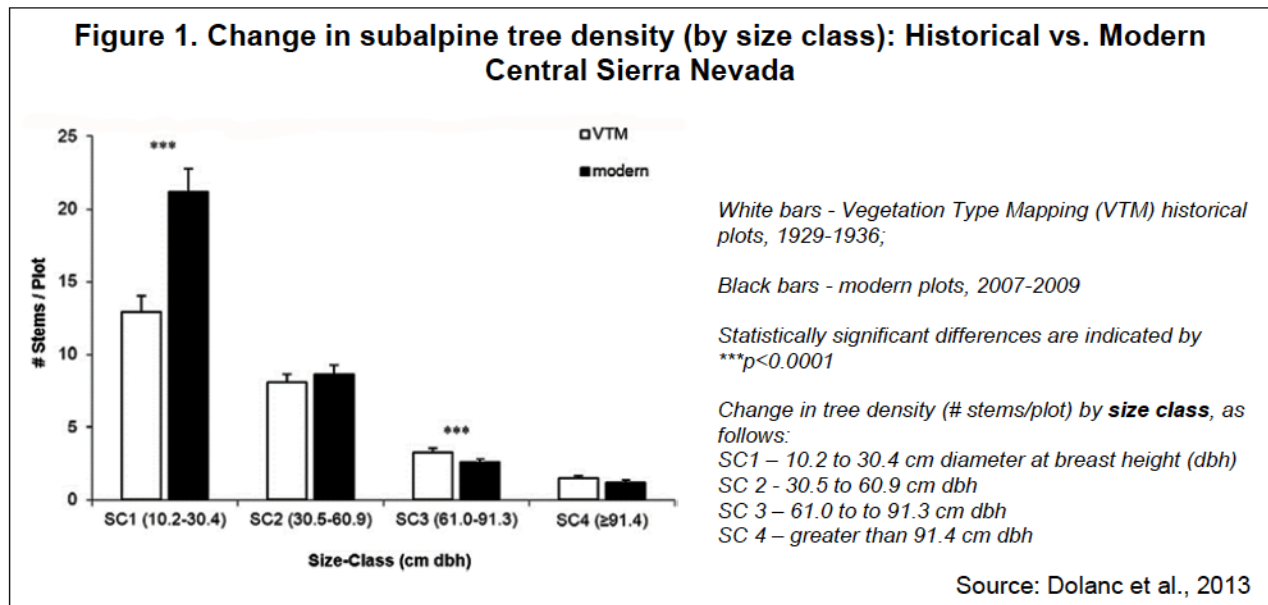


SUBALPINE FOREST DENSITY

Subalpine forests in the Sierra Nevada have more small trees and fewer large trees than they did in the early decades of the 20th century.



What does the indicator show?

Figure 1 shows an increase in the density of small trees (measured as the number of stems in each plot) in higher-elevation (subalpine) forests in the central Sierra Nevada since the 1930s. The figure compares the densities of trees by size class in historical plots (based on Vegetation Type Mapping (VTM) data collected between 1929 and 1936), with modern-day plots (based on resampling data between 2007 and 2009).

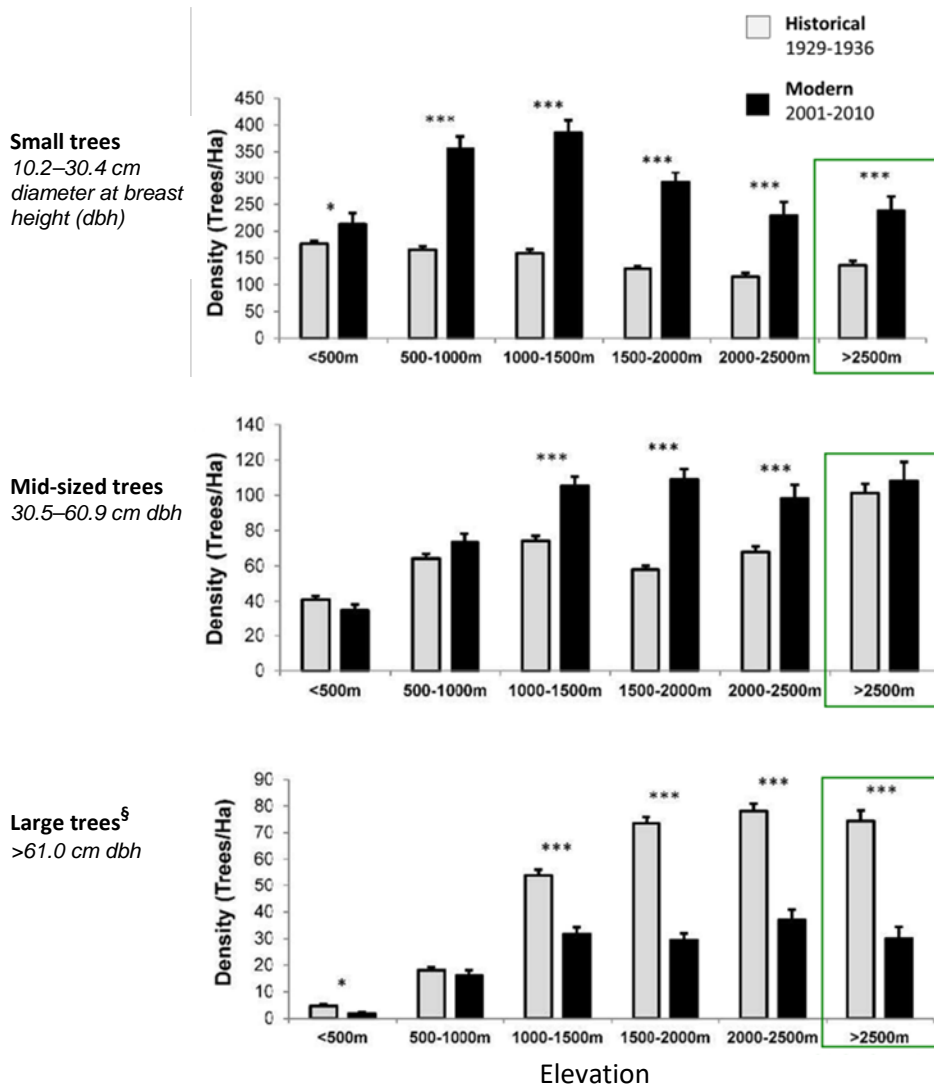
There are now many more small trees (categorized as SC1, with diameters measuring 10.2 to 30.4 centimeters (cm) (4 to 12 inches) at a height of 1.4 meters (4.5 feet) – a measurement referred to as “diameter at breast height,” or dbh. Also, there are fewer large trees (those categorized as SC3 and SC4, exceeding 61 cm (24”) dbh). Thus, in the subalpine zone, the density of small trees increased by 62 percent while large tree densities decreased by 21 percent — a net increase of 30 percent more trees present today than in the 1930s. These shifts are ubiquitous throughout the subalpine zone (2300 to 3400 meters (m) or approximately 7,500 to 11,000 feet elevation) of the central Sierra Nevada (see map, Figure 3); further, the shifts occurred to a surprisingly consistent degree for the eight most common tree species native to this zone.

Figure 2 shows that declines in the density of large trees and increases in the density of small trees also occurred at lower elevations. These findings are from a more recent study by Dolanc et al. (2014a), which compared contemporary Forest Inventory Analysis (FIA) forest survey plots to the historical VTM data across a larger area that spans a broader range of elevations in the north and central Sierra Nevada. At subalpine elevations (>2500 m), the increases in small trees and the decrease in large trees recorded in this study are similar to those found in the first study (Figure 1; Dolanc



et al., 2013). The similarity between the two studies provides further evidence of widespread and prevalent changes in the Sierra Nevada forest structure.

Figure 2. Change in tree density by elevation* and size class: Historical vs. Modern, North and Central Sierra Nevada



Gray bars - Vegetation Type Mapping (VTM) historical plots, 1929-1936
Black bars - Forest Inventory and Analysis (FIA) modern plots, 2001-2010
 The last set of bars (outlined in green) show changes at the subalpine elevation (>2500m)
 Statistically significant differences are indicated by * $p < 0.05$, ** $p < 0.001$, and *** $p < 0.0001$

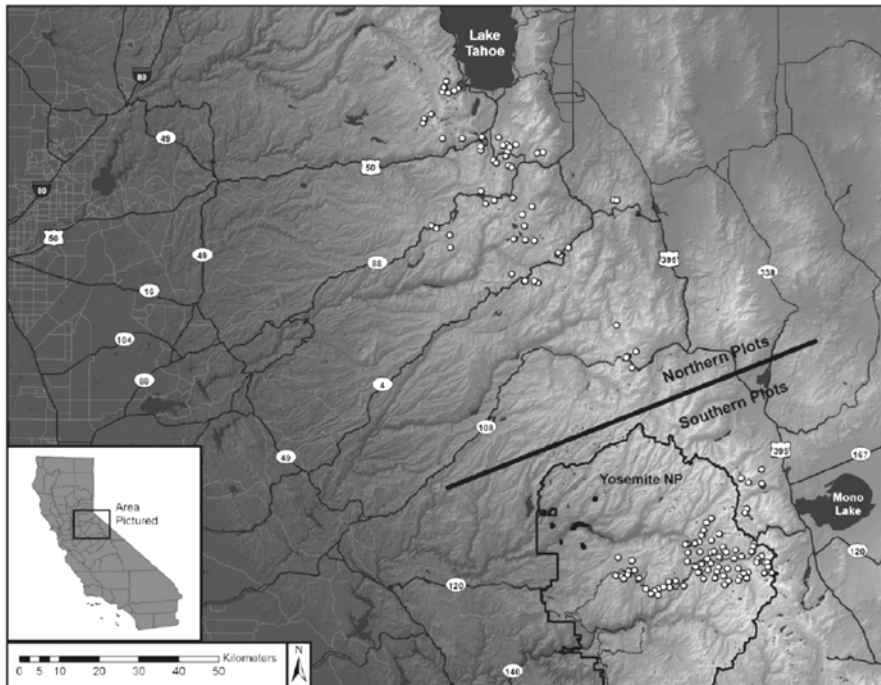
[§]“Large trees” in this figure are classified as “SC3” and “SC4” in Figure 1.

Source: Dolanc et al., 2014a

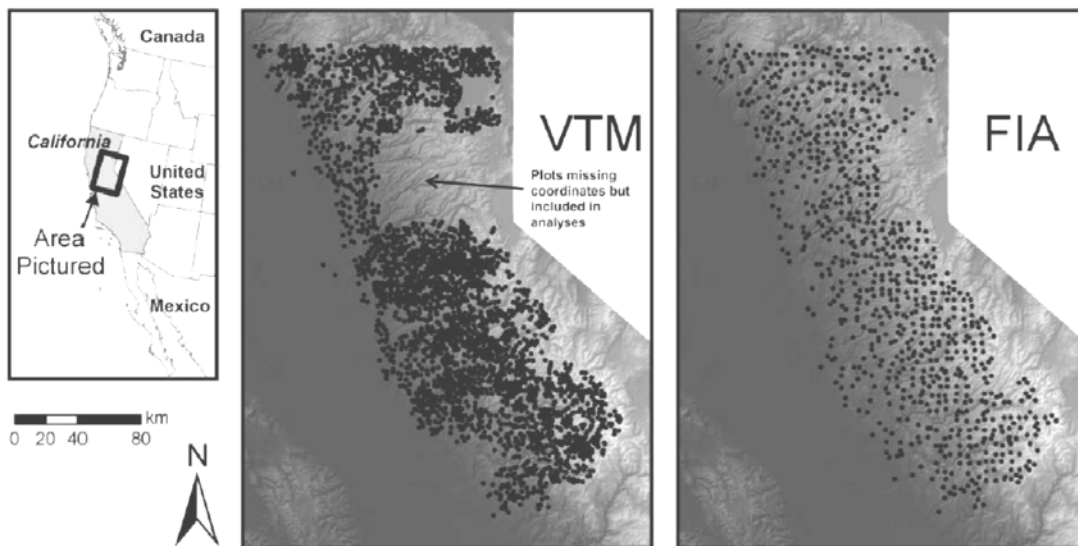


Figure 3. Maps showing Sierra Nevada study areas

A. Central Sierra Nevada study area for Figure 1 (circles show survey plots)



B. Northern and Central Sierra Nevada study area for Figure 2 (dots show study plots; arrow points to VTM plots with missing coordinates but for which elevation and tree data are available; these are included in analyses)



Sources: (A) Dolanc et al, 2013;
(B) Dolanc et al., 2014a

Why is this indicator important?

Shifts in forest structure could have detrimental effects on the ecology of the Sierra Nevada. Compared to small trees, large trees store considerable amounts of carbon, provide soil nutrients, provide nests and shelters, and play critical roles in hydrological



regimes. Younger and smaller trees cannot provide these functions to the same extent as large trees, if at all (Lindenmayer et al., 2012).

In addition, increased tree density from small trees provides more fuel for larger and more frequent fires. Though much of California's vegetation is adapted to frequent fire, fire in the subalpine zone has historically been infrequent and isolated (van Wagtendonk and Fites-Kaufman, 2006). Recently, however, wildfires have been documented to be increasing in elevation in the Sierra Nevada (Schwartz et al., 2015). Subalpine forests have historically been sparse, with insufficient accumulation of dead, woody residue on the forest floor to act as fuel to carry a fire very far. However, an increasing number of smaller trees will naturally lead to increased fuel and could ultimately lead to larger and more frequent fires. Since most species native to subalpine regions are not adapted to fire, this has the potential to shift dominance at these elevations toward lower-elevation, fire-adapted species, effectively accelerating an upward shift of ecological zones.

Densification of forests and warming temperatures could also make conditions more favorable for insect outbreaks and disease. Beetle infestations have caused widespread mortality in high-elevation forests in the Pacific Northwest and Rocky Mountain regions, including two species present in Sierran subalpine, lodgepole and whitebark pine. These infestations were linked to changing climate and forest conditions that are conducive to the beetle's life cycle (Kurz et al., 2008). Increased density of Sierran subalpine forests and warming temperatures are expected to lead to increased tree mortality and conditions ripe for outbreaks in the Sierra Nevada. Such outbreaks have occurred during the recent drought (Meyer et al., 2016; Sierra Nevada Conservancy, 2017). A similar situation exists for white-pine blister rust, which affects 5-needle pines throughout the western mountains, including western white pine and whitebark pine, two species found in Sierran subalpine (Tomback and Achuff, 2010). Continued large-scale beetle outbreaks and/or disease could lead to a compositional shift in favor of species more resistant to these pathogens. In addition to these potential negative effects, major shifts in composition and structure to an ecosystem are likely to lead to numerous other, unforeseen biological changes in the ecosystem.

Tracking trends and patterns in how the high elevation forests in this region are changing helps advance the understanding of the factors driving these changes, and improves the ability to anticipate future changes.

What factors influence this indicator?

In the subalpine zone of the Sierra Nevada, deep spring snowpack and low summer moisture limit the germination and establishment of seedlings (known as "recruitment"), and the growth and survival of young trees. The Sierra Nevada is experiencing warmer temperatures, a greater proportion of rain to snow, and earlier snowmelt dates (Dettinger and Cayan, 1995; Coats, 2010; Millar et al., 2012; Knowles et al., 2006), as well as overall decreases in snowpack during the recent drought (Berg and Hall, 2017). These climate-related changes could be making growing seasons longer, creating favorable conditions for tree recruitment and enhancing the survival of small trees (Dolanc et al., 2014a). At the same time large trees, which have a higher water demand,



may be dying off due to insufficient moisture (McIntyre et al., 2015). Thus, the changes in tree densities are likely influenced by regional climatic changes since the 1930s. Interestingly, no apparent change in the relative abundance of tree species were observed (Dolanc et al., 2013).

Certain factors that help explain the increased tree densities at low to mid-elevations may not explain the changes observed at subalpine elevations. Fire suppression appears to be a primary factor for increased tree density at low to mid-elevations. However, fire suppression activities have been minimal at sub-alpine elevations due to the low occurrence of wildfire, implicating changing climatic conditions as the factor associated with increased small tree densities at these elevations. (Dolanc et al., 2014a; Dolanc et al., 2014b). Timber harvest and logging may explain some of the declines in large trees over time at lower elevations as well. However, logging has been minimal in Yosemite National Park, which has also experienced significant declines in large trees (Dolanc et al., 2014a; Lutz et al., 2010).

Increasing concentration of nitrogen may also contribute to densification of small trees. Increased deposition of nitrogen from pollution sources upwind has been documented in the Lake Tahoe Basin. However, because nitrogen deposition is highly contingent upon the location of pollution sources, its effects are highly variable across the landscape (Fenn et al., 2003) and therefore not likely to account for the rather consistent and widespread shift in subalpine structure. It has also been suggested that higher concentrations of carbon dioxide could cause major structural shifts, but research has shown that this is unlikely to happen in high-elevation forests (Grace et al., 2002). Similarly, although ozone pollution from upwind areas may increase mortality of ponderosa and Jeffrey pine in the Sierra Nevada, its effects on densification are likely minimal. The greatest tree mortality impacts from ozone have been observed south of the study area shown in Figure 3. In addition, declines in ponderosa and Jeffrey pine large tree densities were roughly in line with that of other species not affected by ozone (Dolanc et al., 2014a).

Technical Considerations

Data Characteristics

Data for Figure 1: Plots of approximately 809 m² (8712 ft²) were originally sampled from 1929-1934 as part of the Wieslander Vegetation Type Mapping (VTM) project that represented the US Forest Service's original forest inventory in California (Wieslander et al., 1933; Thorne and Le, 2016). From 2007-2009, 139 historic vegetation plots were resampled throughout wilderness areas at 2300-3400 m elevation in the central Sierra Nevada. Care was taken to sample modern stand conditions with a protocol compatible with the original surveys, matching plot size, shape and orientation as closely as possible. Nearly half of the 139 plots were concentrated in the Tioga Pass area of Yosemite National Park, with the other half coming from passes located as far north as the Desolation Wilderness. The study area encompasses approximately 5500 km².

Analysis was centered on differences between numbers of stems in historic VTM versus modern stands, using the four size-class dbh (diameter at breast height) categories set



by the VTM team (SC1, SC2, SC3, and SC4). Comparisons were made for all species combined as well as each of the eight most-common tree species.

To determine change in climate over the same time period, data from two weather stations at either end of the study area, Tahoe City in the north and Huntington Lake in the south, were accessed. Thirty-year means were calculated for 1916-1945 and 1976-2005, representing the historic and modern periods influencing each of the sample periods in the vegetation data. Differences in climate between the two time periods were calculated for annual minimum temperature, annual maximum temperature and annual precipitation. Differences in these variables during the July through September growing season were also calculated.

Data for Figure 2:

The US Department of Agriculture Forest Service (USFS) runs the Forest Inventory and Analysis (FIA) program, which collects, compiles and archives data on forest status across the United States. The FIA protocol divides plots into four 7.3-m radius circular subplots, with one central subplot and three outer subplots arranged at 120° angles from each other at distances of 36.5 m from plot center to plot center. Each subplot has a 2.1-m radius circular microplot nested within its boundaries. For all subplots, every tree >12.7 cm (5 in) is measured (DBH, height, etc.) and identified to species. Within microplots, every tree >2.5 cm is measured. The total area of all four subplots combined is 672.45 m².

This study used 4321 historical VTM plots and compared stand composition and structure to 1000 FIA plots occupying the central Sierra Nevada from Lake Tahoe to the southern end of Yosemite National Park. Tree sizes in the FIA plots were re-classed into three size classes used in the VTM study and tree densities were converted to per-area measures. Separate generalized linear model statistical tests were conducted for each elevation band and latitude category using a negative binomial distribution (Dolanc et al., 2014a).

Strengths and Limitations of the Data

The structural shifts observed from subalpine of the Sierra Nevada are the first empirical-based observations of changes in high elevation forests in the Sierra Nevada mountains.

Using VTM data as historic references has been criticized because VTM field crews did not permanently mark their plots, meaning precise relocation of plots is not possible. However, it is possible to navigate to the same slope face and likely the same forest stand using their data on canopy composition, elevation, slope, aspect and several other environmental variables. As long as many locations are resampled, this approach should be sufficient and preferable to studies that use entirely different sets of modern data for comparison with VTM conditions. With resampling, differences between each pair of historic vs. modern plots have been minimized. Because of these considerations, the analysis for this study is focused on overall change (all 139 plots combined). The modern resampling effort covered a large region, with a large sample size. Numerous



recent papers have used the VTM data set as a historic reference and it appears as though this trend will continue. A critique that the VTM plots may have been systematically biased to sampling larger trees has been suggested but never substantiated. Evidence from high elevation plots in the form of downed large trees suggests that the historical densities of large trees recorded are accurate (Dolanc et al., 2013) while the field manual for the VTM surveys instructs the surveyors to sample vegetation representative of the mapped vegetation (Thorne and Le, 2016).

VTM and FIA data differ in sampling protocol and plot selection. However, trends in comparisons of VTM and FIA data are similar in direction and magnitude to those reported in regional studies using a variety of methods, supporting the use of comparing these two data sets. In addition, scatterplot analyses suggest that the VTM crew sampled as wide a variety of stands as the current FIA program (Dolanc et al., 2014b).

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