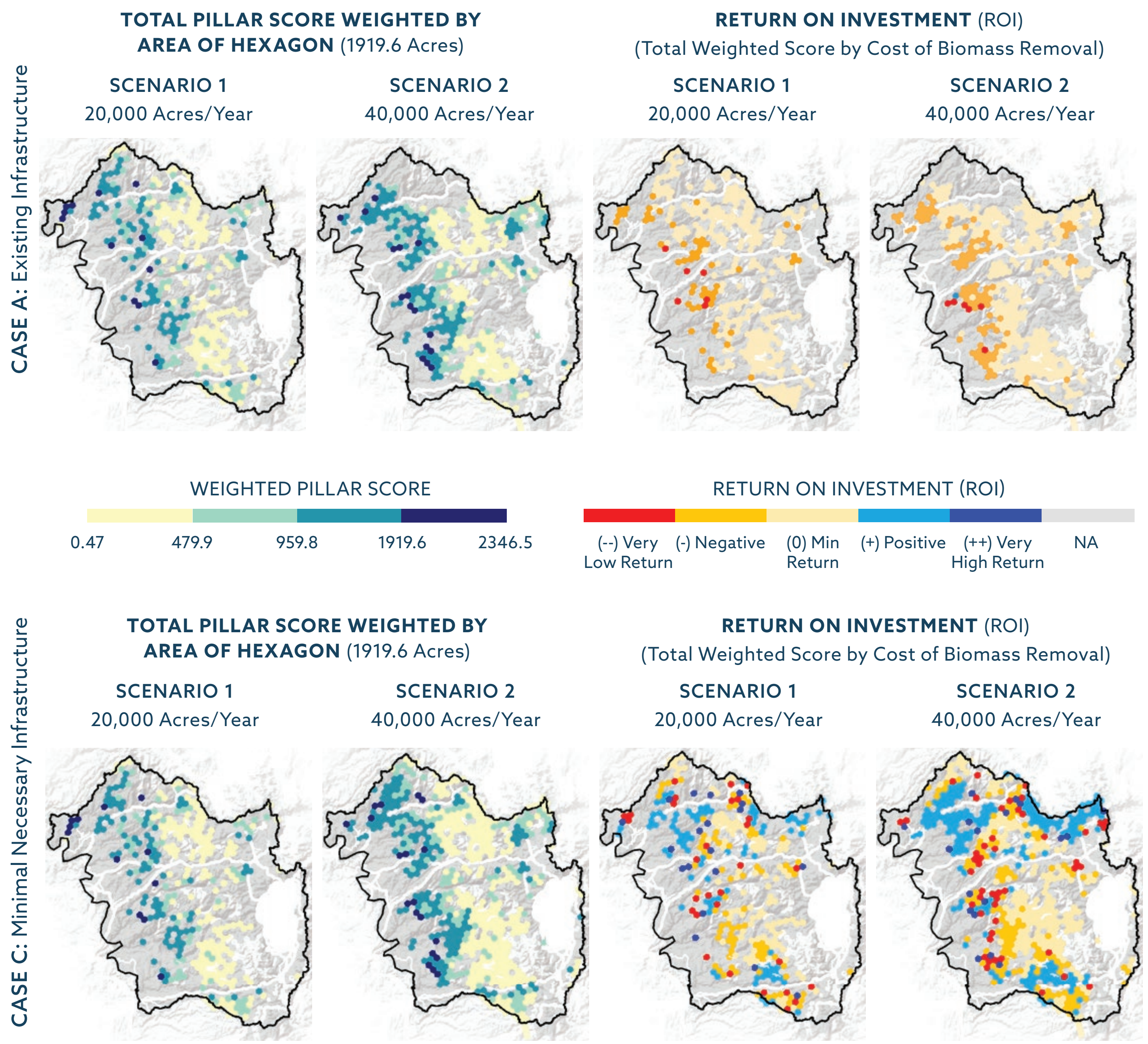
🟥 California Spotted Owl PAC

OVERLAP OF FOUR PILLARS WITH CARBON STOCK

🟫 Total Carbon

TOTAL PILLAR SCORE: 🟨 1 🟩 2 🟩 3 🟦 4

The pillar score map represents the beginnings of a prioritization but is not an optimization and does not include weighting, ranking, or a decision-support tool. Single threshold values were set for each pillar, as opposed to a range of thresholds with different levels of risk or acceptance. We expect that project planning groups working at smaller scales within TCSI will include some but not all pillars in their prioritization schemes, with the acknowledgment that the pillars are interconnected. In conclusion, we assessed the resilience of the current TCSI landscape (2018–2020) and identified areas where some of the core pillars of resilience align.



■ **FIGURE 21.** Return on investment maps for the two infrastructure cases, calculated by taking the four-pillar map score and dividing by the cost surfaces.

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ACKNOWLEDGMENTS

Numerous people contributed to this assessment. Rodd Kelsey from The Nature Conservancy co-directed the assessment with Patricia Manley at the beginning of the project. Shana Gross helped us build upon and incorporate lessons learned from the Lake Tahoe West Partnership Assessment and Restoration Strategy. We worked closely with the North Yuba Project, a project in the planning stage within TCSI, to understand how the assessment and LANDIS-II model could be used to inform landscape-scale forest restoration planning. Becky Estes, Scott Conway, Andrew Salmon, and Angel Hertslet from the North Yuba Project all contributed to shaping how we envision the ways in which planning groups can use the TCSI science enterprise. Traci Allen, Roy Bridgman, Tina Mark, Marilyn Tierney, Stephanie Coppeto, and Sarah Sawyer from the Forest Service and Sue Britting from Sierra Forest Legacy provided guidance on the biodiversity conservation pillar. Terry Wash, Dana Walsh, and Ramiro Rojas from the Forest Service vetted the forest treatment prescriptions used in the timber supply model and LANDIS-II model. Nic Enstice, Sarah Campe, Luke Hunt, John Tangenberg, and Elliott Vander Kolk from Sierra Nevada Conservancy; Shana Gross from the Forest Service—Region 5; Becky Estes from Pacific Southwest Research Station; Jane Freeman from Tahoe Conservancy; David Fournier from Tahoe National Forest; and Angel Hertslet, David Edelson, and Kristen Shive from The Nature Conservancy provided edits and comments on the report.

Wilson, Kristen N., and Patricia N. Manley, editors 2021. Assessment of Current Landscape Conditions: Tahoe-Central Sierra Initiative. An unpublished report of the Tahoe Central Sierra Initiative.

Tahoe-Central Sierra Initiative

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June 1, 2021

Prescribed fire operations near French Meadows Reservoir in May 2021. Photograph by Jerry Dodrill.