

# FINAL REPORT

Title: Vegetation succession in an old-growth ponderosa pine forest following structural restoration with fire: implications for retreatment and maintenance

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## Table of Contents

List of Tables .....	iv
List of Figures .....	iv
List of Abbreviations/Acronyms .....	v
Keywords .....	v
Abstract .....	1
Objectives .....	2
Background .....	3
Materials and Methods .....	6
1. Study site .....	6
2. Sampling design .....	6
3. Data analysis .....	9
Results and Discussion .....	10
1. Taylor plots .....	10
2. PSW plots .....	13
3. Future stand development, potential fire behavior, and fire effects .....	18
4. Tree mortality evaluation – 2014 Campbell Fire .....	21
Conclusions and Implications for Management .....	21
Literature cited .....	21
Appendix A. Contact information .....	24
Appendix B. List of completed/planned products .....	25
Appendix C. Metadata .....	29

## List of Tables

**Table 1.** Summary of forest characteristics in the Taylor plots in 2000 and 2016.

**Table 2.** Potential fire behavior and fire effects in the Taylor plots under three fire weather conditions.

**Table 3.** Average density and basal area for tree species in the PSW plots in 1998 and 2016.

**Table 4.** Averages for understory and overstory variables in the Beaver Creek Pinery in 1998 and 2016.

**Table 5.** Variance of tree characteristics in PSW plots in 1998 and 2016.

**Table 6.** Variance of understory characteristics (and tree cover) in PSW plots in 1998 and 2016.

**Table 7.** Average diversity based on 21 overstory and understory variables in PSW plots in 1998 and 2016.

**Table 8.** Tree mortality by size class for ponderosa pine and black oak as a result of the Campbell Fire.

## List of Figures

**Figure 1.** Heterogeneous structure of the Beaver Creek Pinery, Ishi Wilderness, Lassen National Forest in 2006, 12 years after the last wildfire.

**Figure 2.** Example of the heterogeneous fire resilient structure found within the Beaver Creek Pinery.

**Figure 3.** Location of Beaver Creek Pinery (Lassen National Forest, California), the Graham Pinery, and plots. Severity of the 1990 Campbell Fire and 1994 Barkley Fire is also shown.

**Figure 4.** Maps of tree groups and canopy gaps in 2000 and 2016 in six ~1ha stem map plots.

**Figure 5.** Maps of regeneration density for both ponderosa pine and California black oak seedlings and saplings in 2000 and 2016 in six ~1ha stem map plots.

**Figure 6.** Frequency of ponderosa pine and black oak in PSW plots sampled in 1998 and 2016.

**Figure 7.** Potential flame lengths (m) and fire type (surface, passive crown, active crown) under 80<sup>th</sup> and 98<sup>th</sup> percentile weather conditions, and a "hotter" and "cooler" prescribed fire prescription.

**Figure 8.** Potential tree mortality of ponderosa pine and black oak by size-class under 80<sup>th</sup> and 98<sup>th</sup> percentile weather conditions, and a "hotter" and "cooler" prescribed fire prescription.

**Figure 9.** Average predicted flame length currently, and 10, 20, and 30 years into the future under two potential fire scenarios: a wildfire that occurs under 97<sup>th</sup> percentile weather conditions and a prescribed fire.

**Figure 10.** FVS-FFE predicted potential fire type currently and 10, 20, and 30 years in the future under two fire scenarios: a wildfire that occurs under 97th percentile weather conditions and a prescribed fire.

**Figure 11.** FVS-FFE estimated tree mortality following a simulated wildfire and prescribed fire in 2016 and 2046.

**Figure 12.** Stand visualization images showing simulated fire behavior under prescribed fire and severe wildfire conditions at two different time periods in a plot currently characterized by a low density of larger diameter trees (plot #7798).

**Figure B1.** Field discussion among managers and scientists in the Beaver Creek Pinery, May 9, 2018.

**Figure B2.** Example of a 360° image from the Beaver Creek Pinery, an interactive overview map with georeferenced locations, and demonstration of the Virtual Reality (VR) app.

## List of Abbreviations/Acronyms

BCP – Beaver Creek Pinery

CA - California

DBH – Diameter at Breast Height

ERC – Energy Release Component

FVS – Forest Vegetation Simulator

FVS-FFE – Fire and Fuels Extension of the Forest Vegetation Simulator

GPS – Global Positioning System

PSW – Pacific Southwest Research Station

RAWS – Remote Automatic Weather Station

UTM – Universal Transverse Mercator

VR – Virtual Reality

## Keywords

Fire, forest structure, *Pinus ponderosa*, prescribed fire, *Quercus kelloggii*, restoration, wilderness

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## Abstract

Stand changes brought on by fire exclusion have contributed to reduced resilience to wildfire in ponderosa pine forests throughout the western US. Growing recognition of how structural attributes influence resilience has led to interest in restoring more heterogeneous conditions once common in these forests, but key information about interactions between stand and fuel development in such stands is currently incomplete or lacking. Few contemporary examples of structurally restored old-growth ponderosa pine forest exist. We re-measured plots in the Beaver Creek Pinery (BCP), a remote site in the Ishi Wilderness on the Lassen NF in California, that were installed following a 1994 wildfire, to better understand forest and fuel succession over time. The BCP experienced four wildfires since 1900 that restored the structure to one believed similar to historical ponderosa pine forest. Stand-scale change in overstory and understory vegetation were quantified in 2016 by re-measuring and remapping six one hectare plots that were initially mapped in 2000, and landscape-scale change was evaluated by re-measuring circular plots systematically arranged across the BCP in 1998. Tree recruitment, mortality, and growth were measured and changes in tree group and gap size and structure were calculated. We also examined the relative performance of California black oak, a declining but important species valued by tribes for food and wildlife for habitat, to better understand how fire interval and severity maintain the conifer and oak mixture. Using data from the re-measurement, we modeled stand and fuel development over the next 30 years using the Forest Vegetation Simulator (FVS), in order to predict the type of fire and return interval that would be necessary to maintain the desired heterogeneous structure over time.

At the stand scale, evaluated by re-measuring six one ha plots (Taylor plots) overstory tree density and basal area did not change significantly between 2000 and 2016. However, abundant ingrowth resulted in far higher densities of seedlings and saplings in 2016, and the numbers of single trees declined, while average tree group size increased (groups averaged 6 trees (range 2–38) in 2000 and 9 trees (range 2–240) in 2016). Wildfires initially promoted California black oak regeneration via sprouting, but the number of oak stems declined while the number of ponderosa pine stems increased between the two time periods. On average, the rate of gap infilling from tree regeneration ( $1.44\% \text{ yr}^{-1}$ ) and crown extension into gaps ( $1.05\% \text{ yr}^{-1}$ ) exceeded rates of new gap creation ( $0.58\% \text{ yr}^{-1}$ ). At the landscape scale (evaluated by re-measuring 107 0.08 ha circular plots established on a grid over the entire Pinery – PSW plots), plots remained somewhat less dense on average, with lower average basal area than the Taylor plots, but the same increase in smaller diameter ponderosa pine trees and pine regeneration overwhelming that of black oak was found. Over the two time periods, grass cover declined from 33% to 3%, shrub cover increased from 16% to 31%, and tree canopy cover increased from 14% to 34%. The forest became somewhat more homogeneous, with most structural diversity metrics declining. Still, both the 1998/2000 forest and the 2016 forest resembled reference conditions for pre-fire suppression frequent-fire forests in the western United States. Despite the 22 years that had transpired since the last fire and abundant ingrowth since then, potential fire behavior was predicted to be a surface fire with low overstory tree mortality at the stand scale, and mainly a surface fire with some mostly passive crown fire behavior at the landscape scale, suggesting the current forest would be resilient to a wildfire under most weather and fuel moisture conditions. However, modeling stand growth of forest conditions into the future suggested that a threshold may be crossed within the next ten years, with crown fire becoming the predominant behavior. This would likely result in loss of key structural attributes. Burning under controlled conditions and in the near future will be necessary to reduce the demographic pressure of ponderosa pine, promote black oak, and to maintain and create future spatial heterogeneity.

## Objectives

The structural heterogeneity that once characterized ponderosa pine dominated forests is thought to have been, in large part, generated and maintained by frequent fire. The purpose of this research was to re-measure plots that were established in the Beaver Creek Pinery (Ishi Wilderness, CA) following a 1994 wildfire, the last of four wildfires to impact this forest since 1900, in order to better understand forest and fuel succession in a structurally restored forest over time.

- A. Our first objective was to determine how a restored forest structure has changed in the absence of fire.
  - a. This objective was met by re-measuring six approximately 1 ha stem-mapped plots originally established in 2000 to evaluate stand-scale variation over time, and by re-measuring 104 out of 107 0.2 acre (0.081 ha) plots established on a grid throughout the Beaver Creek Pinery in 1998 to evaluate landscape scale variation over time.
- B. Our second objective was to improve the understanding of how overstory structure influences understory vegetation development and fuel succession in heterogeneous stands. Using data collected from 1998 to 2000 to quantify post 1994 forest structure and local fire severity, we identified relationships between overstory forest structure (i.e. tree density, canopy cover) and understory development in the time period since – up through 2016.
  - a. This objective was and is in the process of being met as laid out in one publication (Pawlikowski et al. 2019) and another in progress publication.
- C. Our third objective was to use forest growth models to project the spatial variability of stand structures into the future and evaluate potential fire behavior and fire effects under different fire weather scenarios, in order to predict how long conditions can be sustained that would permit use of fire as a tool for maintaining desired forest structure.
  - a. This objective is still in the process of being met. Analyses were slowed when funds were pulled back and then when partially restored, transferred to our University partners. No hiring could be done on the USFS side, and staff trained in FVS analyses were not immediately available to work on this project.
- D. In part to compensate for the slower progress possible under “C” above, we added two objectives not in the original proposal. The first was to quantify the effect of wildfire on ponderosa pine and black oak regeneration to help validate predictions of future stand structures in “C” above.
  - a. This objective was met by installing and measuring plots in the ‘Graham Pinery’ adjacent to the Beaver Creek Pinery. This Pinery also burned in 1990 and regeneration was impacted by the 2014 Campbell Fire.
- E. The second added objective was to include immersive content with the website deliverable. Our work reminded us about the challenges of access to this remote area, and thus the limits of using this area as a reference site. Immersive content in the form of 360 degree photographs and videos help bring visuals of forest stand structures to a larger audience.
  - a. This objective was met.

## Background

Most dry forests of the western US once experienced frequent low to moderate severity fire, which thinned trees, created fuel discontinuities at within stand- to landscape-scales, and reduced the likelihood of future high severity fire. Fire exclusion has resulted in an increase in tree density and infilling of gaps with trees (Scholl and Taylor 2010; Knapp et al. 2013), producing a more continuous fuel bed prone to rapid fire spread. In logged areas, this increasing homogeneity has been further reinforced by the removal of the largest most fire-resistant trees.

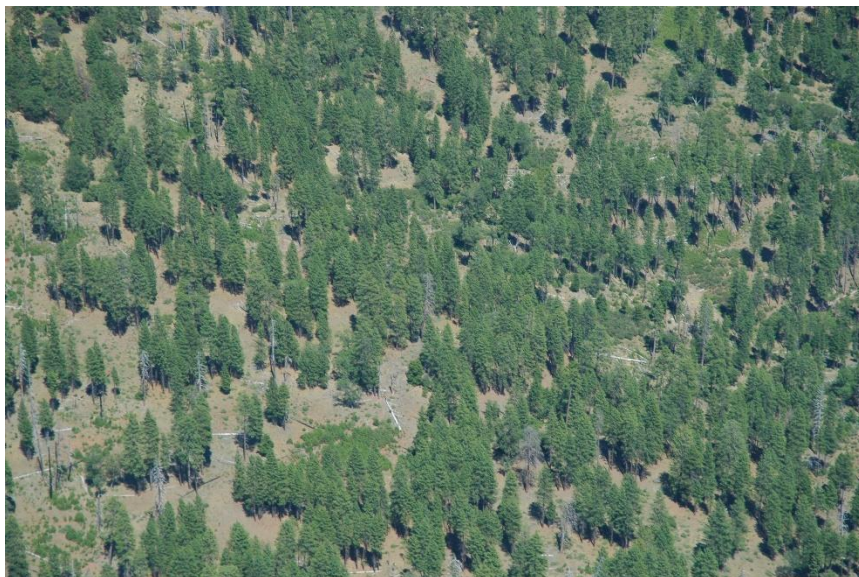
The ecological and fire resilience benefits of forest heterogeneity are increasingly being recognized by land managers (North et al. 2009), and restoring structural features that were historically generated and maintained by frequent fire has become a central tenet of public land forest management in many areas (Allen et al. 2002, North et. al. 2009, Franklin and Johnson 2012). However, to utilize, or at least attempt to emulate, natural processes requires an understanding of how forest ecosystems evolved and functioned prior to recent large scale human intervention. Contemporary examples of ponderosa pine forests with a fully restored structure are rare because most have either been logged or subject to long-term fire exclusion. Historical data on forest structure have provided some clues, but these data are incomplete for many forest types and locales.

The Ishi Wilderness within the Lassen National Forest contains several ponderosa pine (*Pinus ponderosa*) dominated stands mixed with California black oak (*Quercus kelloggii*). These stands or “pineries” are situated on broad plateaus above river canyons, where because of their remoteness, they have never been logged and fire has not been as readily controlled as it has been elsewhere. The most well documented of these, the Beaver Creek Pinery (BCP), is a frequently cited contemporary example of a heterogeneous wildfire-resilient forest containing a structure similar to what historical ponderosa pine forests once looked like (Skinner and Taylor 2006, Larson and Churchill 2012) (Figure 1). The BCP experienced four wildfires in the 20<sup>th</sup> century (Skinner and Taylor 2006, Taylor 2010). The latest 1990 and 1994 fires restored the structure to one more similar to the historic forest structure present prior to fire exclusion (Figure 1). This was due to fortuitous burning conditions with fire hot enough to kill many of the young trees that had established in the preceding fire-free period (1924 to 1990) but not too hot to kill the entire stand. The tree diameter distribution in the BCP following the 1994 Barkley Fire was very similar to the 1938 diameter distribution in old-growth ponderosa and Jeffrey pine forests at a site farther east in the Blacks Mountain Experimental Forest (Skinner and Taylor 2006). Furthermore, the trees were arranged in small (100 m<sup>2</sup> to 1500 m<sup>2</sup>) groups varying in age and size (Figure 2), the same structure and scale noted in ponderosa pine forests throughout the west, prior to logging and fire exclusion (Show and Kotok 1924, Cooper 1961, White 1985). Most other ponderosa pine forests have highly altered structural components, due to fire exclusion and past timber harvest, making the BCP an important reference ecosystem. The fact that the BCP was resilient to the 1990 and 1994 wildfires that burned under extreme summer fire weather conditions led to the initial interest in identifying and understanding the structural attributes contributing to this resilience.

Another key feature of the BCP is the abundance of healthy black oaks, which comprise almost a quarter of the trees (Taylor 2010). Black oaks are important for wildlife, with trees providing resting and nesting habitat (Steger et al. 1997, Purcell et al. 2009) as well as acorns for deer, black bear, and other wildlife species. Black oak acorns were also a preferred food for the Yahi and other tribes who once inhabited the mid-elevation forests of California (Anderson 2007). Acorns continue to be valued by



tribes today, but suitable gathering areas, with a high enough density of trees with healthy crowns, are increasingly rare. The absence of disturbance, such as fire, has shifted the balance from hardwoods to conifers in many areas. Historically, frequent fire in the flashy oak leaf litter fuelbed killed many pine seedlings, preventing replacement of oak by pines. In the absence of fire, conifers often become established and eventually overtop and out-compete the shorter black oak, eliminating them from forest stands (e.g. Scholl and Taylor 2010).



**Figure 1.** Heterogeneous structure of the Beaver Creek Pinery, Ishi Wilderness, Lassen National Forest in 2006, 12 years after the last wildfire.

Because they are not a widely used timber species, black oak was once considered undesirable and removed from multispecies stands. The value of oaks, as wildlife habitat and an important component of structurally heterogeneous stands because of their ability to break up crown fuel continuity and reduce the likelihood of crown fire, is recognized today. As a result, there is increased interest in restoring black oak as a component of mid-elevation forests (Anderson 2007, Cocking et al. 2014). However, little information is available to managers about the interactions between fire frequency and severity that promote and maintain the balance between oaks and conifers. One concern is that with a longer fire return interval, invading conifers may become large enough to survive low to moderate intensity fire, potentially shifting the competitive balance between species (Cocking et al. 2014). Thus, frequent fire may be key for long-term persistence of black oak (Taylor 2010). However, how the time-dependent threshold conditions for fuels and fire intensity regulate the potential for oaks vs. pines in these mixed forests is not well understood.

Since 1994, at least three fires have been suppressed that could have benefitted the BCP by removing ingrowth and reducing fuel buildup. In the absence of fire, tree seedlings, saplings, and small trees are rapidly filling canopy openings. As saplings and small trees increase in size, they are increasingly resistant to low intensity surface fire (Battaglia et al. 2008). At some point a threshold will be crossed where the type of low intensity fire that was historically the norm no longer has the thinning power to maintain the heterogeneous and fire resilient structure of the BCP. Higher intensity fire will then become necessary to thin the stand. With fuel build-up, higher intensity fire will also become more likely. Such fire is less predictable and could also irreparably damage the ponderosa pine and black oak overstory.



**Figure 2.** Example of the heterogeneous fire resilient structure found within the Beaver Creek Pinery, with regeneration focused in gaps – thus creating different age classes that are spatially separated. Note also the understory with abundant shrubs, grasses and forbs. Since this 2006 photo, regeneration has expanded into areas occupied by overstory vegetation.

About a century ago, many ponderosa pine forests had a structure similar to that found in BCP today. At that time, the choice was made to suppress fire and allow conifer regeneration to grow (Show and Kotok 1924). The widespread success of this fire suppression policy and subsequent forest densification and fuel accumulation is a major factor contributing to uncharacteristically severe wildfires being experienced throughout the western U.S. today (Brown et al. 2004). It is also a major reason for the decline of ponderosa pine and black oak and a shift to more fire-sensitive species.

A great deal of effort is currently being expended to restore ponderosa pine and pine/black oak forests by reducing density, favoring larger more fire resistant trees, and promoting a more heterogeneous structure. Data quantifying the diversity of resilient fire-created structures is needed, as is information on how to best maintain such forests into the future. Prior to the onset of fire suppression policy, the BCP burned at a median interval of 12 years (Taylor 2010) – a similar interval to many other western dry pine forest types. Even if some fire can be restored to this landscape through managed wildfire or prescribed fire, given liability and risk constraints (Ryan et al. 2013) and the backlog of areas in need of treatment (North et al. 2012), a longer interval between future fires is highly probable for this and most other western forest landscapes that historically witnessed frequent fire. Once structure is restored, it is therefore vital to understand the consequences of likely future changes to the fire regime on the maintenance of resilient and heterogeneous conditions. Data from over twenty years post-fire provide key information on spatial variability in stand growth and fuel development in ponderosa pine and black oak forests. These data are essential for identifying the persistent effects of fire on spatial heterogeneity and fire resilience, which is needed for guiding management, especially in landscapes that are designated to use fire as the primary vegetation and fuels management tool. While exact thresholds may be regionally specific, the underlying concepts are broadly applicable over the range of ponderosa pine and mixed ponderosa pine/ hardwood forest.

## Materials and Methods

### 1. Study site

The Beaver Creek Pinery is located about 11 miles (18 km) north of Cohasset, Butte County, California (N 40° 4' 37'' Latitude, W 121° 42' 45'' Longitude) on a plateau on the northwest side of Deer Creek canyon, at an elevation of about 2800 feet (853 m) (Figure 3). The total acreage is about 110 ha. The two dominant tree species are ponderosa pine and California black oak. Common understory shrubs include *Arctostaphylos manzanita* subsp. *roofii*, *A. viscida*, *Ceanothus integerrimus*, *C. prostratus*, *C. lemmonii*, *Frangula californica*, *Mahonia aquifolium*, and *Toxicodendron diversilobum*. Average annual temperature and precipitation in Cohasset (800 m, 20 km southwest) is 16°C and 145 cm, respectively. Most precipitation occurs between October-April. The Yana (Yahi) tribe lived in the region for 3,000 years prior to European settlement in the mid-19th century, and Ishi, the last tribal member living in what is now the Ishi wilderness, emerged from the area in 1911 (Kroeber 1961). The Yana used fire to promote plant growth for food, fiber, and game (Anderson 2005). Burning was used, in particular, to promote black oak growth and acorn production and rates of acorn collection. Fire was a frequent disturbance in the BCP before fire suppression was imposed in Lassen National Forest in 1905. The mean and median point fire return interval in the BCP were 16- and 12-years, respectively, and burns occurred mainly late in the growing season (Taylor, 2010). Four fires burned in the BCP in the 20<sup>th</sup> century, specifically in 1901, 1924, 1990 and 1994; the most recent burns in 1990 (Campbell) and 1994 (Barkley) burned at predominantly low- to moderate-severity with some moderate- to high-severity patches in the 1990 Campbell Fire (Figure 3). These fires killed mainly smaller diameter trees and created canopy gaps favorable for ponderosa pine and black oak regeneration (Taylor 2010).

### 2. Sampling Design

Initial vegetation sampling followed wildfires in the BCP in 1990 and 1994 and was conducted in two types of plots. One set of plots (from here on: PSW plots) were established on a 100 m x 100 m grid across the Pinery. The second set of plots (from here on: Taylor plots) were six larger (0.9 ha to 1.0 ha) stem maps. Vegetation data collected in 2016 for both the PSW and Taylor plots repeated data collected in 1998 and 2000, respectively. Plots in the adjacent Graham Pinery plots were newly established and measured just once – in 2017, following the 2014 Campbell Fire.

#### PSW plots.

A 100 m x 100 m grid (n=107) was established across the BCP before the initial data collection in July 1998. To characterize forest and fuel succession post-fire at each grid point, circular inventory plots were established. Large trees (>29.5cm dbh) were measured in a 0.08 ha plot, small trees (9.2-29.5cm dbh) were measured in a 0.02 ha plot and tree saplings (<9cm dbh, >1.4m tall) and seedlings (<1.4m tall) were tallied by species in a 0.004 ha plot. Understory cover of litter, bare ground, rock, coarse woody debris, grass, forbs, and shrubs were estimated within the 0.004 ha plot. Diameter at breast height (DBH) was measured for all trees; total tree height and height to base of live crown was measured on the first tree of each species encountered clockwise from north. If dead, the decay condition class of the snag was noted according to a five category scale based on Thomas et al. (1979). Photographs were also taken from the plot center in 1996 in each of the four cardinal direction in a subset of plots. Photographs were repeated in 2016.

Surface fuel loading in each PSW plot was quantified using Brown's (1974) planar intercept method, using two 20 m transects placed. The first azimuth was randomly selected and the second was

placed 120° from the first. Transect slope (%) was determined with a clinometer. To better correlate loading with fire effects in the variable radius vegetation plots, 1hr and 10hr fuels were counted between 4 m and 6 m (2 m total) starting from the central grid point, 100hr fuels are counted between 4 m and 10 m (6 m total), and 1000hr fuels are evaluated over the entire 20 m length of the transect. For the 1000hr fuel category, diameters were measured, species of log determined and the decay class condition (sound or rotten) noted. Maximum depth of elevated dead woody fuel (bottom of the litter layer to height of the tallest piece of woody fuel) was measured in three 30-cm increments (4.0 – 4.3 m, 8.0 – 8.3 m, and 12.0 – 12.3 m). Litter and duff depth measurements were taken at three locations 0.5 m to the right (facing out from plot center) of the transect (5 m, 9 m, and 13 m).

### **Taylor plots**

The Taylor plots were selected based on 1) the presence of large diameter trees ( $\geq 1.0$  m dbh); 2) homogeneous growing site conditions; and 3) stand characteristics representative of the range of variation in the structural attributes (age, size, horizontal pattern) of the forest in the BCP. The location of each plot corner was identified with a GPS and staked and elevation, slope pitch, slope aspect, slope configuration, and slope position were recorded (Taylor 2010). Each plot was subdivided into 10 m x 10 m grid cells, and stem location (x, y) from the origin (0, 0) was determined for all tree seedlings (0.2 to 1.4 m tall), tree saplings ( $>1.4$  m tall and  $< 5$  cm dbh), and trees  $>5$  cm dbh, with a metric tape.

Data recorded for each tree included relative height class (suppressed, intermediate, lower main canopy, upper main canopy, emergent), species, and dbh. Saplings and seedlings were classified by origin (established from seed or by sprouting). Since canopy openings are often sites for tree establishment, tree canopy cover above each grid cell was estimated using one of three classes: open ( $<33\%$  cover), intermediate (33-66% cover), and closed ( $>66\%$  cover). The number of contiguous cells with  $<33\%$  cover was also identified in each plot to estimate the gap size ranges ( $m^2$ ) in each plot. Finally, the cover of shrubs, forbs, and grasses was estimated in each grid cell.

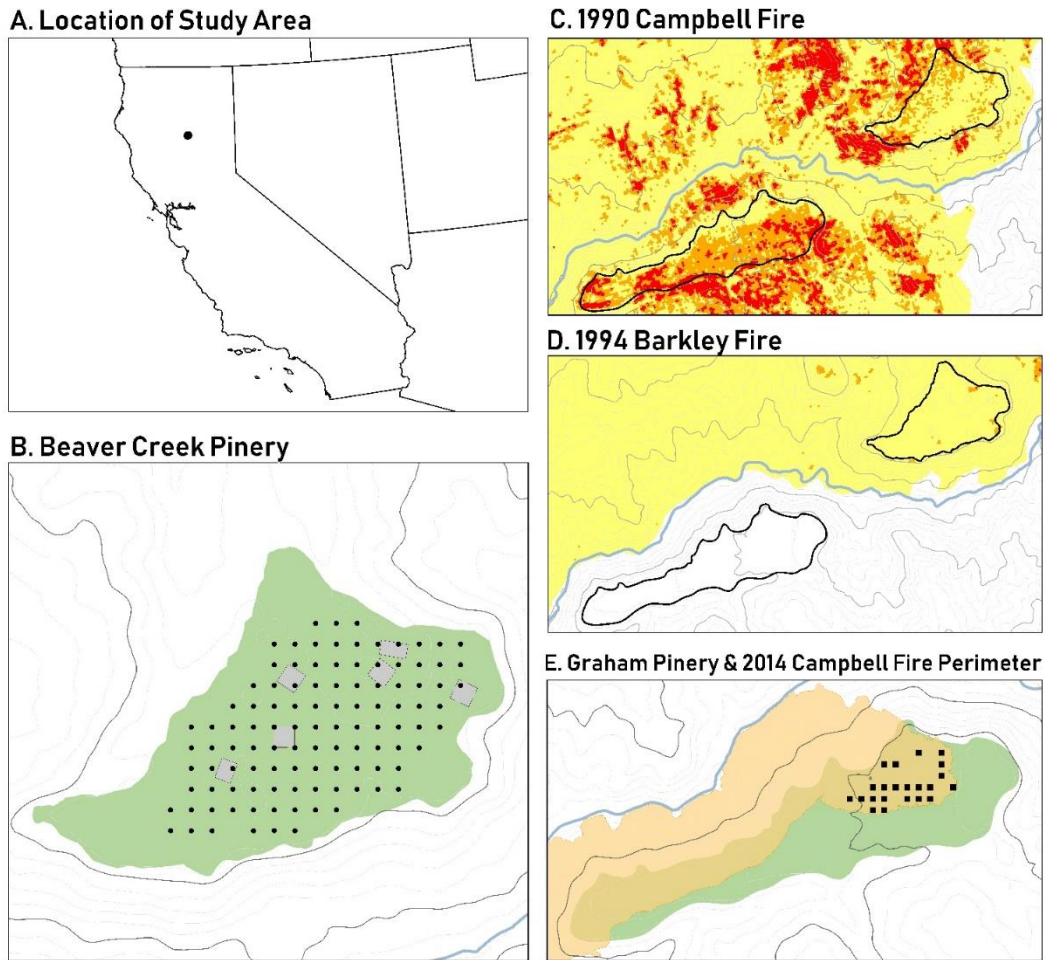
### **Potential fire behavior and fire effects**

The surface fuel loadings from Brown's transects, vegetation structure data and expert opinion were then used to identify a standard fuel model to characterize surface fuel conditions at each PSW plot gridpoint. Ultimately, five different fuel models were used in our analysis for the PSW plots– TL08 (n=70), TL09 (n=4), TU04 (n=15), SH07 (n=2) (Scott and Burgan 2005), and 6 (n=12) (Anderson 1982). Surface fuel loadings in the Taylor plots were most similar to TL08 (Scott and Burgan 2005), and this surface fuel model was used for all of these plots.

### **Graham Pinery plots**

The objective for these plots was to gauge the effect of a wildfire (the 2014 Campbell Fire) on ponderosa pine and black oak regeneration similar in age and size to trees and saplings found in the BCP, and validate modeled predictions of mortality. The Graham Pinery is located south of the BCP, on the other side of Deer Creek. Elevation is similar to the BCP, but vegetation is more black oak dominated with fewer ponderosa pine, on the account of previous higher severity wildfires. A total of 63 points, on a 100 x 100 meter UTM grid (NAD83) were placed on a map of the portion of the Graham Pinery within the boundary of the 2014 Campbell Fire in GIS. Because ground travel into the Graham Pinery is a limiting factor, we restricted our grid to points within a mile of the NE corner of the Pinery, where a trail to access the Pinery reaches the Campbell Fire line. Twenty two of the points were

randomly selected and sampled. Plot center was determined using a GPS. Several points were thrown out due to being on the edge of a cliff or because of excessive poison oak.



**Figure 3.** A) Location study area in Lassen National Forest, California. B) The Beaver Creek Pinery with the 107 PSW plots and six 1 ha Taylor plots. Severity (Low, Moderate, and High) of the C) 1990 Campbell Fire, D) 1994 Barkley Fire across the Beaver Creek Pinery based on Monitoring Trends in Burn Severity data, and E) plots in the adjacent Graham Pinery and the perimeter of the 2015 Campbell Fire.

In the field we used evidence of post-fire mortality to gauge pre-Campbell Fire structure, and estimate what proportion of seedlings, saplings, and trees were killed. Protocols used here were similar to those used for the PSW plots in the BCP, but modified for rapid assessment of effects on forest structure. Tree heights were not determined, and fuel data were not collected. Plot sizes for black oak seedlings, saplings, small trees, and large trees were the same as those used in the BCP. Because of the lower density of ponderosa pine, we collected data using larger radius plots. Number of saplings, small trees, and large trees were counted in 0.08 ha (16.05 m radius) plots, and number of seedlings were counted in 0.02 ha (8.02 m radius) plots. Probable pre-Campbell Fire status was estimated by assuming

all stems without wood char (through the bark) were live at the time of the fire. Post-fire status and present status (if different) were then also noted. Photographs were taken in all four cardinal directions from plot center.

### **3. Data Analysis**

#### **Taylor Plots**

Global and local statistics were used to quantify tree group spatial characteristics. The standardized L-function of Ripley's K, a global statistic based on point pattern analysis, was used to identify the type, scale, and intensity of pattern for trees in 2000 and 2016. To delineate specific tree groups and determine the size and density of tree groups within plots for 2000 and 2016, an inter-tree distance algorithm was used (Plotkin et al. 2002). A 6-m inter-tree distance was chosen to delineate groups into five functional categories: 1) individual (1 tree), 2) small (2-4 trees), 3) medium (5-9 trees), 4) large (10-15 trees), and 5) extra-large (>15 trees).

Gap characteristics (frequency, area) in 2000 and 2016 were quantified using an empty space function to calculate distances to the nearest tree (Diggle 2013). Areas greater than 9m from a tree stem were delineated as a gap (see Clyatt et al. 2016 for full protocol) and differences in mean gap size and open area in 2000 and 2016 were identified using separate paired t-tests and a relaxed probability of significance ( $p = 0.1$ ) because the number of plots was small ( $n = 6$ ). The relationship between canopy cover and the abundance of tree regeneration was identified by comparing seedling and sapling density under canopy conditions (open, intermediate, or closed) in 2000 and 2016 using a non-parametric Kruskal-Wallis tests with a Dunn's post-hoc test.

#### **Structural and spatial heterogeneity**

To examine how forest structure changed at the scale of the Pinery and determine whether forest conditions became more or less heterogeneous over time, we conducted several analyses. First, we compared changes in live and dead tree density (by species and size class), regeneration density, and understory characteristics using paired t-tests to determine if and what components of vegetation structure, on average, increased over the period. A consistent increase in the density and size of vegetation characteristics would suggest convergence in post-fire structural homogeneity. Second, we compared the difference in variance over the same period for the same variables using a Levine's test. Reduced variance across the variables would suggest convergence in conditions and a reduction of structural homogeneity over time. Finally, we identified overall changes in structural diversity by calculating diversity indices (species richness-S; Shannon's diversity-H, evenness-E; Simpson's diversity) with the same variables for each plot in both 1998 and 2016. We then compared overall changes in each of these indices using paired t-tests.

#### **Current potential Fire Behavior**

Potential fire behavior and fire effects following 22-years of post-fire succession in the PSW plots were determined for each plot using FFE-FVS software (Rebain 2010). Potential fire behavior and effects were modelled for prescribed fire under cooler conditions, prescribed fire under hotter conditions, and wildfire under 80<sup>th</sup> and 98<sup>th</sup> percentile ERC conditions. Values for fire weather variables (temperature, wind speed, fuel moisture) at the different ERC percentiles were generated using FireFamilyPlus and RAWS weather data from the Cohasset field station (~800m elevation, 20 km

southwest of BCP). Canopy fuel variables were estimated from the tree lists for each plot using Crown Mass in the Fuel Management Analyst Plus software (FMA, Carlton 2004). A Similar approach was used for the Taylor plots, with potential fire behavior and fire effects estimated using FMA for three weather conditions: the 50<sup>th</sup>, 80<sup>th</sup>, and 98<sup>th</sup> percentile values of fire season (May 1 – September 31) ERC.

### **Future stand development and potential fire behavior and fire effects**

Our hypothesis was that a structurally heterogeneous forest maintains fire resilience longer than a homogenous forest and that the longer post-fire vegetation develops, the narrower the range of fire conditions will be that can maintain or restore the desired condition. We tested this idea using the vegetation data collected in the PSW plots, the FVS vegetation simulator, the Fire and Fuels Extension (FFE) to FVS (Keyser 2009; Rebaun 2010), and weather data from the Cohasset RAWS station (NESS ID 041211). Two weather conditions were used for the future burning scenarios: 1) a wildfire under extreme fire weather conditions (97<sup>th</sup> percentile) and; 2) a prescribed fire implemented under more controlled conditions. Weather variables were restricted to the typical May through October fire season. Prescribed fire weather and fuel moisture conditions were provided by local fire personnel with extensive experience in the area (Patrick Doyle, personal communication). Mean potential fire behavior and fire effects were calculated for plot for each time step and compared using repeated measures statistics.

The calibration of mortality predictions based on outcomes from the 2014 Campbell Fire in the Graham Pinery was conducted on Graham Pinery tree lists by individual plot, using the same fuel model selection methods as for the BCP. Weather variables were estimated using the Jarbo Gap RAWS. This RAWS station experiences similar wind as sites in the Deer Creek Canyon (Patrick Doyle, personal communication), and thus preferred for wind-driven fire events. Most of the spread of the Campbell Fire across the Graham Pinery occurred during the night of Jan. 2/3, under a NNE wind. Tree mortality was predicted using FFS-FFE, with averages between 20:00 on Jan. 2<sup>nd</sup> and 03:00 on Jan. 3<sup>rd</sup> for wind speed and air temperature. The burn season was considered to be fall (even though the fire took place in early winter), and 100% of the area was assumed burned.

## **Results and Discussion**

### **1. Taylor plots**

On average, tree density and basal area for ponderosa pine and black oak were similar ( $p > 0.1$ ) in 2000 and 2016, however ponderosa pine had much higher rates of recruitment and lower rates of mortality than black oak. As expected, ingrowth of both species was concentrated in the smallest-size classes (saplings; 5-15 cm and 15-25 cm trees) and mortality was highest for small (5-15 cm) and large (100-120 cm) ponderosa pine and for large (65-75 cm) oak.

### **Spatial Analysis**

In 2000, average tree group size was 5.5 trees per group, this increased to 9.2 trees per group in 2016. Maximum group size also increased from 28 to 240 trees. The average number of groups per plots remained similar: 18 ha<sup>-1</sup> (range 11-27 ha<sup>-1</sup>) in 2000 and 22 groups ha<sup>-1</sup> (range 15-30 ha<sup>-1</sup>) in 2016. Canopy gaps averaged 6.0 ha<sup>-1</sup> (range 1-10) in 2000 and 7.2 ha<sup>-1</sup> (range 1-9) in 2016. Total gap area decreased from 2000 to 2016 ( $p = 0.07$ ). Area occupied by regeneration increased between 2000 and 2016 and this was mainly due to the increase of ponderosa pine. Area occupied by black oak regeneration declined between the two time periods. In 2016, both ponderosa pine and black oak

seedlings were more abundant within canopy gaps (< 33% cover) than in either intermediate or closed canopy conditions ( $p < 0.05$ , Kruskal Wallis H-test). For saplings, the same pattern was observed for ponderosa pine, but not black oak.

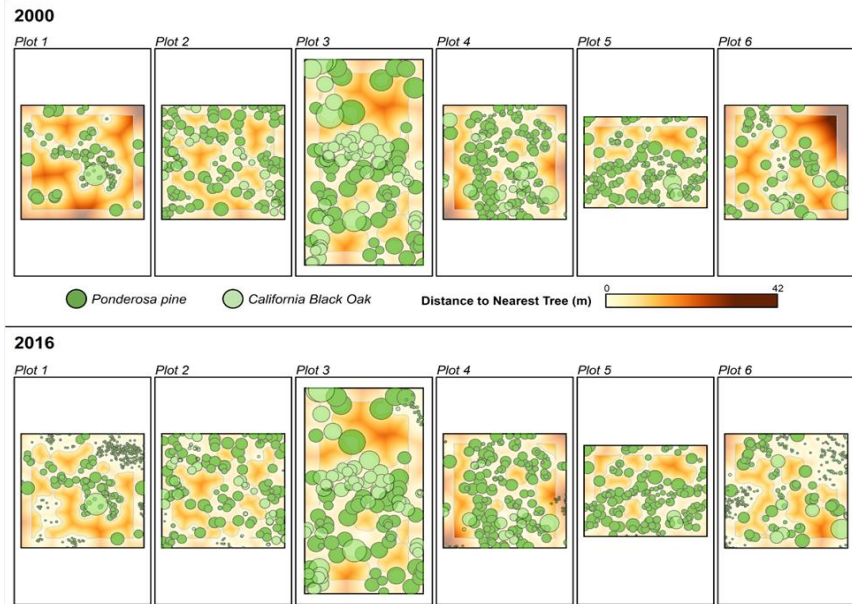
### Current potential fire behavior

Fire behavior modelling predicted potential flame lengths <1m under all weather conditions. Plots with passive crown fire and the highest flame lengths had the highest density of small diameter trees (<15 cm dbh). Average probability of mortality was highest (100%) for saplings (<5cm dbh, >1.4 m tall) and lowest ( $\leq 1.4\%$ ) for large trees (>30 cm dbh). Between species, oaks had a greater probability of top-kill than ponderosa pine.

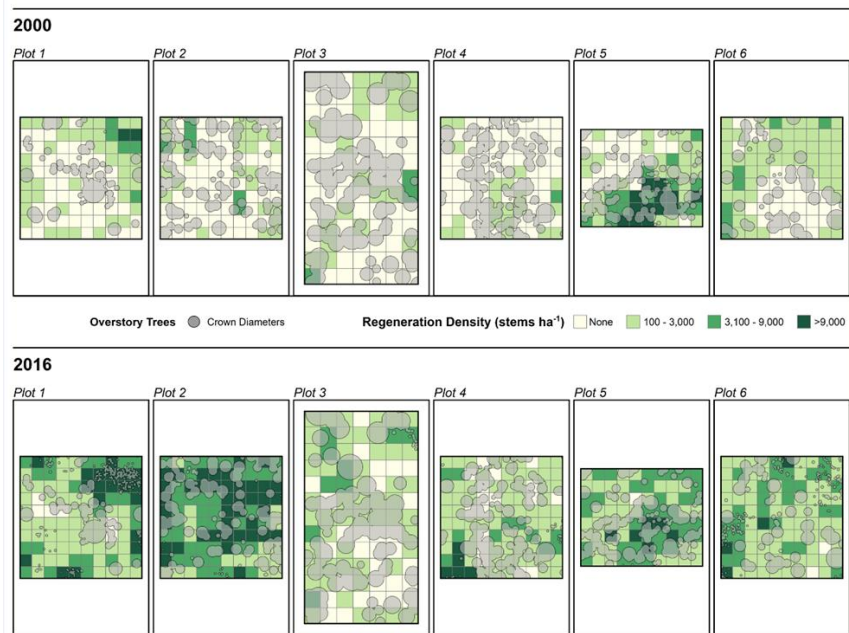
**Table 1.** Summary of forest characteristics in the Taylor plots in 2000 and 2016.

		Plot		1		2		3		4		5		6	
				2000	2016	2000	2016	2000	2016	2000	2016	2000	2016	2000	2016
Ponderosa Pine	Basal Area (m <sup>2</sup> ha <sup>-1</sup> )	Live	13.57	12.64	28.20	27.47	27.80	29.45	26.91	30.76	28.56	33.89	16.04	16.14	
		Snags	1.43	2.93	1.88	5.06	0.08	1.40	1.95	0.91	2.69	1.45	5.05	6.22	
	Tree Density (ha <sup>-1</sup> )	Live	82	410	103	106	65	90	139	163	184	176	64	281	
		Snags	17	13	16	30	1	2	13	15	34	14	17	22	
	Seedlings		675	3231	691	9151	41	804	121	1553	1760	3019	730	1872	
	Saplings		-	1556	-	1563	-	75	3	239	-	104	-	640	
California Black Oak	Basal Area (m <sup>2</sup> ha <sup>-1</sup> )	Live	0.91	0.97	1.78	2.05	7.62	7.21	2.88	1.86	1.26	0.64	2.05	1.91	
		Snags	-	-	0.84	0.21	0.52	1.51	0.37	0.32	-	0.65	0.59	0.55	
	Tree Density (ha <sup>-1</sup> )	Live	1	1	26	44	63	59	19	14	3	2	7	10	
		Snags	-	-	17	3	8	11	4	2	-	1	3	2	
	Seedlings (ha <sup>-1</sup> )		60	50	342	50	252	14	61	4	41	26	73	63	
	Saplings (ha <sup>-1</sup> )		1	2	70	46	27	23	4	-	-	1	3	13	
Average Shrub Cover (%)		5	16	21	35	19	37	5	15	22	28	6	29		
Average Herb Cover (%)		43	23	24	11	28	30	21	24	32	14	48	23		





**Figure 4.** Maps of tree groups and canopy gaps in 2000 (top row) and 2016 (bottom row) in six ~1ha stem map plots in the Beaver Creek Pinery. Background shading indicates the distance to the nearest tree (empty space function) and regions >9 m away from any tree are outlined and in bold. Darker green circles represent ponderosa pine and light green circles California black oak.



**Figure 5.** Maps of regeneration density for both ponderosa pine and California black oak seedlings and saplings in 2000 (top row) and 2016 (bottom row) in six ~1ha stem map plots in the Beaver Creek Pinery. Darker shading represents higher density of regeneration and overstory tree groups are gray and partially transparent.

## 2. PSW plots

On average, the PSW plots contained somewhat fewer trees of both black oak and ponderosa pine and lower basal area than the Taylor plots. The PSW plots represented more of a landscape view and included a greater diversity of overstory and understory structures than found in the Taylor plots.

**Table 2.** Potential fire behavior and fire effects in the Taylor plots under three fire weather conditions. The fuel model for all fires was TL08 (Scott and Burgan 2005).

	Weather percentile		
	50th	80th	98th
Fire type	5 surface, 1 passive crown	5 surface, 1 passive crown	5 surface, 1 passive crown
Mean flame length (m)	0.80	0.86	0.90
Mean probability of mortality			
Saplings (>1.4 m tall <5cm dbh)	100	100	100
Small trees (5-30 cm dbh)	77.8	78.3	79.0
Large trees (>30 cm dbh)	0.75	1.1	1.4

### Structural and Spatial Heterogeneity

On average, ponderosa pine and California black oak tree density and regeneration (except black oak seedlings) density increased ( $P < 0.01$ ), and snag density decreased ( $P < 0.01$ ) in the plots over the post-fire period (Table 3). Changes were larger for ponderosa pine than for black oak. Understory conditions also changed. Percent cover of grass ( $P < 0.001$ ) and bare ground ( $P < 0.001$ ) decreased, while coarse woody debris cover, bare ground cover, tree canopy cover, and shrub cover increased (Table 4). Cover of forbs and bare ground, on average, was unchanged.

**Table 3.** Average density and basal area for tree species in the PSW plots in 1998 and 2016 in the Beaver Creek Pinery, Lassen National Forest, California. Differences in mean values ( $p < 0.05$ ) between 1998 and 2016 for a particular characteristic are indicated with an \*.

		Density ( $\text{ha}^{-1}$ )				Basal Area ( $\text{m}^2 \text{ha}^{-1}$ )	
		Live Trees	Snags	Saplings	Seedlings	Live Trees	Snags
1998	<i>P. ponderosa</i>	68.6*	14.7*	30.3*	1993.9*	12.4	4.5*
	<i>Q. kelloggii</i>	7.6*	2.7	7.0*	55.9	1.5	0.6
	<i>Total</i>	76.2*	17.4*	37.3*	2049.8*	13.9	5.1*
2016	<i>P. ponderosa</i>	181.4*	8.3*	1651.9*	3215.1*	15.8	1.9*
	<i>Q. kelloggii</i>	14.0*	2.4	62.3*	69.5	1.4	0.3
	<i>Total</i>	195.4*	10.7*	1714.2*	3284.6*	17.2	2.2*

**Table 4.** Averages for understory and overstory variables in the Beaver Creek Pinery in 1998 and 2016. Differences in mean values ( $p < 0.05$ ) between 1998 and 2016 for a particular characteristic are indicated with an \*.

Year	Grass cover (%)	Forb cover (%)	Shrub cover (%)	Tree cover (%)	Litter (%)	Coarse woody debris (%)	Bare Ground (%)
1998	33.4*	8.2	16.5*	14.5*	34.6*	0.2*	5.2
2016	3.0*	9.7	31.0*	34.2*	47.9*	4.8*	2.8

In terms of overall pine-oak demographics over the 1998-2016 period, ~6% of plots had a black oak-dominated overstory in 1998 compared to ~10% of plots in 2016. In 1998, ~20% of plots had black oak present in the overstory and ~20% of plots had oak regeneration in the understory; by 2016, ~30% of plots had oak in the overstory and ~24% of plots have oak in the understory. Of the plots with oak in the overstory in 1998 ( $n=27$ ), 22% had an increase in oak abundance and 44% had a decrease. Of the plots with no oak in 1998 ( $n=80$ ), 5 of them gained oak in the overstory and understory, 7 gained oak only in the overstory, and 3 plots gained oak in the understory.

Changes in the variance of overstory and understory vegetation characteristics also occurred (Table 5, 6). Variance increased between 1998 and 2016 for live ponderosa pine trees, ponderosa pine and black of saplings, tree cover, shrub cover and coarse woody debris cover. On the other hand, variance declined over the same period for snag density, grass cover, forb cover, litter cover, and bare ground cover.

**Table 5.** Variance (standard deviations are reported) of tree characteristics in PSW plots in 1998 and 2016 in the Beaver Creek Pinery, Lassen National Forest, California. Differences in variance values ( $p < 0.05$ ) between 1998 and 2016 for a particular characteristic are indicated with an \*.

		Density ( $\text{ha}^{-1}$ )				Basal Area ( $\text{m}^2 \text{ha}^{-1}$ )	
		Live Trees	Snags	Saplings	Seedlings	Live Trees	Snags
1998	<i>P. ponderosa</i>	95.3*	37.5*	165.4*	4372.2	10.6	5.9*
	<i>Q. kelloggii</i>	23.5	7.2	41.9*	158.0	3.8	2.0
<hr/>							
2016	<i>P. ponderosa</i>	291.0*	20.1*	3890.3*	6613.76	12.1	3.8*
	<i>Q. kelloggii</i>	32.2	10.6	230.6*	296.3	3.8	1.4

Changes in the variance of individual variables were intuitive. For example lower variance for grass, forbs, and shrubs in 2016 reflects wider distribution among plots than two years post-fire in 1998. Similarly, lower variance of ponderosa pine snag density and basal area in 2016 reflects spatial variation in the density of snag creation caused by variable fire severity in 1990 and 1994, and then cumulative snag fall during the next 22 years which reduced variation among plots. This process is also seen in the increased variance of coarse woody debris over the same time period. Higher variance for regeneration and tree density (except black oak trees) increased due to infilling from 22 years of regeneration and growth of seedlings and saplings into trees.

**Table 6.** Variance (standard deviations are reported) of understory characteristics (and tree cover) in PSW plots in 1998 and 2016 in the Beaver Creek Pinery, Lassen National Forest, California. Differences in variance values ( $p < 0.05$ ) between 1998 and 2016 for a particular characteristic are indicated with an \*.

Year	Grass cover	Forb cover	Shrub cover	Tree cover	Litter	Coarse woody debris	Bare Ground
1998	25.1*	10.2*	20.2*	11.4*	31.3*	2.0*	5.2*
2016	5.2*	9.8*	26.1*	25.6*	26.0*	7.9*	2.8*

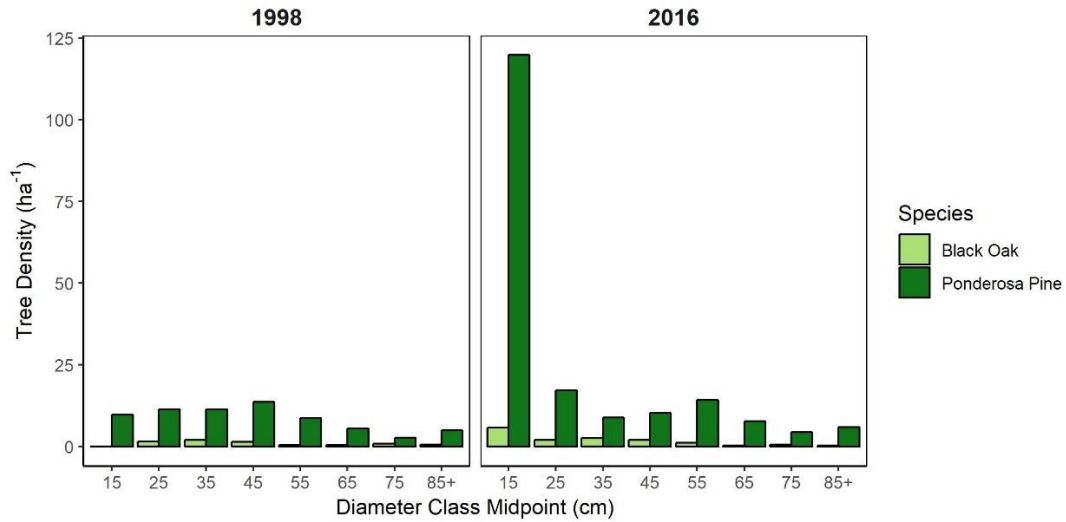
Measures of diversity that include a suite of vegetation structural variables provide a measure of how heterogeneity has changed across all PSW plots between 1998 and 2016 (Table 7). Average richness (number of variables) increased while other measures that incorporate both richness (presence/absence) and measures of abundance declined. The declines in  $H'$ ,  $E$ , and  $D$  all point to an overall reduction in structural heterogeneity across the Pinery, based on the suite of structural variables considered.

**Table 7.** Average diversity based on 21 overstory and understory variables in PSW plots ( $n=103$ ) in 1998 and 2016 in the Beaver Creek Pinery, Lassen National Forest, California. Differences in diversity ( $p < 0.05$ ) for a particular metric between years are indicated with an \*. Variables considered include: cover of litter, coarse woody debris, grass, forbs, shrubs, bare ground, trees density and basal area of live and standing dead ponderosa pine and black oak trees; seedlings and saplings of ponderosa pine and black oak.

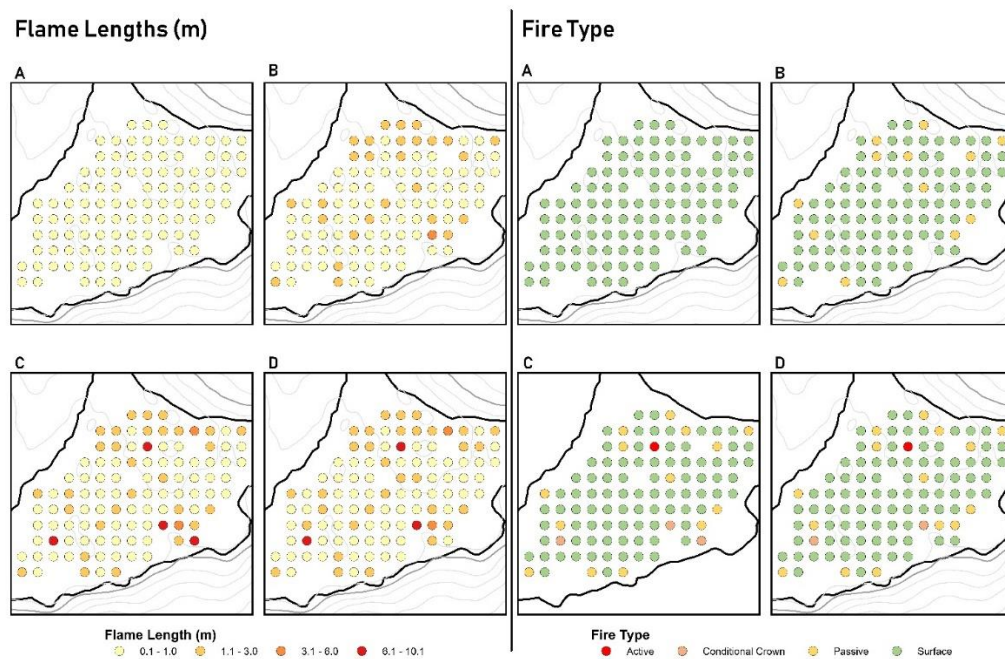
Year	Species Richness (S)	Shannon Diversity ( $H'$ )	Evenness ( $H'/\ln(E)$ )	Simpson Diversity ( $D=1/D$ )
1998	9.2*	1.24*	0.57*	0.54
2016	10.5*	1.09*	0.47*	0.50

Post fire regeneration and growth of new establishment, and growth of trees that survived the fires, were both evident in the change in the size-class distribution of ponderosa pine and black oak. The fire initiated regeneration pulse is represented by the increase in small diameter stems of both species and increased growth is seen in the upward shift of the modal diameter class of larger trees of both

species (Figure 6). The size-class distributions of ponderosa pine and black oak were both different ( $P < 0.05$ ) in 2016 compared to 1998.

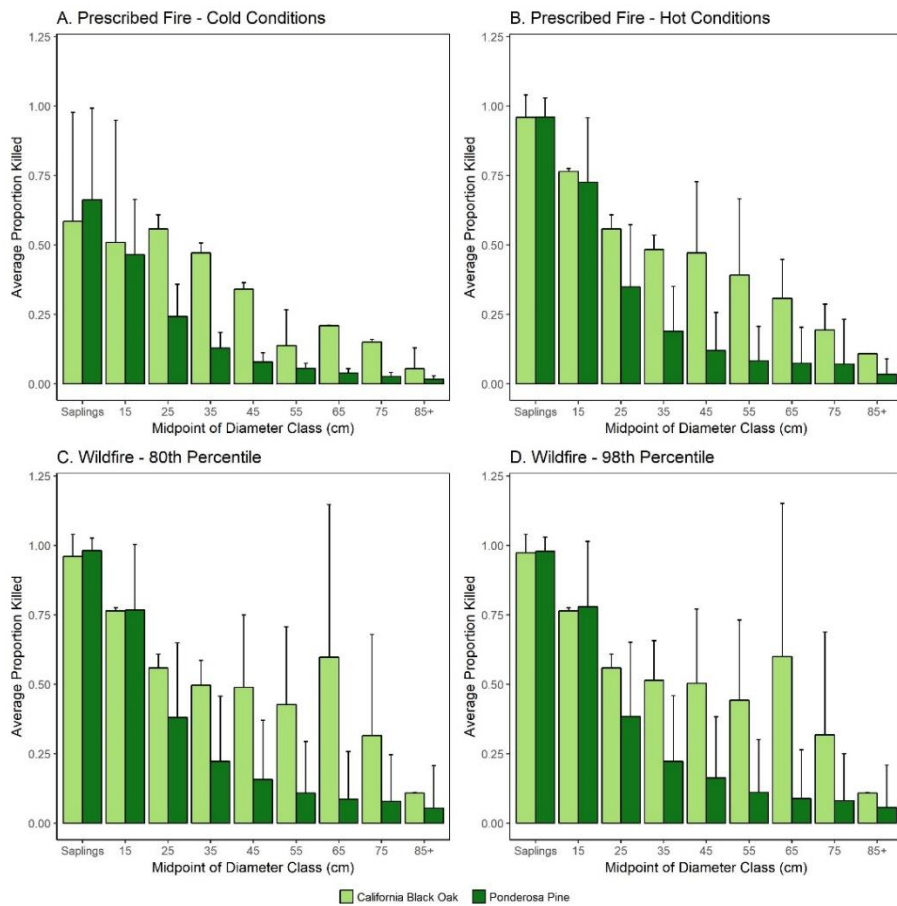


**Figure 6.** Frequency of ponderosa pine (dark green) and black oak (light green) in PSW plots sampled in 1998 and 2016 in the Beaver Creek Pinery, Lassen National Forest, California. The size-class distributions of both species were different in 2016 compared to 1998 (Kolmogorov-Smirnov two sample test,  $P < 0.05$ ).



**Figure 7.** Potential flame lengths (m) and fire type (surface, passive crown, conditional crown, active crown) under cooler prescribed fire (A), hotter prescribed fire (B), 80<sup>th</sup> ERC (C), and 98<sup>th</sup> ERC (D) weather conditions in the Beaver Creek Pinery, Lassen National Forest, California.

Potential fire behavior and fire effects were more variable in the PSW, compared to the Taylor plots, because conditions were modeled using a wider range of fuel models and weather conditions (Figure 7). Potential flame lengths for wildfires under 80<sup>th</sup> and 98<sup>th</sup> percentile conditions and the hot prescribed fire conditions were quite similar. In contrast, the cold prescribed fire condition had uniformly low flame lengths.

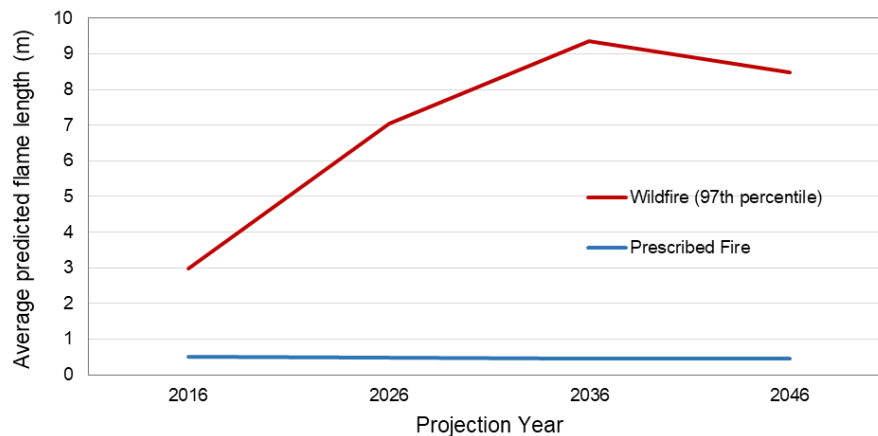


**Figure 8.** Potential tree mortality (%) (mean±SD) of ponderosa pine and black oak by size-class under 80<sup>th</sup> (upper left), 98<sup>th</sup> (upper right), hot prescription (lower right) and cold prescription (lower left) weather conditions in the Beaver Creek Pinery, Lassen National Forest, California.

As expected the potential percentage tree mortality in each size-class was related to flame length and showed the same pattern over the four weather conditions. Percentage mortality was higher and similar for the 80<sup>th</sup> and 98<sup>th</sup> percentile and hot prescribed fire conditions, and lower for the cold prescribed fire condition. Oaks in all size-classes were more likely to be killed than ponderosa pine and most saplings and small diameter trees were killed by any type of fire. Potential mortality for all tree stems < 55 cm dbh was relatively high ( $\geq 30\%$ ) for all except for the cold prescription.

### 3. Future stand development, potential fire behavior, and fire effects

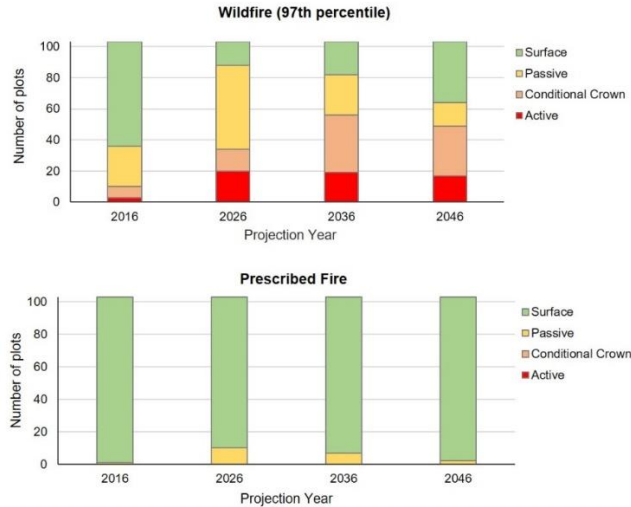
When stand growth is projected into the future, our preliminary results indicate that predicted flame lengths will be significantly higher ( $p < 0.0001$ ) under the wildfire scenario than the prescribed fire scenario at all time steps (Figure 9). Under 97<sup>th</sup> percentile weather conditions, predicted flame lengths during a wildfire would be well above desired flame lengths (1-2 m); estimated flame lengths ranged from an average of 3 m in 2016 to over 9 m in 2036. In contrast, predicted flame lengths under the prescribed fire scenario were  $< 1$  m for the entire time period analyzed.



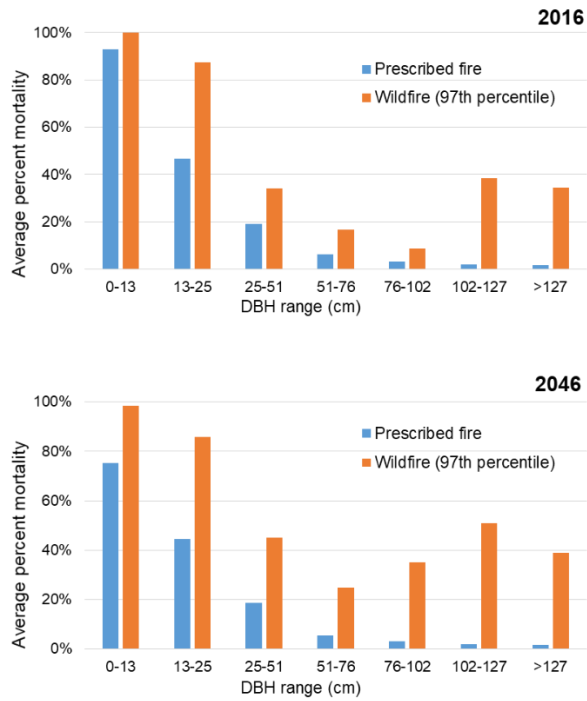
**Figure 9.** Average predicted flame length currently, and 10, 20, and 30 years into the future under two potential fire scenarios: a wildfire that occurs under 97<sup>th</sup> percentile weather conditions and a prescribed fire.

While our preliminary analysis for fire type indicates that the risk of active crown fire within the BCP is currently low, even under more severe wildfire conditions, our results also indicate that the risk of more severe wildfire behavior will increase relatively quickly during the next 10-30 years (Figure 10). The proportion of plots with potential active crown fire increased from 3% in 2016 to 20% in 2026. On the other hand there was no projected increase in potential active crown fire at each time step with prescribed fire and fire type was mainly surface fire with some small areas of passive crown fire.

Estimates of tree mortality following a simulated wildfire and a prescribed fire at two time steps, 2016 and 2046 shows that fire-related tree mortality was significantly ( $< 0.0001$ ) higher under the wildfire than the prescribed fire scenario at all time steps (Figures 11, 12). Tree mortality after prescribed fire was concentrated in smaller diameter size classes ( $< 13$  cm) with 75-93% of stems being killed in both 2016 and 2046. Larger trees ( $> 76$  cm) were generally more resistant to prescribed fire regardless of implementation year, and had low projected mortality of  $< 3\%$ . Small tree mortality was high under the wildfire scenario (98-100% of trees killed in 2016 and 2046 respectively). The risk of large tree mortality was much higher under the simulated wildfire scenario with estimated average percent mortality for trees  $> 76$  cm of 11-37% in 2046.

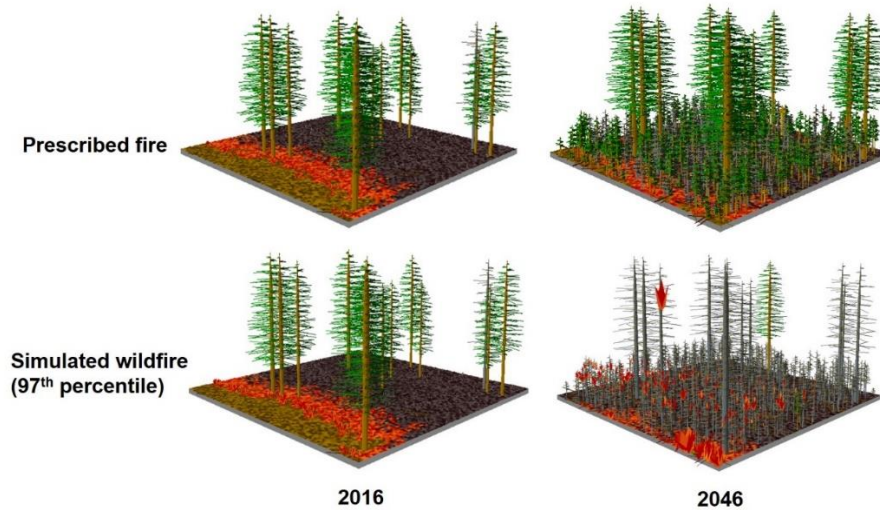


**Figure 10.** FVS-FFE predicted potential fire type currently and 10, 20, and 30 years in the future under two fire scenarios: a wildfire that occurs under 97th percentile weather conditions and a prescribed fire. The total number of plots was 103.



**Figure 11.** FVS-FFE estimated tree mortality following a simulated wildfire and prescribed fire in 2016 and 2046.





**Figure 12.** Stand visualization images produced by FVS-FFE showing simulated fire behavior in a plot characterized by a low density of larger diameter trees (plot #7798). Simulated fires were modeled under prescribed fire and severe wildfire conditions at two different time periods - 2016 and 2046.

**Table 8.** Tree mortality by size class (seedling through large tree) for ponderosa pine (*Pinus ponderosa* – PIPO) and black oak (*Quercus kelloggii* - QUKE) as a result of the Campbell Fire, which burned across the Graham Pinery on January 2-3, 2014. Modeled mortality estimated using the Fire and Fuels Extension of the Forest Vegetation Simulator.

Tree species	Size Class	No stems ha <sup>-1</sup> (pre-fire)	No stems ha <sup>-1</sup> (post-fire)	% Mortality	% Mortality (modeled)
PIPO	Seedling (30-60cm)	13.5	0	100	-
	Seedling (61-90cm)	6.7	0	100	-
	Seedling (91-137cm)	20.2	0	100	-
	Sapling (0-3.8cm DBH)	84.8	0	100	100
	Sapling (3.9-6.3cm DBH)	29.7	2.2	93	98
	Sapling (6.4-8.9cm DBH)	7.9	1.7	78	83
	Tree (9-29.4cm DBH)	15.2	5.1	66	78
	Tree (≥29.5cm DBH)	5.6	5.1	9	0
QUKE	Seedling (30-60cm)	33.7	0	100	-
	Seedling (61-90cm)	22.5	0	100	-
	Seedling (91-137cm)	22.5	0	100	-
	Sapling (0-3.8cm DBH)	411.7	10.3	97	100
	Sapling (3.9-6.3cm DBH)	421.9	20.6	95	90
	Sapling (6.4-8.9cm DBH)	256.9	79.0	69	80
	Tree (9-29.4cm DBH)	289.6	87.6	70	73
	Tree (≥29.5cm DBH)	50.5	44.9	11	46

#### **4. Tree mortality evaluation – 2014 Campbell Fire**

Seedlings of both ponderosa pine and black oak experienced 100% mortality, at least within our plots. Sapling stem mortality ranged from 78-100% for ponderosa pine and 68-97% for black oak (Table 8). Large trees experienced between 9-11% mortality (higher value for black oak). The mortality predictions made using FVS-FFE were very close to actual numbers for all sapling and tree size classes for both species, except that the mortality of large black oaks was substantially over predicted (Table 8).

### **Conclusions and Implications for Management**

Re-measurement of plots established shortly after the last (1994) fire in the Beaver Creek Pinery demonstrated that in the 22 intervening years without fire, substantial change has occurred, both at the within-stand and landscape scales. While the fire-created heterogeneity in the overstory was largely retained, dense ponderosa pine ingrowth has established in gaps and by some measures, heterogeneity has declined. Our results support a perspective that wildfire can maintain and restore resiliency by preserving, for a time, latent structure (such as legacy trees and canopy openings) in forests with relatively limited anthropogenic disturbances (Larson et al., 2013). Modeling of potential fire behavior suggests that large, old, overstory trees are currently still resilient to fire but most seedlings, saplings and small diameter trees would be killed. Thus, the overstory tree group and gap forest structure will likely persist for an extended period following the last wildfire. However, with ingrowth rapidly filling in gaps, wildfire or prescribed fire at relatively frequent intervals will be needed to reduce the demographic pressure of ponderosa pine, promote black oak, and to maintain and create future spatial heterogeneity in vegetation and fuels.

How much longer until a threshold is crossed where future fire will be unlikely or less likely to retain the heterogeneous and resilient forest conditions? While we are still currently working on refining our FVS-FFE models in an effort to improve the accuracy of predictions, preliminary results suggest that this resilience may not persist for long into the future. Wildfires simulated under 97<sup>th</sup> percentile weather conditions resulted in higher predicted flame lengths, active crown fire potential, and large tree mortality than a prescribed fire implemented in the same time period. Our preliminary analysis also suggests that as vegetation and fuels develop within the BCP, the effectiveness of prescribed burning at maintaining and restoring desired conditions, may also diminish. Burning in the next 10-20 years, under controlled conditions, will likely be the most effective strategy for reducing surface fuels and small trees, and for maintaining the unique structural heterogeneity of the BCP. However, waiting increases the risk of losing the structural integrity of the Pinery to a wildfire, as modeled results suggest that within the next ten years crown fire will become the predominant behavior, as a result of stand development and growth of large numbers of ponderosa pine seedlings and saplings.

### **Literature Cited**

Allen, C.D., M. Savage, D.A. Falk, K.F. Suckling, T.W. Swetnam, T. Schulke, P.B. Stacey, P. Morgan, M. Hoffman, and J.T. Klingel. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. *Ecological Applications* 12: 1418-1433.

- Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. US Department of Agriculture, Forest Service, General Technical Report GTR INT-122.
- Anderson, M.K., 2005. *Tending the Wild: Native American Knowledge and the Management of California's Natural Resources*. University of California Press.
- Anderson, M.K. 2007. Indigenous uses, management, and restoration of oaks of the far western United States. Technical Note No. 2, U.S. Dept. of Agriculture, Natural Resource Conservation Service.
- Battaglia, M.A., F.W. Smith, and W.D. Shepperd. 2008. Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests? *Forest Ecology and Management* 256: 2029-2038.
- Brown, J. K. 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep INT-16. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.
- Brown, R.T., J.K. Agee, and J.F. Franklin, J.F. 2004. Forest restoration and fire: principles in the context of place. *Conservation Biology* 18: 903-912.
- Carlton, D. Fuels Management Analyst Plus Software, Version 3.02; 2004.
- Clyatt, K.A., J. S. Crotteau, M.S. Schaedel, H.L. Wiggins, H. Kelley, D.J. Churchill, and A. J. Larson. 2016. Historical spatial patterns and contemporary tree mortality in dry mixed-conifer forests. *Forest Ecology and Management* 361: 23–37.
- Cocking, M.I., J.M. Varner, and E.E. Knapp. 2014. Long-term effects of fire severity on oak-conifer dynamics in the southern Cascades. *Ecological Applications* 24: 94-107.
- Cooper, C.F. 1961. Pattern in ponderosa pine forests. *Ecology* 42: 493-499.
- Diggle, P.J., 2013. *Statistical Analysis of Spatial and Spatio-Temporal Point Patterns*. 3rd ed. CRC Press, Boca Raton, Florida.
- Franklin, J.F., and K.N. Johnson. 2012. A restoration framework for federal forests in the Pacific Northwest. *J. Forestry* 110: 429-439.
- Keyser, C. 2008. Inland California and Southern Cascades (CA) variant overview: Forest Vegetation Simulator. Internal Report, USDA Forest Service Forest Management Service Center, Fort Collins CO. 64p.
- Knapp, E.E., C.N. Skinner, M.P. North, and B.L. Estes. 2013. Long-term overstory and understory change following logging and fire exclusion in a Sierra Nevada mixed conifer forest. *Forest Ecology and Management* 310: 303-314.
- Kroeber, T. 1961. *Ishi in Two Worlds*. University of California Press.
- Larson, A.J., R.T. Belote, C.A. Cansler, S.A. Parks, and M.S. Dietz. 2013. Latent resilience in ponderosa pine forest: effects of resumed frequent fire. *Ecological Applications*. 23: 1243–1249.
- Larson, A. J., and D. Churchill. 2012. Tree spatial patterns in frequent fire forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. *Forest Ecology and Management* 267: 74-92.
- North, M., B. Collins, and S. Stephens. 2012. Using Fire to Increase the Scale, Benefits, and Future Maintenance of Fuels Treatments. *Journal of Forestry* 110:392-401.
- North, M.P., P. Stine, K. O'Hara, W. Zielinski, and S. Stephens. 2009. An ecosystem management strategy for Sierran mixed-conifer forests. Gen. Tech. Report PSW-GTR-220. U.S. Dept. of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.
- Pawlikowski, N.C., M. Coppoletta, E. Knapp, and A.H. Taylor. 2019. Spatial dynamics of tree group and gap structure in an old-growth ponderosa pine-California black oak forest burned by repeated wildfires. *Forest Ecology and Management* 434: 289-302.
- Plotkin, J.B., J. Chave, and P.S. Ashton. 2002. Cluster analysis of spatial patterns in Malaysian tree

- species. *American Naturalist* 160: 629–644.
- Purcell, K.L., A.K. Mazzoni, S.R. Mori, and B.B. Boroski. 2009. Resting structures and resting habitat of fishers in the southern Sierra Nevada, California. *Forest Ecology and Management* 258: 2696–2706.
- Rebain, Stephanie A. comp. 2010 (revised September 29, 2014). *The Fire and Fuels Extension to the Forest Vegetation Simulator: Updated Model Documentation*. Internal Rep. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Management Service Center. 407p.
- Ryan, K.C., E.E. Knapp, and J.M. Varner. 2013. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. *Frontiers in Ecology and the Environment* 11 (Online Issue 1): e15–e24
- Scholl, A.E., and A.H. Taylor. 2010. Fire regimes, forest change, and self-organization in an old-growth mixed conifer forest, Yosemite National Park, USA. *Ecological Applications* 20: 362-380.
- Scott, J.H., Burgan, R.E. 2005. Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Report, USDA Forest Service RMRS-GTR-153.
- Show, S.B., and E.I. Kotok. 1924. The role of fire in California pine forests. US Dept. of Agriculture, Dept Bulletin No. 1294. 80pgs.
- Skinner, C.N., and A.H. Taylor. 2006. Southern Cascades Bioregion. In: *Fire in California's Ecosystems*. Edited by N.G. Sugihara, J.W. vanWagtendonk, F. Fites-Kaufman, K.E. Shaffer, and A.E. Thode. University of California Press, Berkeley. Pp. 195-224.
- Steger, G.N, T.E. Munton, K.D. Johnson, and G.E. Eberlein. 1997. Characteristics of nest trees and nest sites of California spotted owls in coniferous forests of the southern Sierra Nevada. *Transactions of the Western Section of the Wildlife Society* 33: 30-39.
- Thomas, J.W., R.G. Anderson, C. Maser, and E.L. Bull. 1979. Snags. In J.W. Thomas (ed.) *Wildlife Habitats in Managed Forests: the Blue Mountains of Oregon and Washington*, U.S. Department of Agriculture, Forest Service, Agricultural Handbook No. 553. Washington, D.C. Pp. 60-77.
- Taylor, A.H. 2010. Fire disturbance and forest structure in an old-growth *Pinus ponderosa* forest, southern Cascades, USA. *Journal of Vegetation Science* 21: 561-572.
- White. A.S. 1985. Presettlement regeneration patterns in a southwestern ponderosa pine stand. *Ecology* 66: 589-594.

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## Appendix B: List of Completed/Planned Products

### Thesis

Pawlikowski, N. 2018 Post-fire forest succession, group-gap dynamics, and implications for fire resilience in old growth ponderosa pine forest. Masters Degree, Department of Geography, The Pennsylvania State University.

### Articles in peer-reviewed journals

Pawlikowski N.C., Coppoletta M., Knapp E.E., Taylor A.H. 2019. Spatial dynamics of tree group and gap structure in an old-growth ponderosa pine-California black oak forest burned by repeated wildfires. *Forest Ecology and Management* 434:289-302.

Wallgrün J.O., Masrur A., Zhao J., Taylor A., Knapp E, Chang J. 2019. Low-Cost VR Applications to Experience Real World Places Anytime, Anywhere, and with Anyone. WEVR workshop at IEEE VR.

Taylor A.H., Pawlikowski N.C., Knapp E.E., Coppoletta, M. Post-fire dynamics of a ponderosa pine-California black oak forest restored by repeated wildfires (manuscript in preparation).

Coppoletta M., Knapp E.E., Taylor A.H., Doyle P.T. Future potential fire behavior in a structurally restored ponderosa-pine black oak forest. (manuscript in preparation)

### Conference/Symposium abstracts

Pawlikowski N., Taylor A.H., Knapp E.E., and Coppoletta M. 2017. Forest change following restorative fires in an old-growth ponderosa pine forest, southern Cascades, CA. Association of American Geographers, Boston MA. April 10-13.

Pawlikowski N., Taylor A., Coppoletta M., Knapp E., 2017. Forest development following wildfire in old-growth *Pinus ponderosa* forest, southern Cascades, California. Seventh International Fire Ecology and Management Congress, Orlando, FL, Nov. 28-Dec. 2.

Pawlikowski, N., Taylor A.H., Coppoletta, M., and Knapp, E.E. 2017. Forest Structure and Development following Wildfires in an Old-Growth Ponderosa Pine Forest. *Ecological Society of America Annual Meeting*, Portland, OR. August 7-10, 2017.

Taylor, A.H., Masrur, A., Nassry, M., Wallgrun, Jan., and Klippel, A. An Immersive Experience of Wildfire Use for Ecological Restoration in the Ishi Wilderness, Southern Cascades, California. *US-Region International Association for Landscape Ecology Annual Meeting*, Chicago, IL. April 5-9, 2018

Pawlikowski, N.C., Taylor A.H. Retaining Fire Resilience: 20 Years of Post-Fire Forest Succession. *US-Region International Association for Landscape Ecology Annual Meeting*, Chicago, IL. April 5-9, 2018 (poster)

Taylor A., Pawlikowski N., Knapp E., Coppoletta M. 2018. Retaining fire resilience: twenty years of forest development following wildfire in old growth ponderosa pine forest. International Association of Wildland Fire and Association for Fire Ecology, Fire Continuum Conference. Missoula MT, May 21-24.

Wallgrün J.A., Masrur A., Klippel A., Taylor A., Knapp E. Environmental Decision Making with Immersive Technology: The Case Study of Wildfire Management in the Ishi Wilderness. American Geophysical Union. Washington DC, Dec 10-14, 2018.

### **Field demonstration/ tour**

On May 8-10, 2019 the project Principal Investigators led a group of 20 land managers and researchers on a field tour of the Beaver Creek Pinery (Figure B1). The group included professionals with diverse perspectives and included foresters, fire managers, wildlife biologists, and ecologists from the U.S. Forest Service, Nature Conservancy, Penn State University, and the National Park Service. The goal of the field tour was to introduce land managers to the diverse forest structure within this important reference site and share our research results to date. We also wanted to discuss how information gathered from the Beaver Creek Pinery could help inform management actions aimed at restoring and maintaining fire resilience and diversity in dry pine forests across the region.

Throughout the day, field tour leaders presented information on the site's fire history and cultural significance, as well as the findings and management implications from our JFSP-funded project. Numerous participants noted how the fine-scale heterogeneity that is present in the Beaver Creek Pinery is largely lacking in many of the contemporary forests that they manage. In many western pine forests of the Sierra Nevada and southern Cascades, past timber harvest combined with ongoing fire suppression, has resulted in increased tree densities, shifts in species composition, and reduced resilience to wildfire; conditions that are often outside the natural range of conditions that would be present under an intact fire regime. As a result, many of the land managers that participated in our field tour are responsible for planning and implementing large-scale restoration projects aimed at creating more heterogeneous forest structure. However, to do this effectively, requires an understanding of how these systems looked and functioned prior to large scale human intervention. The participants of the field tour agreed that information gathered from places like the Beaver Creek Pinery would provide managers with invaluable information on forest structure, which could be used to develop sideboards for defining desired conditions and restoration outcomes.

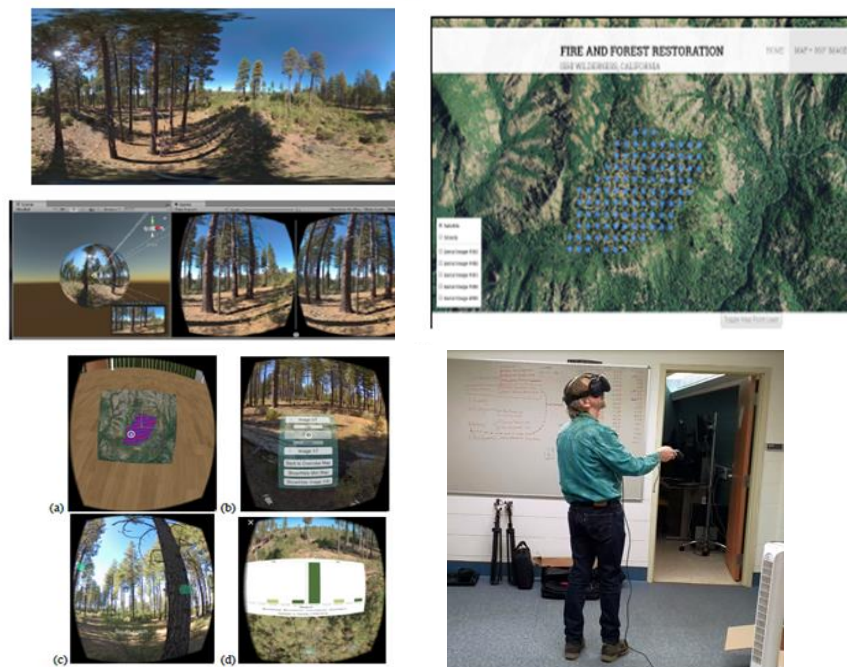
**Figure B1.** Field discussion among managers and scientists in the Beaver Creek Pinery, May 9, 2018.



One outcome of the field tour was increased enthusiasm and momentum for reintroducing fire into the Beaver Creek Pinery. As a result, we are currently working with the Lassen National Forest and local non-profit organizations to secure funding to plan and implement a large-scale collaborative restoration project that would use prescribed fire in the Beaver Creek Pinery and other parts of the Ishi Wilderness.

## Website

Our data indicate that the Beaver Creek Pinery is an example of a ponderosa pine-black oak reference forest with considerable value for ecosystem management but access to it is difficult. Consequently we developed immersive experiences (virtual reality (VR), and augmented reality) to allow visits to the Beaver Creek Pinery by anyone with an internet connection to a website or an Android phone app with a headset (<https://ishiwildfire.geog.psu.edu/index.html>) (Figure B2). This was accomplished by first taking high resolution 360° photographs of each PSW plot with a Panono camera at a height of 1.8 m and 8.2 m to provide a viewer with two height perspectives of the forest. The photographs were then overlain on an interactive map for each plot location so users can move to different locations in an immersive experience. We also associated field measurements (1998, 2016) and ground photographs (1996, 2016) with each 360° photograph so viewers can assess change over time at each plot both quantitatively and qualitatively.



**Figure B2.** Top left, example of a 360° image and the process of using the image to texture the inside of a sphere surrounding the camera in Unity3D; Top right, interactive overview map with georeferenced locations; Bottom left, screen shots of the mobile VR including grid locations, navigation menu, visual guidance, overlay of associated data; Bottom right; a person navigating in the Beaver Creek Pinery using the VR app.



The interactive map (<https://ishiwildfire.geog.psu.edu/map.html>) was also overlain on five historic layers of aerial photographs to provide a longer perspective on vegetation change in the Beaver Creek Pinery. 360° videos of scientists interpreting forest conditions and processes were also made and links provided on the website. Fully immersive experiences with Mobile VR applications using mobile headsets for phone or Oculus GO were also developed and are available for public download (see example of a short tour [https://www.youtube.com/watch?v=Brrx\\_3w1Fww&feature=youtu.be](https://www.youtube.com/watch?v=Brrx_3w1Fww&feature=youtu.be) (Figure B2). A joint experience prototype for a guided experience in the Beaver Creek Pinery is currently under development. Wallgrün et al. (2019) provides additional details on VR development for this project. The wide range of experiences and ways of interacting with data and forest conditions dramatically extends access to our research to managers, scientists, and members of the public compared to standard methods of outreach and deliverables. We believe there is a significant opportunity to increase the value of past and future field-based JFSP research by applying a similar model of VR content development and deployment.

## **Appendix C: Metadata**

Data and metadata for the initial 1998 measurement of the PSW plots in the BCP have been archived in the US Forest Service Research and Development Data Archive.

Knapp, Eric E. 2017. Overstory and understory data from a contemporary reference stand: the Beaver Creek Pinery, Lassen National Forest, CA. Fort Collins, CO: Forest Service Research Data Archive. <https://doi.org/10.2737/RDS-2017-0054>

Data and metadata for the 2016 re-measurement of the PSW plots will be archived in a similar fashion as soon as papers are completed. Our plan is to archive both the 2000 and 2016 data for the Taylor plots, and the Graham Pinery data (collected in 2017) as well.