# An Ecological and Distributional Analysis of Great Basin Bristlecone Pine (*Pinus longaeva*)

Gregory Watson Taylor

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Steven L. Petersen, Chair
Loreen A. Flinders
Stanley G. Kitchen

Department of Plant and Wildlife Sciences

Brigham Young University

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ABSTRACT

An Ecological and Distributional Analysis of Great Basin Bristlecone Pine (*Pinus longaeva*)

Gregory Watson Taylor
Department of Plant and Wildlife Sciences, BYU
Master of Science

Understanding the impacts of climate change is critical for improving the conservation and management of ecosystems worldwide. Ecosystems vary along a precipitation and temperature gradient, ranging from tropical jungles to arid deserts. The Great Basin is a semi-arid eco-region that is found within the western United States. Plant communities within the Great Basin range from sagebrush valleys to sub-alpine conifer forests found at high elevation areas. It is predicted that the Great Basin will experience prolonged periods of drought, more intense fires, and greater variability in average annual and monthly precipitation, all in response to changes in climate patterns. At the lower elevations, sagebrush communities are expected to experience less suitable habitat conditions, however, less is understood about vegetation response at upper elevations. Understanding forest composition and structure at these upper elevations within the Great Basin will help us better understand potential impacts from climate change. In chapter 1, we characterized *Pinus longaeva* (Great Basin bristlecone pine D.K. Bailey) forest structure and composition. We mapped this tree species distribution and characterized forest structure and composition using a sampling protocol that included both biophysical variables and individual tree characteristics. We collected data from 69 mixed and homogenous *P. longaeva* stands found within the Great Basin and Colorado Plateau. Results suggest that *P. longaeva* forest structure and composition exhibit high structural variability in tree characteristic measurements like density, basal area, growth rate, age, and in biophysical variables such as substrate type, slope, aspect, elevation, average monthly temperature and precipitation, latitude, and longitude. This study also found that variability in forest composition and structure in *P. longaeva* forests allows for greater flexibility in the breadth of life-history strategies and probable resiliency to climate change. In chapter 2 we used remote sensing images with high spatial resolution to identify 685 unique *P. longaeva* stands on 42 mountain ranges. *Pinus longaeva* was found on the White Mountains on the western edge of the Great Basin to the Colorado Plateau's Henry Mountain and West Tavaputs Plateau in the East, and from the Spring Mountains in the South to the Ruby and Spruce Mountains in the North. Stands covered 113,886 ha across the geographic distribution. A comparison between our maps and those produced by David Charlet found a total of 36% overlap of *P. longaeva*. We mapped 58 unique stands that the control dataset lacked and 11 stands that we did not include. We believe that this is the most comprehensive *P. longaeva* distribution map created to date.

Keywords: Great Basin bristlecone pine, forest ecology, community structure, indicator species, tree growth rate, life-history strategy, Shannon's Diversity Index

# ACKNOWLEDGEMENTS

First, I would like to express my gratitude to my advisor Steve Petersen for his unlimited patience with me as I worked on this thesis. His friendship, reliability, and commitment aided me as I worked through personal challenges and setbacks during the writing process. I would also like to thank Teresa Gomez for her GIS expertise and constant good humor. Her thoughtful reviews provided great insight along the journey. I would like to thank my MS committee members Stan Kitchen, for his excellent mentorship in forest ecology and his help that provided me with improved writing skills, and Loreen Allphin for her help with writing and statistics.

I could not have accomplished this without the support of my family and friends. They encouraged me each step of the way. I would like to personally thank my parents, Gary and Ann Taylor, for their constant support and love.

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CHAPTER 1

# *Pinus longaeva* Stand Composition and Structure Reveals Variability within the Ecological Community

Gregory W. Taylor[1], Stanley G. Kitchen[2], Loreen Allphin[1]Steven L. Petersen[1]
[1]Department of Wildlife Sciences, Brigham Young University, Provo, UT 84602
[2]US Forest Service, Rocky Mountain Research Station, Provo, UT 84606

## ABSTRACT

High spatiotemporal variability in forest composition and structure is expected across heterogeneous landscapes. An understanding of this complexity can inform forest practices including improved silvicultural practices, forest conservation, and actions that benefit natural resource policy and preservation of forest resources. Within the Great Basin plant community composition and structure changes across the elevation gradient with salt desert and sagebrush shrubland dominating the lower elevations and sub-alpine forests and alpine tundra dominating the highest elevations. Of these conifers, *Pinus longaeva* D.K. Bailey (Great Basin bristlecone pine) is most often associated with these upper reaches. *Pinus longaeva* is a slow-growing, often long-lived species found in Great Basin and Colorado Plateau forests located in the western USA. Stands that include this conifer exhibit diverse structure and composition in response to variability in abiotic (e.g. precipitation, temperature, substrate, slope, aspect, elevation, fire regime) and biotic (e.g. competition, bark beetle infestation, avian seed dispersers) drivers. The purpose of this study is to characterize the structural and compositional variability within *Pinus longaeva* forested communities. To assess this variation, we analyzed data assembled from 69 forest stands of variable composition with *P. longaeva* present. Stands were representative of the full geographic and elevational range of the species. Plot sampling and data processing protocols followed those developed by the USFS, Forest Inventory and Analysis program and included

measurement or estimation of biophysical, stand and individual tree characteristics. We calculated average growth rate, tree species richness and Shannon-Wiener's diversity indices (based upon tree density and basal area) for each plot. Stands ranged in elevation from 2179 to 3476 m and included one to seven tree species per stand. *Pinus longaeva* dominated stands at higher elevations, while stand composition at lower elevations was more heterogeneous. At lower elevations, *P. longaeva* stands were more commonly found on northeast slopes, while at higher elevations there was no correlation to aspect. Density and live tree basal area for *P. longaeva* increased with elevation up to approximately 3250 m. Indicator species analysis found that *Abies concolor* appeared 50% of the time in plots where *P. longaeva* was present, compared to aspen which was present only 2%. Observed variability in forest composition and structure across an elevational gradient may indicate greater flexibility in *P. longaeva* life-history strategy than has been previously reported.

## INTRODUCTION

Forested ecosystems provide critical ecosystem services including sustainable hydrological cycling (Salati 1987, Lexer et al. 2002), protection against erosion (Hartanto et al. 2003), nitrogen cycling (Spies and Franklin 1991), carbon fixation, oxygen production (Schimel 1995), critical habitat for numerous flora and fauna species (Tews et al. 2004), food and fiber resources (Ogle 1996, Johns 1997), unique chemical compounds used in current medicines (Abelson 1990), and places of natural beauty and wonder for human recreation (Prideaux 2015). The specific capacity of forest communities to sustain desirable ecological outcomes in the presence of natural and human-caused disturbance is intrinsically tied to composition and structure at the stand scale. In its simplest form, stand composition is a measure of the cumulative contributions or relative abundances of tree species in all life-history stages while

stand structure varies with density, size, age, and spatial arrangement of individual trees (McElhinny et al. 2005). Characterization of the ecological processes and factors that influence compositional and structural variability provide a platform from which to assess risk to naturally occurring forest systems and the benefits that they provide (Lexer et al. 2002). As climate change occurs resulting in prolonged periods of drought (Dai 2012), increased wildfire intensity (Westerling et al. 2006), and an increase in summer precipitation and decrease in winter precipitation (Barnett et al. 2005, Trenberth 2011) it will become important to understand the composition and structure of different landscapes across the world—specifically forests. Here we focus on the *Pinus longaeva* D.K. Bailey (Great Basin bristlecone pine) forests of the Great Basin. Prolonged periods of drought in the Great Basin may make certain trees within *P. longaeva* forests more susceptible to pine beetles, white pine blister rust, and wildfire (Allen et al. 2010). As fuel loads (desiccated trees) increase, wildfire intensity also increases, which could result in structural changes in *P. longaeva* forests. Climate change may also extend the growing seasons at higher elevations resulting in increased inter-species competition within *P. longaeva* forests (Davis and Shaw 2001, Walther et al. 2002).

*Pinus longaeva* forests are scattered across the central and southern Great Basin and portions of the Colorado Plateau, ranging in elevation from 2,200 to 3,500 m (Hiebert and Hamrick 1984). The climate for the region is semiarid continental with temperatures decreasing and precipitation increasing with elevation (Peterson, 1994). Precipitation comes in the form of cold-season (October–May) snow or rain and monsoonal rains in summer months (June–August). In its range, *P. longaeva* is subject to harsh environmental conditions that include low temperatures, desiccating winds, low soil water retention capacity, and high soil erosion potential (LaMarche 1969, Lanner 2002). *Pinus longaeva* grows predominately in rocky dolomitic and limestone based soils (LaMarche 1969, Beasley and Klemmedson 1980); however, stands have

been documented growing in mixed alluvium, basalt, chert, granite, Precambrian schist, quartzite, rhyolite, siltstone, and sandstone derived soils (Nelson 1976, Charlet 2015, Orlemann 2017).

Bailey (1970) provided the first detailed life history, genetic, and morphological descriptions for this species, describing the species as "erect trees showing pendulous and twisting branching". He noted that *P. longaeva* trees are most commonly found on limestone or dolomite substrates in the Great Basin. Additionally, he found that *P. longaeva* is temperature sensitive at high elevations (a shorter growing season at upper tree-line) and precipitation dependent at lower elevations. Other studies on *P. longaeva* provide additional insight into their general ecology and geographic distribution. Past research has identified high genetic heterozygosity within stands, but low heterozygosity between stands based upon evaluation of a limited number of stands in eastern Nevada and western Utah (LaMarche 1969, 1973). Results were interpreted as indicative of high levels of gene flow among stands over time (Hiebert and Hamrick 1984). Research by LaMarche (1969, 1973) focused primarily on tree ages and recruitment in high-elevation stands located in the White Mountains of California (particularly the Schulman grove). Further research characterized *P. longaeva* tree ages and growth patterns in relation to environmental conditions for two stands in eastern Nevada (Beasley and Klemmedson 1980).

Despite focused research conducted on limited stands and with sizeable portions of the distribution mapped, there remains large gaps in our understanding of *P. longaeva* stand composition and structure and species distribution. For example, little is known about the age structure, growth rates, and community composition at the lowest elevations where *P. longaeva* occurs. Additionally, comparisons of community composition and structure across the entire *P. longaeva* distribution do not exist.

The purpose of this study is to (1) characterize variability in *P. longaeva* stand composition and structure in its known geographic and ecological (elevational) distributions, (2) identify patterns of stand variability that might be linked to ecological function and (3) ascertain abiotic drivers responsible for regulating stand dynamics in bristlecone pine forests. We address these objectives by (1) quantifying *P. longaeva* community composition (abundances and diversity of all tree species) and structure (density, basal area, and age/size structure) for a series of sites representative of the full species range, (2) employing the use of correlation analysis that facilitates identification of non-random patterns among traits across all sites, and (3) assessing the influence of abiotic drivers (i.e. precipitation, substrate type, temperature, elevation, slope, aspect) on tree and stand traits across the study area. We hypothesized that there would be substantial stand-level differences in composition and structure, and that the differences would be predictable and follow biophysical gradients. Our null hypothesis was that there would be no differences between *P. longaeva* forest structure and composition across its geographic distribution, or than differences would be manifest independent of the biophysical environment. If supported, our hypothesis could indicate the evolution of a plastic life-history strategy that has allowed this species to exist across a broad range of environmental conditions. Flexibility in life-history strategy may in turn provide needed resiliency to environmental stressors such as climate change, novel pathogens, and bark beetle outbreaks (Miller et al. 2017).

## METHODS

### *Study Design and Plot Selection*

The USDA Forest Service Inventory and Analysis (FIA) Program utilizes a systematic network of thousands of permanently-located plots (326,247 plots in 2015) and standardized

forest mensuration protocols to produce comprehensive assessments of forest condition and trend across the conterminous United States (Vogt and Smith 2016). We acquired data for the 51 plots from the Great Basin and Colorado Plateau ecoregions in which *P. longaeva* trees were present (Figure 1-1). We augmented these data by establishing an additional 18 plots using FIA protocols in forested locations known to include *P longaeva*. For these plots, study stands were selected to represent the full geographic and elevational range (2179-3456 m) of the species. Coordinates were randomly pre-selected from within boundaries of targeted forest stands and located in the field using hand-held GPS devices. The combination of traditional FIA plots and our additional, targeted plots provide data for a total of 69 distinct and representative *P. longaeva* forest communities (Table A-1).

Study plots included four circular subplots (radius 7.32 m), one of which is positioned at the plot center and the other three centered at a horizontal distance of 36.58 m from plot center at bearings of $0^o$, $120^o$, $240^o$. We estimated slope, aspect, and elevation for each subplot. (Hijmans et al. 2005).

*Stand Composition*

Within each subplot, distance and azimuth from subplot center was measured for all living and standing dead trees with diameters at breast height (DBH; 1.4 m above ground level; side slope position) that exceeded 2.54 cm. Trees with separate pith at ground level were treated as separate trees (Woudenberg et al. 2010). Tree density (trees/ha) was calculated by species and for all species combined by multiplying the sum of trees in the four subplots by 14.88. Tree length (height) was estimated and DBH measured using calipers or a metric steel diameter tape. We calculated individual tree basal area (Husch et al. 2003), summed values by plot and converted results to $m^2$/ha. We measured a total of 2324 trees of which 925 (40%) were *P.*

*longaeva* and the remainder assigned to 12 other species. Eighty-four percent (1947) of measured trees were alive.

*Stand Age Structure and Growth Rate*

We extracted cores from 1,210 trees located in our 18 supplemental plots using standard three-thread increment borers. Coring was attempted for most living trees (very small conifers and non-conifers were not included) and some snags with solid wood for 14 of the 18 plots. We selected representative trees by size class for the other four plots. Small conifer age estimates were made by counting sets of branch whorls. We extracted core samples at 20-100 cm above side-slope ground level and cored up to four times per tree in order to obtain a sample as close to tree center (pith) as possible. For multi-branched sets of trees that appeared to have a common origin (single seed cache), we attempted to obtain a datable core from a single tree and assumed a common age for the group. Tree cores were labeled and stored in paper tubes for protection during transportation from the field to the laboratory. For the 51 FIA plots, we used age estimates developed by FIA crews. For these plots, aged trees were meant to be representative of the size classes present and the proportion of trees with assigned ages varied among plots.

We glued tree cores onto mounts, and sanded surfaces with increasingly fine sand paper until cell and ring structure were clearly visible using a binocular microscope (15-75 power). Tree cores were cross-dated using locally-developed annual ring-width chronologies and lists of marker (narrow) rings (Stokes and Smiley 1968) to determine the year associated with the pith or inner-most ring. For samples missing pith, age was estimated by matching ring curvature and spacing to concentric rings in a transparent overlay and adjusting for missing rings (Applequist 1958). We treated pith dates as conservative estimates of establishment dates, employing no correction factors because of unknown and variable time lapses between germination and the

year trees reached core height. We calculated growth rate (cm/yr) for each tree with an estimated age by dividing diameter by tree age.

*Tree Species Richness and Diversity*

The number of species per plot (four subplots) were summed to assess tree species richness (1-7). Plots were arbitrarily defined with 1-3 tree species as homogeneous plots and plots with ≥ 4 tree species as heterogeneous. We calculated separate Shannon-Wiener Diversity Indices (SDIs) based on tree species density and BA values for each site using the following equation:

$$H' = -\sum_{i=1}^{S}(p_i ln p_i)$$

where $p_i$ represents the proportion of individuals of one particular species found divided by the total number of individuals found, $S$ represents the number of species in the sample, and $H'$ represents the Shannon-Wiener diversity index (Pielou 1975).

The Shannon-Wiener Diversity Index characterizes species diversity in a community by accounting for both abundance and evenness of the species present (Shannon 2013).

*Data Analysis*

To determine correlation significance of plot structure and composition values with biophysical characteristics of the environment, we constructed matrices using stand composition, stand structure, and stand environmental variables (Tables A-2 toA-4). A square-root transformation was applied to BA and density (all species combined and bristlecone pine only)

values to normalize and reduce the variance in the dataset. In order to adjust for the circular nature of the aspect angle, a trigonometric transformation was applied (Beers et al. 1966). Both sine and cosine transformations were used, but in every case, only one transformation was needed to explain the variable's contribution to the analysis. This is because cosine is simply a functional transformation of sine. Without loss of generality, sine was chosen.

*Indicator Species Analysis*

An Indicator Species Analysis (ISA) model was used to identify the strength of association between *P. longaeva* and other tree species using PC-ORD version 6.0 (McCune and Mefford 2011). Indicator Species Analysis (ISA) assesses the degree to which a particular species characterizes a group based on its abundance in the sample units (Peck 2010). It provides an indicator value (IV) which marks the relative abundance and constancy within each group of that species. The higher the value the more abundant and constant that species is in the forest stand. This value is determined by multiplying the relative species frequency by that species relative abundance. We analyzed the quantitative species abundance dataset using the Dufrene and Legendre analysis option (Dufrene and Legendre 1997). We selected the randomization option and used the time of day as the random number seed. No IV values under 20.0 or with an alpha level < .02 were considered significant (Dufrene and Legendre 1997).

## RESULTS

*Pinus longaeva* was found growing in both homogeneous and heterogeneous stands across the range of the species. We classified, 37 plots and associated stands as homogeneous (1-3 species) and 32 as heterogeneous (≥4 species). Tree species recorded within the plots included

*Abies concolor* Gord. & Glend. (white fir), *Abies lasiocarpa* Hook. (subalpine fir), *Cercocarpus ledifolius* Nutt. (curl-leaf mountain mohagany), *Juniperus osteosperma* Torr. (Utah juniper), *Juniperus scopulorum* Sarg. (Rocky Mountain juniper), *Picea engelmannii* Parry (Engelmann spruce), *Pinus edulis* Engelm. (twin-needle pinyon), *Pinus flexilis* James (limber pine), *Pinus longaeva*, *Pinus monophylla* Torr. & Frem. (single-leaf pinyon), *Pinus ponderosa* Dougl. (ponderosa pine), *Populus tremuloides* Michx. (quaking aspen), and *Pseudotsuga menziesii* Mirb. (Douglas fir) (Figure 1-2). The more dominant species occurring with *P. longaeva* include *A. concolor*, *C. ledifolius, P. flexilis*, and *P. menziesii*, however this varied across the plots. Tree species richness within our plots ranged from one (11 plots) to seven tree species (2 plots), however, study plots with more than five species (6 plots) were uncommon (Figure 1-3).

Variables associated with stand composition and structure varied by orders of magnitude among plots (Table 1-1). Mean values for homogeneous and heterogeneous plots differed substantially for most structural traits.

Of all the biophysical variables examined, elevation demonstrated stronger correlations with measured and calculated stand variables (Figures 1-4 to1-6). Comparisons between mean live tree age ($r = 0.263$, $p = 0.0332$), mean live tree growth rates ($r = 0.089$, $p = 0.4620$), *P. longaeva* live tree age ($r = 0.217$, $p = 0.0887$), and *P. longaeva* growth rates ($r = 0.105$, $p = 0.4142$) with elevation do not demonstrate any significant relationship, besides mean live tree age (Figure 1-4a-d). Total basal area for all trees ($r = 0.466$, $p < 0.0001$) and for *P. longaeva* trees ($r = 0.524$, $p < 0.0001$) exhibited significant correlations with elevation (Figure 1-5a, b). Density for all trees combined varied independent of elevation ($r = 0.237$, $p = 0.0497$), however density for *P. longaeva* trees was significantly and positively correlated with elevation ($r = 0.659$, $p < 0.0001$) (Figure 1-6a, b). Tree species richness ($r = 0.699$, $p < 0.0001$) (Figure 1-2) and all measures of stand diversity (SDI; based upon total live tree basal area ($r = -0.691$, $p < 0.0001$)

(Figure 1-5c) and based upon total live tree density (r = -0.658, $p$ <0.0001) (Figure 1-6c), were inversely correlated with elevation.

Homogeneous and heterogeneous plot comparisons demonstrate differences and similarities across plot variables (Table 1-1). These comparisons demonstrate statistically significant differences ($p < 0.05$) between elevation, tree diameter, PILO tree diameter, plot tree basal area, PILO plot tree basal area, PILO plot tree density, plot SDI based on basal area, and plot SDI based on density.

*Indicator Species Analysis*

*Abies concolor (*IV=*56.3; p< 0.0000)* and *P. tremuloides (*IV=*16.7; p = 0.0504)* received the highest indicator values in the analysis, however only *A. concolor* was predictive of *P. longaeva* plots. *Abies concolor* appeared in 35 of 69 plots, whereas *P. tremuloides* only appeared in 2 of the 69 plots. This suggests that there is a 50% probabilty that where *P. longaeva is A. concolor* will also be present, and that where *P. longaeva* is *P. tremuloides* will most likely not be present. This analysis was independent of plot type (homogeneous vs heterogeneous). The other ten species expressed low indicator values that suggest that they do not appear with higher levels of certainty in *P. longaeva* plots. We did see that *A. concolor, A. lasiocarpa, P. engelmanni, P. flexilis, P. longaeva*, and *P. menzeiseii* occurred more frequently in the homogeneous plots, while *C. ledifolius, J. osteosperma, J. scopulorum, P. edulis, P. monophylla, P. tremuloides* and *P. ponderosa* were found more frequently in the heterogeneous plots.

# DISCUSSION

*Stand Composition and Structure:*

The results of this study found that *P. longaeva* forest plots are highly variable in composition and structure across the geographic and elevational range of the species. The high variability of forest composition and structure in *P. longaeva* stands is likely due to variations among biophysical variables (Salzer et al. 2009). A previous study by Hiebert and Hamrick (1984) supports our findings that tree species richness in our plots varied from five to seven species at lower elevations, while upper elevations had less than four species present. As the ISA showed that *A. concolor* was frequently present in our plots, a study by Guisan et al. (1999) found that *A. concolor* occurs at mid-elevation plots abundantly in the southern Great Basin. *Populus tremuloides* does not appear often in plots where *P. longaeva* is present because it prefers deeper soils found on a slope or on a depression where water accumulates. *Populus tremuloides* are for the most part water dependent plants, so they mostly grow in areas with greater soil water availability (Weigle and Frothingham 1911). *Pinus longaeva* grows in areas that most likely will go through a drying experience that aspen do not tolerate well.

Previous studies show that there is a correlation between age and elevation; however, these studies were based on three to four *P. longaeva* localities that are known for their old-aged trees (LaMarche 1969, LaMarche and Mooney 1972, LaMarche 1973, Hiebert and Hamrick 1984). We found that age was not significantly correlated with elevation, but rather mean tree age varied independent of elevation. This proved true for plots where just *P. longaeva age* was compared across elevations as well. Our study presents a representation of the entire *P. longaeva* forest distribution in which we compare tree diameter and age across a wide range of elevation, which are direct factors for determining growth rate. While Salzer et al. (2009) describes varied

growth rates at higher *P. longaeva* elevation plots, we also found variation among growth rates across the elevation gradient. Stevens (1992) also found that increases in elevation directly correlates with a decrease in tree species richness of forests in general.

Our results are similar to that of Salzer et al. (2009) in that *P. longaeva*-dominant stands were more homogeneous, tree ages were generally older, and basal areas and densities were larger (Tables A-3 and A-4) than heterogeneous plots with *P. longaeva* present but not a dominate species. It is important to note that Hiebert and Hamrick (1984) found that population densities were highest at the lower elevations in their plots, whereas we found plot density levels (all trees combined) varied an elevation gradient Figure 6a).

Weisberg and Baker (1995) suggest that soil moisture and microclimatic conditions at higher elevations are more suitable to tree seed germination and establishment, likely due to higher precipitation levels, cooler air and soil temperatures, and lower evapotranspiration rates. Although precipitation is generally greater with increasing elevation, shallow soils typical of upper tree line locations experience lower soil water infiltration rates that can limit seedling growth for tree species (Kupfer and Cairns 1996, Sveinbjörnsson 2000), however in our study we found *A. lasiocarpa, A. concolor, P. engelmanni, P. flexilis, P. longaeva*, and *P. menzeiseii* present at higher elevations, thus suggesting that while the effects of shallow soils may deter some species from growing, it did not affect all. We also found *P. longaeva* at high elevation plots growing more often on north-eastern aspects and moderate to steep slopes. This is because those aspects have slower evaporation and likely evapotranspiration rates which result in plants having greater soil water availability. This leads to greater plant productivity, higher organics, and higher nutrient availability, which result in deeper soils due to water and weathering potential as well as greater root development. Additionally, higher elevations experience shorter

growing seasons, which may prevent other tree species that need a longer growing season from competing with *P. longaeva.*

Previous research has demonstrated that *P. longaeva* exhibits low shade tolerance (Bailey 1970). Interestingly, we observed the effects of shade on tree and stand development. One would expect that where there is competition for light – whether between species or within – density of *P. longaeva* would be affected. In fact, at lower elevations where the stands were more heterogeneous, *P. longaeva* was dominated by other species. In more homogenous stands, although the trees are stronger due to a reduction in interspecies competition, they still distribute more sparsely indicating that they compete with each other for light. Other factors driving competition for space include: aspect, slope, soil type, soil depth, water availability, and climatic conditions. Interestingly, at the heterogeneous plots we found that aspect served as a better indicator of *P. longaeva* distribution where suitable site conditions are more limited. Specific to these areas, rock substrate was a good indicator of stand locations. Petersen et al. (2004) found that rocks provide microsite conditions that improve soil moisture retention and decreased evapotranspiration rates resulting in higher establishment compared to non-rocky plots. Sampled *P. longaeva* trees were consistently found growing on dolomitic sandstone and limestone soil substrates (Wright and Mooney 1965). In areas with low soil water retention capacity porous limestone and sandstone enable greater water retention compared to granitic or volcanic substrate types common within the Great Basin (Estrada-Medina et al. 2010, Estrada-Medina et al. 2013). These highly porous soils allow for deeper root penetration and establishment, which enhances tree growth in difficult physical and environmental conditions (Schoonover and Crim 2015).

## CONCLUSIONS

Our study is the first to compare *P. longaeva* forest composition and structure from biophysical variables across the known geographic distribution. This qualitative analysis indicates that plots vary in structure and composition in the geographic distribution and across elevational gradients. We predict that flexibility in the breadth of life-history strategies allows for greater variability in forest composition and structure in *P. longaeva* stands. Our analyses demonstrate that *P. longaeva* has adapted to a wide variety of environmental conditions and maintained sexually viable stands over time. The results show that *P. longaeva* stand composition and structure varies in its geographic distribution (western Colorado Plateau, southern and central Great Basin). This flexibility in breadth of life-history strategies we hypothesize increases the tree's fitness, prolongs its longevity, and enhances its resilience to potentially harmful factors like climate change. A better understanding of *P. longaeva* forest composition and structure provides a foundation from which to assess the specific capacity of these forests to sustaining desirable ecological outcomes in the future.

## ACKNOWLEDGMENTS

This project was partially funded by a grant from the USDA Forest Service, Western Wildland Environmental Threat Assessment Center and the Rocky Mountain Research Station (RJVA-14-JV-11221632-099). Additional funding was also provided by Brigham Young University, Charles Redd Foundation Center for Western Studies. We appreciate the support and resources provided by the Brigham Young University Geospatial Habitat Analysis Laboratory. We especially thank Teresa Gomez for her valuable input and reviews. We thank Chris Balzotti for assistance in data collection.

LITERATURE CITED

Abelson, P. H. 1990. Medicine from plants. Science 247:513-514.

Allen, C. D., A. K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D. D. Breshears, E. H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J.-H. Lim, G. Allard, S. W. Running, A. Semerci, and N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management 259:660-684.

Applequist, M. 1958. A simple pith locator for use with off-center increment cores. Journal of Forestry.Bailey, D. K. 1970. Phytogeography and taxonomy of pinus subsection Balfourianae. Annals of the Missouri Botanical Garden 57:210-249.

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438:303.

Beasley, R. S., and J. O. Klemmedson. 1980. Ecological relationships of bristlecone pine. The American Midland Naturalist 104:242-252.

Beers, T. W., P. E. Dress, and L. C. Wensel. 1966. Notes and observations: Aspect transformation in site productivity Research. Journal of Forestry 64:691-692.

Charlet, D. A. 2015. Atlas of Nevada conifers: a phytogeographic reference. Second edition. University of Nevada Press, Reno, NV. Unpublished data.

Dai, A. 2012. Increasing drought under global warming in observations and models. Nature Climate Change 3:52.

Davis, M. B., and R. G. Shaw. 2001. Range shifts and adaptive responses to quaternary climate change. Science 292:673-679.

Dufrene, M., and P. Legendre. 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecological monographs 67:345-366.

Estrada-Medina, H., W. Tuttle, R. C. Graham, M. F. Allen, and J. J. Jiménez-Osornio. 2010. Identification of underground karst features using ground-penetrating radar in Northern Yucatán, México. Vadose Zone Journal 9:653-661.

Estrada-Medina, Hector, R. C. Graham, M. F. Allen, J. J. Jimenez-Osornio, and S. Robles-Casolco. 2013. The importance of limestone bedrock and dissolution karst features on tree root distribution in northern Yucatan, Mexico. Plant and Soil 362:37-50.

Guisan, A., S. B. Weiss, and A. D. Weiss. 1999. GLM versus CCA spatial modeling of plant species distribution. Plant Ecology 143:107-122.

Hartanto, H., R. Prabhu, A. S. Widayat, and C. Asdak. 2003. Factors affecting runoff and soil erosion: plot-level soil loss monitoring for assessing sustainability of forest management. Forest Ecology and Management 180:361-374.

Hiebert, R. D., and J. L. Hamrick. 1984. An ecological study of bristlecone pine (*Pinus-longaeva*) in Utah and Eastern Nevada. Great Basin Naturalist 44:487-494.

Hijmans, R. J., S. E. Cameron, J. L. Parra, P. G. Jones, and A. Jarvis. 2005. Very high resolution interpolated climate surfaces for global land areas. International journal of climatology 25:1965-1978.

Husch, B., T. W. Beers, and J. A. Kershaw. 2003. Forest mensuration. 4th edition. John Wiley & Sons, Inc. , Hoboken, New Jersey.

Johns, A. G. 1997. Timber production and biodiversity conservation in tropical rain forests. Cambridge University Press.

Kupfer, J. A., and D. M. Cairns. 1996. The suitability of montane ecotones as indicators of global climatic change. Progress in Physical Geography 20:253-272.

LaMarche, V. C. 1969. Environment in relation to age of bristlecone pines. Ecology 50:53-59.

LaMarche, V. C. 1973. Holocene climatic variations inferred from treeline fluctuations in the White Mountains, California. Quaternary Research 3:632-660.

LaMarche, V. C., and H. A. Mooney. 1972. Recent climatic change and development of the bristlecone pine (P. longaeva Bailey) krummholz zone, Mt. Washington, Nevada. Arctic and Alpine Research 4:61-72.

Lanner, R. M. 2002. Why do trees live so long? Aging Research Reviews 1:653-671.

Lexer, M. J., K. Hönninger, H. Scheifinger, C. Matulla, N. Groll, H. Kromp-Kolb, K. Schadauer, F. Starlinger, and M. Englisch. 2002. The sensitivity of Austrian forests to scenarios of climatic change: a large-scale risk assessment based on a modified gap model and forest inventory data. Forest Ecology and Management 162:53-72.

McCune, B., and M. J. Mefford. 2011. PC-ORD. Multivariate analysis of ecological data. . MjM Software, Gleneden Beach, Oregeon, U.S.A.

McElhinny, C., P. Gibbons, C. Brack, and J. Bauhus. 2005. Forest and woodland stand structural complexity: Its definition and measurement. Forest Ecology and Management 218:1-24.

Miller, S., A. Schoettle, K. Burns, R. Sniezko, and P. Champ. 2017. Preempting the pathogen: Blister rust and proactive managment of high-elevation pines. Science You Can Use Bulletin:11.

Nelson, M. G. 1976. The montane coniferous forests of the northern Deep Creek Range, Utah. Unpublished thesis, University of Utah, Salt Lake City:73.

Ogle, B. 1996. People's dependency on forests for food security. Current issues in non-timber forest products research:219-242.

Orlemann, A., Flinders, Steven H., Allphin, Loreen. 2017. The discovery of Great Basin bristlecone pine, Pinus longaeva, in the Tushar Mountains of the Fishlake National Forest in Central Utah, USA. Western North American Naturalist 77:7.

Peck, J. E. 2010. Multivariate analysis for community ecologists: step-by-step using PC-ORD. MjM Software Design, Gleneden Beach, Or.

Petersen, S. L., B. A. Roundy, and R. M. Bryant. 2004. Revegetation methods for high-elevation roadsides at Bryce Canyon National Park, Utah. Restoration Ecology 12:248-257.

Peterson, F. 1994. Sand dunes, sabkhas, streams, and shallow seas: Jurassic paleogeography in the southern part of the western interior basin. Mesozoic Systems of the Rocky Mountain Region:233-272.

Pielou, E. C. 1975. Ecological diversity. Wiley Interscience, New York.

Prideaux, B. 2015. Recreation in forests.

Salati, E. 1987. The forest and the hydrological cycle.

Salzer, M. W., M. K. Hughes, A. G. Bunn, and K. F. Kipfmueller. 2009. Recent unprecedented tree-ring growth in bristlecone pine at the highest elevations and possible causes. Proceedings of the National Academy of Sciences 106:20348-20353.

Schimel, D. S. 1995. Terrestrial ecosystems and the carbon cycle. Global Change Biology 1:77-91.

Schoonover, J. E., and J. F. Crim. 2015. An introduction to soil concepts and the role of soils in watershed management. Journal of Contemporary Water Research & Education 154:21-47.

Shannon, C. E. 2013. A mathematical theory of communication. Bell System Technical Journal 27:379-423.

Spies, T. A., and J. F. Franklin. 1991. The structure of natural young, mature, and old-growth douglas-fir forests in Oregon and Washington. Wildlife and vegetation of unmanaged Douglas-fir forests: 91-109.

Stevens, G. C. 1992. The elevational gradient in altitudinal range: an extension of rapoport's latitudinal rule to altitude. The American Naturalist 140:893-911.

Sveinbjörnsson, B. 2000. North American and European treelines: External forces and internal processes controlling position. AMBIO: A Journal of the Human Environment 29:388-395.

Tews, J., U. Brose, V. Grimm, K. Tielbörger, M. Wichmann, M. Schwager, and F. Jeltsch. 2004. Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures. Journal of Biogeography 31:79-92.

Trenberth, K. E. 2011. Changes in precipitation with climate change. Climate Research 47:123-138.

Vogt, J. T., and W. B. Smith. 2016. Forest inventory and analysis fiscal year 2015 business report. United States Department of Agriculture, USA.

Walther, G.-R., E. Post, P. Convey, and A. Menzel. 2002. Ecological responses to recent climate change. Nature 416:389.

Weisberg, P. J., and W. L. Baker. 1995. Spatial variation in tree seedling and krummholz Growth in the forest-tundra ecotone of Rocky Mountain National Park, Colorado, U.S.A. Arctic and Alpine Research 27:116-129.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase Western U.S. forest wildfire activity. Science 313:940-943.

Woudenberg, Sharon W., Conkling, Barbara L., O'Connell, Barbara M., LaPoint, Elizabeth B., Turner, Jeffery A., Waddell, Karen L. 2010. The forest Inventory and analysis database: database description and users manual version 4.0 for Phase 2. Gen. Tech. Rep. RMRS-GTR-245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Wright, R. D., and H. A. Mooney. 1965. Substrate-oriented distribution of bristlecone pine in the White Mountains of California. The American Midland Naturalist 73:257-284.

FIGURES

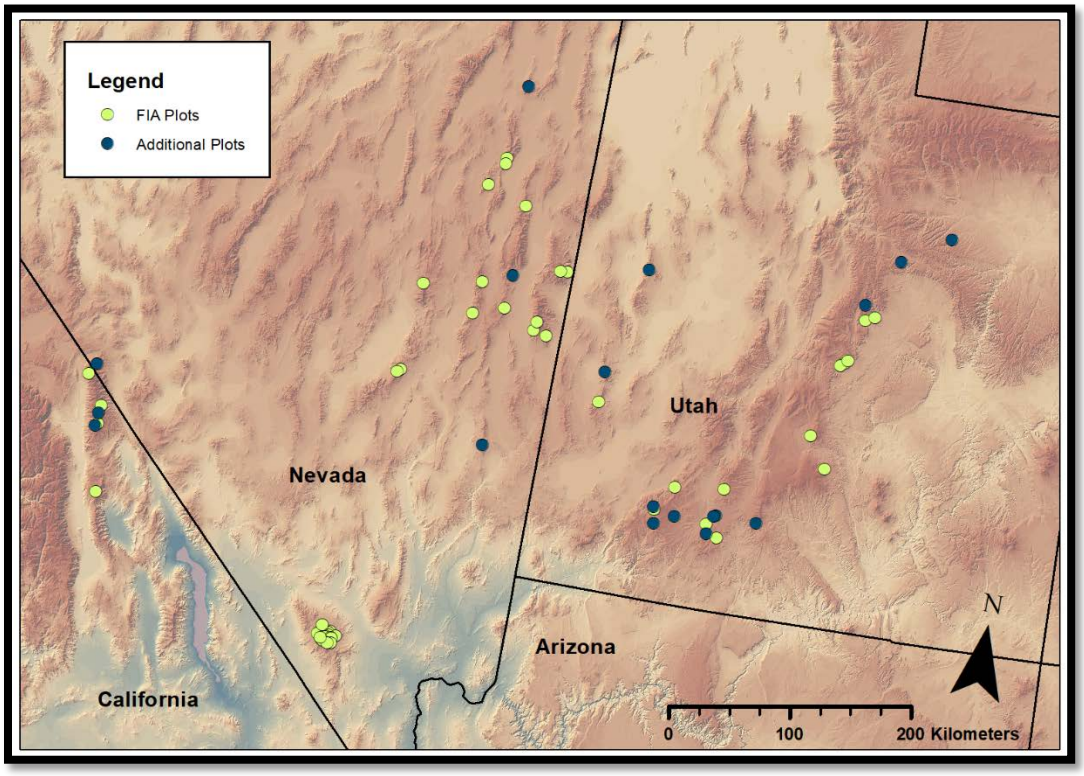


Figure 1 - 1. Distribution map showing study plots in the western and eastern Great Basin and Colorado Plateau. Light green points represent Forest Inventory Analysis (FIA) plots and dark blue points represent additional plots.

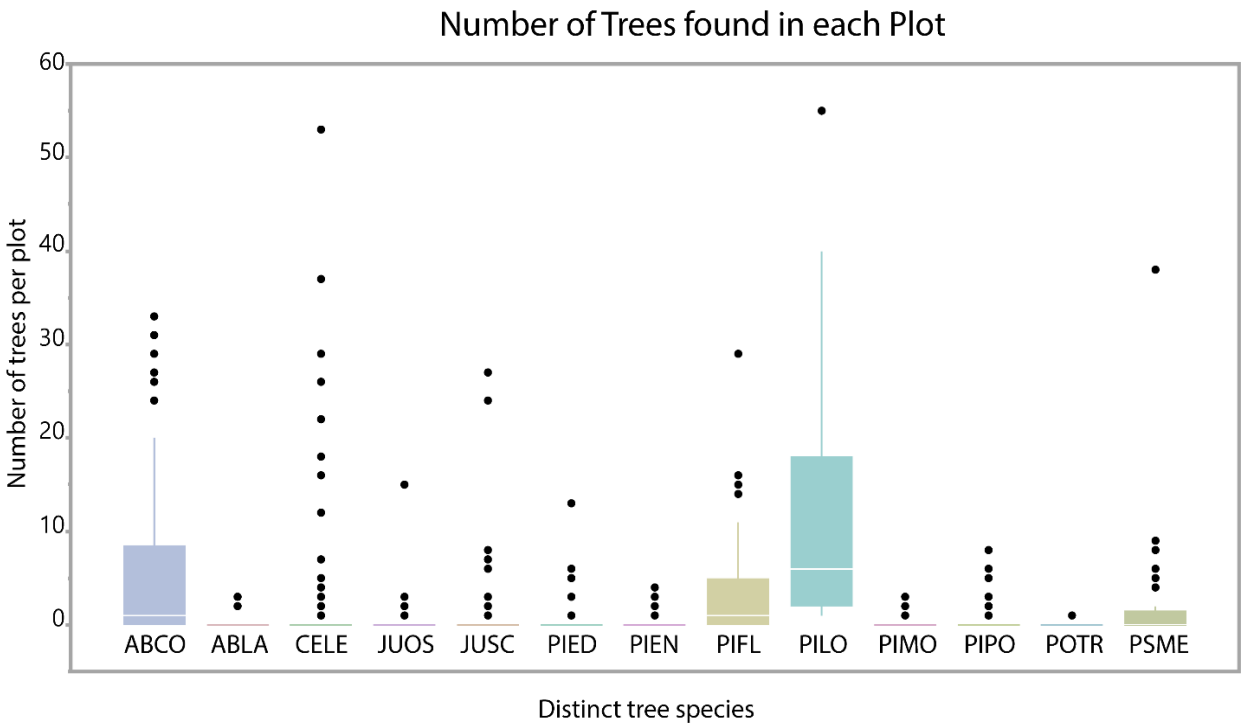


Figure 1 - 2. The boxplots indicate the number of trees per species that occur per plot.

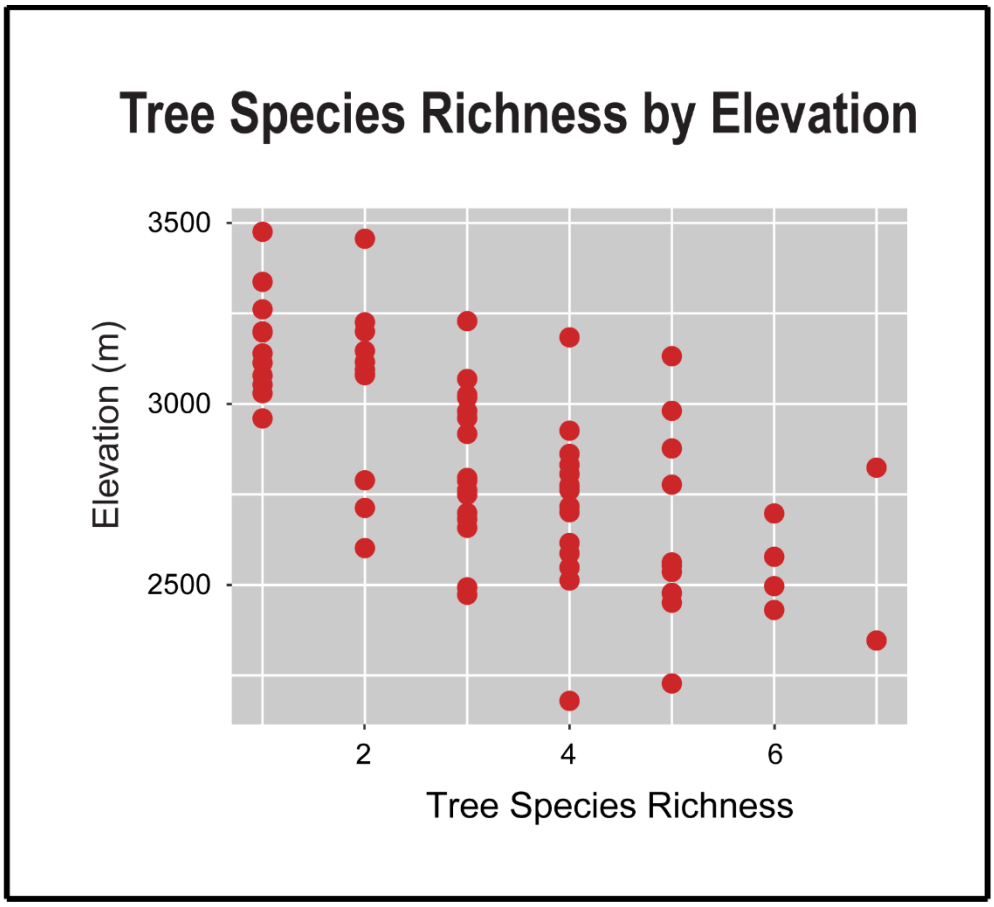


Figure 1 - 3. The scatterplot depicts the relationship between tree species richness and elevation across all plots. Tree species richness ranged from 1–7 species (r = -0.699).

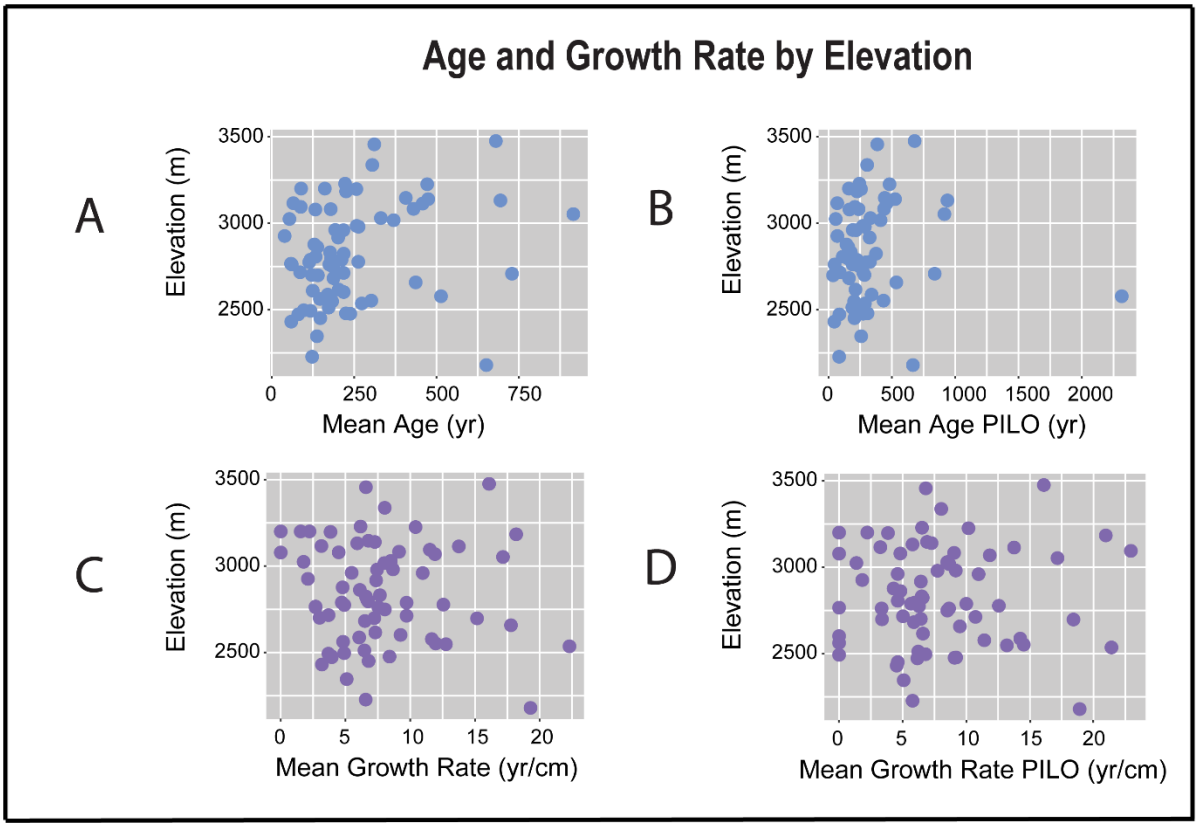


Figure 1 - 4. Scatterplots depict mean age (r = 0.263), mean age for PILO (r = 0.217), mean growth rate (r = 0.089), and mean growth rate for PILO (r = 0.105) associations with elevation. Points in each graph represent study plots. Total tree metrics are depicted on the left and *P. longaeva* (PILO) metrics are depicted on the right.

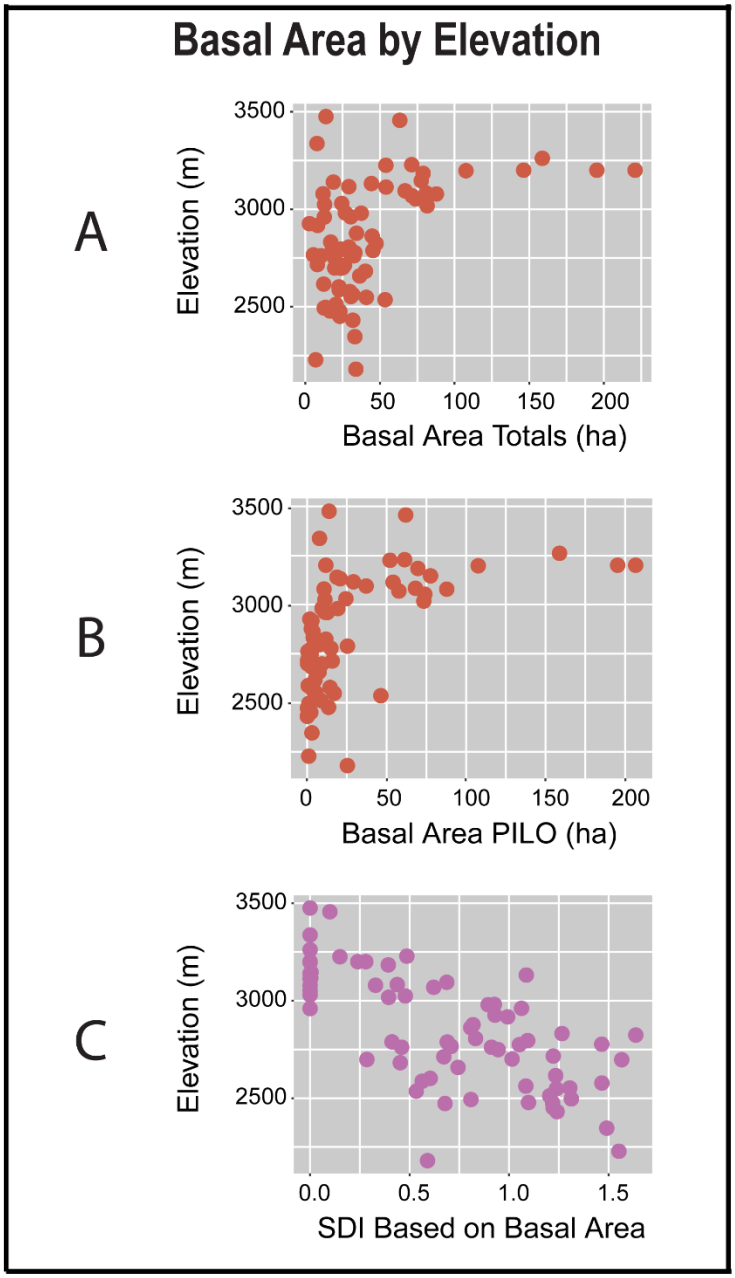


Figure 1 - 5. Scatterplots depict basal area (r = 0.466), basal area for PILO (r = 0.524), and SDI based on basal area (r = -0.691) associations with elevation. Points in each graph represent study plots.

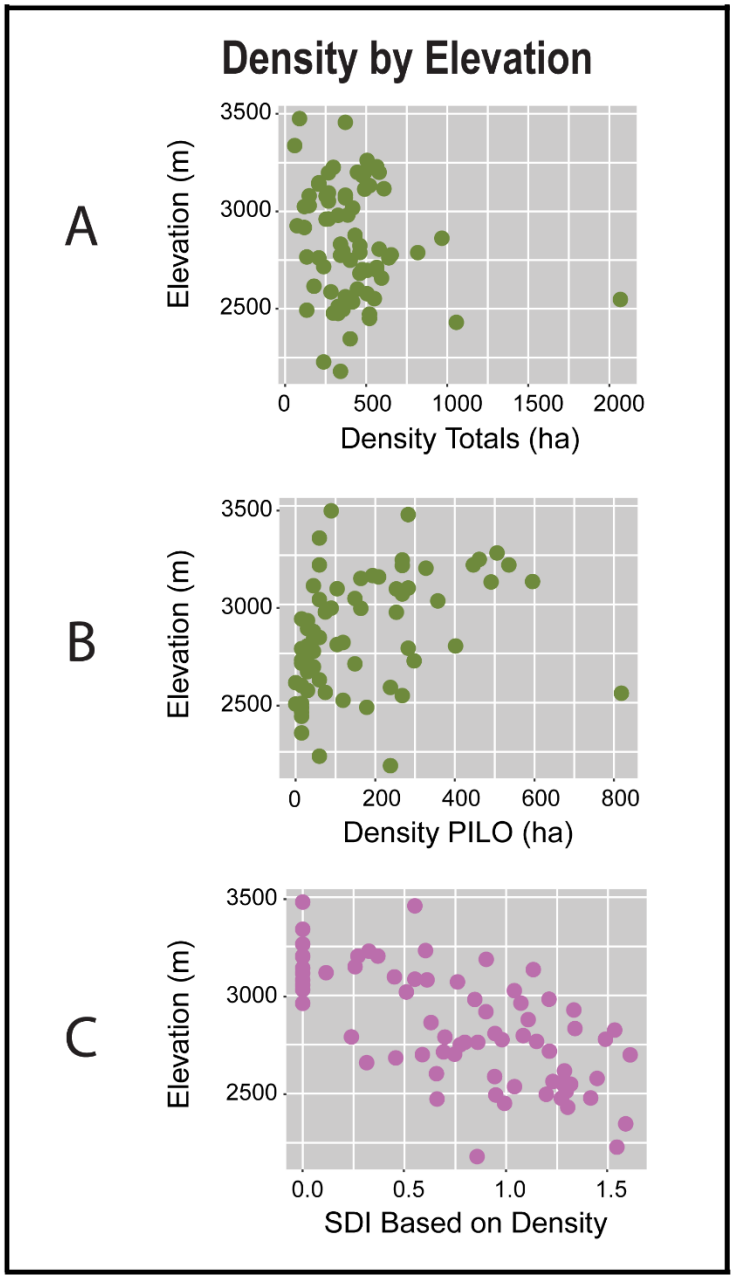


Figure 1 - 6. Scatterplots depict density (r = 0.237), density for PILO (r = 0.659), and SDI based on density (r = -0.658) associations with elevation. Points in each graph represent study plots.

TABLES

Table 1 - 1. Average range values for variables measured at each plot as well as mean values for each variable categorized as either homogeneous or heterogeneous. The t-test p-values are expressed from a two-tailed test. * Represents statistical significance.

| Variable Measured | Range | Homogeneous Plots (expressed as means) | Heterogeneous Plots (expressed as means) | Standard Error | T-test p-value |
|---|---|---|---|---|---|
| **Biophysical Variables** | | | | | |
| Plot elevation | 2179 – 3476 (m) | 3020 (m) | 2662 (m) | 55.87 (m) | 0.0001* |
| Plot slope | 9 – 112 (degrees) | 49 (degrees) | 49 (degrees) | 5.43 (degrees) | 0.8705 |
| Plot aspect | 10 – 358 (degrees) | 221 (degrees) | 195 (degrees) | 26.93 (degrees) | 0.3285 |
| **Stand Composition and Structure** | | | | | |
| Tree age | 39 – 915 (yrs) | 280 (yrs) | 212 (yrs) | 44.64 (yrs) | 0.1320 |
| PILO tree age | 34 – 2315 (yrs) | 357 (yrs) | 282 (yrs) | 79.48 (yrs) | 0.3477 |
| Tree diameter | 13.50 – 72.60 (cm) | 371 (cm) | 253 (cm) | 26.71 (cm) | 0.0001* |
| PILO tree diameter | 10.20 – 100.90 (cm) | 371 (cm) | 253 (cm) | 36.39 (cm) | 0.0093* |
| Tree growth rate | 1.54 – 22.30 (mm/yr) | 1.83 (mm/yr) | 1.71 (mm/yr) | 0.29 (mm/yr) | 0.6971 |
| PILO tree growth rate | 1.36 – 22.94 (mm/yr) | 1.73 (mm/yr) | 1.50 (mm/yr) | 0.28 (mm/yr) | 0.4225 |
| Plot tree basal area | 2.72 – 220.95 (cm/tree) | 56.48 (cm/tree) | 27.96 (cm/tree) | 8.98 (cm/tree) | 0.0027* |
| PILO plot tree basal area | 0.12 – 206.60 (cm/tree) | 43.62 (cm/tree) | 9.74 (cm/tree) | 8.98 (cm/tree) | 0.0005* |
| Plot tree density | 59.52 – 2068.30 (live trees/hectare) | 364 (live trees/hectare) | 484 (live trees/hectare) | 68.95 (live trees/hectare) | 0.0908 |

| | | | | | |
|---|---|---|---|---|---|
| PILO plot tree density | 14.88 – 818.40 (live trees/hectare) | 210 (live trees/hectare) | 109 (live trees/hectare) | 39.76 (live trees/hectare) | 0.0130* |
| **Tree Diversity** | | | | | |
| Plot SDI basal area | 0 – 1.64 | 0.37 | 1.09 | 0.08 | 0.0001* |
| Plot SDI density | 0 – 1.61 | 0.42 | 1.19 | 0.07 | 0.0001* |

# APPENDIX

Table A - 1. List of study plots by ID, name, and geographic location.

| Plot ID | Plot Name | Latitude | Longitude | Elevation (m) |
|---|---|---|---|---|
| **3239** | Spring x5 | 36.344 | -115.713 | 2716.378 |
| **3251** | Spring x10 | 36.341 | -115.709 | 3017.520 |
| **3252** | Spring x6 | 36.331 | -115.638 | 2795.626 |
| **3257** | Spring x9 | 36.318 | -115.645 | 2959.913 |
| **3263** | Spring x7 | 36.307 | -115.737 | 2806.294 |
| **3265** | Spring x15 | 36.307 | -115.581 | 2430.780 |
| **3272** | Spring x1 | 36.303 | -115.650 | 3115.970 |
| **3282** | Spring x2 | 36.299 | -115.746 | 2823.972 |
| **3284** | Spring x13 | 36.295 | -115.680 | 3113.837 |
| **3293** | Spring x3 | 36.285 | -115.671 | 2926.080 |
| **3294** | Spring x8 | 36.286 | -115.618 | 2657.856 |
| **3295** | Spring x4 | 36.284 | -115.609 | 2877.007 |
| **3310** | Spring x16 | 36.262 | -115.703 | 3475.634 |
| **3323** | Spring x11 | 36.254 | -115.692 | 3197.657 |
| **3324** | Spring x14 | 36.247 | -115.610 | 2698.699 |
| **3332** | Spring x12 | 36.242 | -115.639 | 3052.877 |
| **52373** | White Mtn FIA 2 | 37.536 | -118.197 | 3261.360 |
| **73693** | Inyo Mtn | 36.960 | -118.056 | 3200.400 |
| **80025** | N. Schell Creek | 39.684 | -114.614 | 2450.897 |
| **81219** | E. Paragonah | 37.857 | -112.713 | 2774.899 |
| **81361** | W. Emery 1 | 38.959 | -111.318 | 2562.149 |
| **82024** | S. Schell Creek | 38.916 | -114.631 | 2749.296 |
| **82061** | E. Joe Valley 2 | 39.298 | -111.179 | 2227.783 |
| **82294** | E. Hatch | 37.626 | -112.363 | 2346.350 |

| | | | | |
|---|---|---|---|---|
| **82454** | Troy Peak 1 | 38.325 | -115.488 | 3029.712 |
| **82518** | Ward | 39.076 | -114.891 | 2788.920 |
| **82559** | Dutton | 37.900 | -112.248 | 2917.241 |
| **83072** | Moriah 1 | 39.267 | -114.099 | 2862.072 |
| **83167** | 1000 Lake | 38.396 | -111.521 | 3079.394 |
| **84170** | W. Emery 3 | 38.940 | -111.349 | 2587.142 |
| **84663** | Cherry 2 | 40.001 | -114.889 | 2761.488 |
| **84806** | S. Twisted Forest | 37.666 | -112.871 | 2761.488 |
| **85420** | Lion Mtn | 38.172 | -111.343 | 2512.162 |
| **85904** | S. Wahwah | 38.373 | -113.575 | 2496.617 |
| **86134** | S. Egan | 38.834 | -114.923 | 2552.395 |
| **86279** | Springs 2 | 36.275 | -115.714 | 2700.833 |
| **86472** | White Mtn FIA 3 | 37.790 | -118.375 | 3200.400 |
| **86560** | S. Snake 1 | 38.775 | -114.187 | 2831.592 |
| **87487** | W. Emery 2 | 38.986 | -111.286 | 2476.500 |
| **87529** | E. Joes Valley 1 | 39.329 | -111.096 | 2766.060 |
| **87776** | Troy Peak 2 | 38.303 | -115.514 | 3146.450 |
| **88149** | Hunter Point | 39.784 | -115.016 | 2472.842 |
| **88638** | Bryce Cyn | 37.539 | -112.242 | 2616.098 |
| **88990** | N. White Pine | 38.977 | -115.444 | 3024.530 |
| **89580** | S. Snake 2 | 38.800 | -114.317 | 2979.725 |
| **90338** | Moriah 2 | 39.262 | -114.166 | 3228.746 |
| **90503** | Cherry 1 | 39.961 | -114.890 | 2961.132 |
| **90566** | Lincoln | 38.865 | -114.296 | 3337.255 |
| **90642** | Springs 1 | 36.364 | -115.717 | 2682.240 |
| **90986** | White Mtn FIA 1 | 37.448 | -118.181 | 3078.480 |
| **96342** | White Mtn FIA 4 | 37.586 | -118.187 | 3200.400 |
| **BAD** | Badger | 37.557 | -118.344 | 2777.033 |
| **BCPT** | Bristlecone Point | 37.564 | -112.852 | 2980.944 |

| | | | | |
|---|---|---|---|---|
| **BD** | Boundary Peak | 37.878 | -118.320 | 3094.634 |
| **CV** | Cave Mtn | 42.134 | -114.501 | 3225.698 |
| **EST** | East | 39.407 | -117.202 | 3183.941 |
| **HL** | Hill | 37.899 | -114.583 | 2788.310 |
| **MAM** | Mammoth Creek | 37.644 | -118.673 | 2577.694 |
| **PPT** | Powell Point | 37.694 | -117.899 | 3131.820 |
| **PRC** | Price Canyon | 39.762 | -116.926 | 2535.936 |
| **SOW** | Sowers Canyon | 39.983 | -110.471 | 2179.625 |
| **SPM** | Spruce Mtn | 40.552 | -114.822 | 3083.052 |
| **SWA** | Swasey Mtn | 39.394 | -113.326 | 2548.128 |
| **TF1** | Twisted Forest | 37.683 | -112.881 | 3069.031 |
| **TR1** | TR1 | 37.702 | -112.285 | 2478.024 |
| **WAH** | Wah Wah | 38.595 | -113.568 | 2712.720 |
| **WM1** | White Mtn 1 | 37.428 | -118.201 | 3139.440 |
| **WM2** | White Mtn 2 | 37.525 | -118.195 | 3456.432 |
| **WP** | Wilson Point | 37.691 | -112.307 | 2697.480 |

Table A - 2. Biophysical variables matrix

| Plot Name | Percent Slope | Rock Type 1 | Avg Temp | Winter Temp | Summer Temp | Avg Precip | Winter Precip | Summer Precip | sin (Aspect) |
|---|---|---|---|---|---|---|---|---|---|
| 3239 | 15 | limestone | 5.065417 | -0.48333 | 10.61417 | 81.30083 | 129.9167 | 32.685 | -0.25882 |
| 3251 | 60 | limestone | 5.065417 | -0.48333 | 10.61417 | 81.30083 | 129.9167 | 32.685 | 0.573576 |
| 3252 | 45 | limestone | 7.212083 | 1.505833 | 12.91833 | 82.57917 | 131.8033 | 33.355 | -0.32557 |
| 3257 | 95 | limestone | 7.212083 | 1.505833 | 12.91833 | 82.57917 | 131.8033 | 33.355 | -0.17365 |
| 3263 | 65 | limestone | 6.934583 | 1.3425 | 12.52667 | 77.96 | 125.1183 | 30.80167 | -0.5 |
| 3265 | 25 | limestone | 8.820833 | 3.03 | 14.61167 | 44.96083 | 56.36333 | 33.55833 | 0.707106 |
| 3272 | 40 | limestone | 4.155417 | -1.14083 | 9.451667 | 87.72084 | 139.2583 | 36.18333 | 0.615661 |
| 3282 | 40 | limestone | 6.934583 | 1.3425 | 12.52667 | 77.96 | 125.1183 | 30.80167 | -0.64279 |
| 3284 | 70 | limestone | 4.155417 | -1.14083 | 9.451667 | 87.72084 | 139.2583 | 36.18333 | -0.86603 |
| 3293 | 45 | limestone | 4.155417 | -1.14083 | 9.451667 | 87.72084 | 139.2583 | 36.18333 | 0.766046 |
| 3294 | 50 | limestone | 5.115 | -0.42833 | 10.65833 | 93.00416 | 148.3833 | 37.625 | -0.90631 |
| 3295 | 30 | limestone | 5.115 | -0.42833 | 10.65833 | 93.00416 | 148.3833 | 37.625 | 0.642787 |
| 3310 | 50 | limestone | 5.080833 | -0.20167 | 10.36333 | 94.49166 | 151.095 | 37.88833 | 0.766046 |
| 3323 | 70 | limestone | 5.080833 | -0.20167 | 10.36333 | 94.49166 | 151.095 | 37.88833 | 0.642789 |
| 3324 | 55 | limestone | 7.07625 | 1.466667 | 12.68583 | 96.90833 | 155.0317 | 38.785 | -0.08716 |
| 3332 | 75 | limestone | 7.07625 | 1.466667 | 12.68583 | 96.90833 | 155.0317 | 38.785 | -0.90631 |
| 52373 | 30 | sandstone | 0.141667 | -4.5025 | 4.785833 | 79.415 | 133.8933 | 24.93667 | 0.731355 |
| 73693 | 22 | sandstone | 2.874583 | -1.5075 | 7.256667 | 51.93583 | 83.635 | 20.23667 | -0.93969 |
| 80025 | 22 | limestone | 5.436667 | -0.73333 | 11.60667 | 72.5325 | 109.1933 | 35.87167 | 0.325568 |
| 81219 | 25 | limestone | 6.375417 | -0.05333 | 12.80417 | 72.24083 | 111.1067 | 33.375 | 0.615661 |
| 81361 | 64 | shale | 5.83625 | -0.59 | 12.2625 | 66.82917 | 100.3117 | 33.34667 | -0.3746 |
| 82024 | 90 | dolomite | 5.268333 | -0.8525 | 11.38917 | 72.76417 | 111.3033 | 34.225 | 0.173648 |
| 82061 | 70 | shale | 6.070417 | -0.83083 | 12.97167 | 65.1425 | 99.25 | 31.035 | -0.74315 |
| 82294 | 112 | sandstone | 6.31875 | -0.10083 | 12.73833 | 71.3675 | 110.4133 | 32.32167 | -0.74315 |
| 82454 | 73 | limestone | 4.18125 | -1.52667 | 9.889167 | 80.2075 | 122.2567 | 38.15833 | 0.99863 |
| 82518 | 74 | limestone | 6.225 | -0.2225 | 12.6725 | 70.74167 | 108.8283 | 32.655 | 0.587785 |
| 82559 | 44 | ash-flow tuff | 4.994167 | -1.20833 | 11.19667 | 84.1975 | 128.7583 | 39.63667 | -0.79864 |
| 83072 | 38 | limestone | 8.616667 | 1.758333 | 15.475 | 53.125 | 79.84333 | 26.40667 | 0.898794 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 83167 | 17 | alluvium | 5.3425 | -0.94667 | 11.63167 | 65.67417 | 96.775 | 34.57333 | -0.62932 |
| 84170 | 95 | shale | 5.83625 | -0.59 | 12.2625 | 66.82917 | 100.3117 | 33.34667 | -0.46948 |
| 84663 | 29 | dolomite | 5.224583 | -0.8525 | 11.30167 | 76.57167 | 119.7633 | 33.38 | -0.96126 |
| 84806 | 68 | fine-grained mixed clastic | 4.345833 | -1.55083 | 10.2425 | 122.1417 | 195.275 | 49.00833 | -0.52992 |
| 85420 | 65 | sandstone | 5.993333 | -0.57917 | 12.56583 | 62.40333 | 91.625 | 33.18167 | -0.96592 |
| 85904 | 65 | limestone | 7.20125 | 0.720833 | 13.68167 | 76.8175 | 118.7917 | 34.84333 | 0.848048 |
| 86134 | 50 | dolomite | 5.933333 | -0.31417 | 12.18083 | 67.89667 | 104.4033 | 31.39 | -0.62932 |
| 86279 | 50 | limestone | 4.840417 | -0.645 | 10.32583 | 80.235 | 127.5767 | 32.89333 | 0.766044 |
| 86472 | 63 | granodiorite | 2.405417 | -2.60583 | 7.416667 | 60.2625 | 95.23334 | 25.29167 | -0.76605 |
| 86560 | 60 | dolomite | 7.71625 | 1.0375 | 14.395 | 64.00083 | 97.46333 | 30.53833 | 0.258819 |
| 87487 | 59 | shale | 6.34125 | -0.3975 | 13.08 | 62.30917 | 94.08166 | 30.53667 | -0.83867 |
| 87529 | 83 | shale | 6.131667 | -0.62 | 12.88333 | 67.25917 | 102.4783 | 32.04 | 0.743144 |
| 87776 | 72 | limestone | 5.27625 | -0.73583 | 11.28833 | 75.985 | 116.065 | 35.905 | 0.766046 |
| 88149 | 54 | dolomite | 7.070833 | 0.526667 | 13.615 | 60.80667 | 92.91167 | 28.70167 | -0.24193 |
| 88638 | 50 | limestone | 5.614583 | -0.7175 | 11.94667 | 87.36917 | 136.445 | 38.29333 | 0.984808 |
| 88990 | 65 | dolomite | 5.7875 | -0.4875 | 12.0625 | 65.0925 | 100.15 | 30.035 | 0.951056 |
| 89580 | 20 | limestone | 6.4225 | -0.00583 | 12.85083 | 70.93083 | 108.2917 | 33.57 | -0.97029 |
| 90338 | 20 | quartzite | 4.203333 | -1.87417 | 10.28083 | 81.66333 | 126.025 | 37.30167 | -0.90631 |
| 90503 | 51 | limestone | 6.016667 | -0.2975 | 12.33083 | 70.34917 | 109.3217 | 31.37667 | 0.978148 |
| 90566 | 15 | limestone | 2.200417 | -3.71417 | 8.115 | 111.0158 | 171.1383 | 50.89333 | 0.258821 |
| 90642 | 65 | limestone | 8.176667 | 2.418333 | 13.935 | 77.87417 | 125.1983 | 30.55 | -0.86603 |
| 90986 | 10 | sandstone | 2.29375 | -2.40167 | 6.989167 | 72.2525 | 122.595 | 21.91 | 0.406739 |
| 96342 | 65 | granodiorite | 3.179583 | -1.6 | 7.959167 | 70.9525 | 119.5067 | 22.39833 | -0.0349 |
| BAD | 38 | limestone | 5.459167 | -0.71667 | 11.635 | 54.31583 | 65.37833 | 43.25333 | -0.99939 |
| BCPT | 48 | fine-grained mixed clastic | 2.58375 | -3.04 | 8.2075 | 139.6817 | 226.7083 | 52.655 | 0.087158 |
| BD | 45 | diorite | 3.367917 | -1.59917 | 8.335 | 51.76167 | 81.09333 | 22.43 | -0.0349 |
| CV | 25 | limestone | 3.459167 | -2.49917 | 9.4175 | 79.6675 | 122.9783 | 36.35667 | -0.9703 |
| EST | 46 | alluvium | 8.092083 | 1.515 | 14.66917 | 31.6375 | 45.51667 | 17.75833 | -0.90631 |
| HL | 47 | limestone | 7.670416 | 1.464167 | 13.87667 | 69.3725 | 109.13 | 29.615 | -0.52992 |
| MAM | 39 | dacite | 5.313334 | -0.72833 | 11.355 | 47.55083 | 57.37333 | 37.72833 | 0.529921 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| PPT | 9 | rhyolite | 6.063333 | 1.0225 | 11.10417 | 57.77583 | 91.595 | 23.95667 | -0.46947 |
| PRC | 46 | rhyolite | 6.97375 | 0.9425 | 13.005 | 68.19167 | 105.8383 | 30.545 | -0.64279 |
| SOW | 65 | sandstone | 6.38125 | -0.99333 | 13.75583 | 64.1 | 96.445 | 31.755 | -0.74315 |
| SPM | 65 | dolomite | 4.150417 | -1.73 | 10.03083 | 75.66 | 121.8083 | 29.51167 | -0.93969 |
| SWA | 35 | limestone | 7.922083 | 1.005833 | 14.83833 | 78.74167 | 120.8033 | 36.68 | -0.97815 |
| WAH | 18 | limestone | 8.985833 | 2.033333 | 15.93833 | 52.45333 | 78.82333 | 26.08333 | -0.13918 |
| WM1 | 45 | sandstone | 4.029167 | -0.66333 | 8.721667 | 61.935 | 102.515 | 21.355 | -0.98769 |
| WM2 | 29 | sandstone | 0.141667 | -4.5025 | 4.785833 | 79.415 | 133.8933 | 24.93667 | 0.866026 |

Table A - 3. Growth Rate Matrix

| Plot Name | Mean Age | Medium Age | Mean PILO Age | Medium PILO Age | Mean Diameter (mm) | Median Diameter (mm) | Mean Diameter PILO (mm) | Median Diameter PILO (mm) | Mean Growth Rate (Diameter/Age) (mm/yr) | Mean Growth Rate PILO (Diameter/Age) (mm/yr) |
|---|---|---|---|---|---|---|---|---|---|---|
| 3239 | 86 | 75 | 88 | 88 | 233.045 | 207.01 | 175.26 | 175.26 | 2.709826 | 1.991591 |
| 3251 | 369.75 | 370.5 | 411.125 | 435 | 462.0986 | 462.28 | 474.5567 | 480.06 | 1.249759 | 1.154288 |
| 3252 | 180 | 177 | 155.5 | 155.5 | 266.4883 | 226.06 | 261.2571 | 180.34 | 1.480491 | 1.68011 |
| 3257 | 217.4286 | 190 | 217.4286 | 190 | 198.2694 | 172.72 | 198.2694 | 172.72 | 0.911883 | 0.911883 |
| 3263 | 133.1667 | 101.5 | 112.3333 | 109 | 199.6831 | 154.94 | 243.5225 | 214.63 | 1.499497 | 2.167856 |
| 3265 | 59 | 60.5 | 46 | 46 | 185.6704 | 172.72 | 101.6 | 101.6 | 3.146956 | 2.208696 |
| 3272 | 65.4 | 58.5 | 69 | 62 | 208.342 | 182.88 | 212.7885 | 185.42 | 3.185657 | 3.083891 |
| 3282 | 218.2222 | 244 | 375 | 375 | 331.7568 | 287.02 | 570.6533 | 589.28 | 1.52027 | 1.521742 |
| 3284 | 457.75 | 364.5 | 457.75 | 364.5 | 332.74 | 287.02 | 332.74 | 287.02 | 0.726903 | 0.726903 |
| 3293 | 39 | 32.5 | 70 | 70 | 185.928 | 167.64 | 383.54 | 383.54 | 4.767385 | 5.479143 |
| 3294 | 436.6667 | 282 | 535.5 | 535.5 | 245.5545 | 191.77 | 563.88 | 563.88 | 0.562339 | 1.052997 |
| 3295 | 129 | 139.5 | 142 | 142 | 270.0283 | 200.66 | 331.47 | 331.47 | 2.093242 | 2.334296 |
| 3310 | 680 | 850 | 680 | 850 | 422.4867 | 388.62 | 422.4867 | 388.62 | 0.621304 | 0.621304 |
| 3323 | 256.5455 | 220 | 256.5455 | 220 | 667.4555 | 688.34 | 667.4555 | 688.34 | 2.601705 | 2.601705 |
| 3324 | 139.9167 | 112.5 | 36 | 36 | 193.6416 | 166.37 | 106.68 | 106.68 | 1.383978 | 2.963333 |
| 3332 | 915 | 974.5 | 915 | 974.5 | 532.9767 | 593.09 | 532.9767 | 593.09 | 0.582488 | 0.582488 |
| 52373 | | | | | 220.359 | 242 | 220.359 | 242 | | |
| 73693 | 161 | 161 | 161 | 161 | 725.5933 | 740.41 | 725.5933 | 740.41 | 4.506791 | 4.506791 |
| 80025 | 147.2222 | 153 | 205 | 205 | 216.9886 | 213.36 | 444.5 | 444.5 | 1.473885 | 2.168293 |
| 81219 | 113.6667 | 94 | 300 | 300 | 231.5817 | 218.44 | 477.52 | 477.52 | 2.037376 | 1.591733 |
| 81361 | 146 | 146 | | | 303.1744 | 292.1 | 392.43 | 392.43 | 2.076537 | |
| 82024 | 185.3333 | 165 | 247.5 | 247.5 | 230.4815 | 215.9 | 290.83 | 290.83 | 1.243605 | 1.175071 |
| 82061 | 122.375 | 105.5 | 84 | 84 | 186.5313 | 184.15 | 145.415 | 142.24 | 1.524259 | 1.731131 |
| 82294 | 137.0526 | 118 | 258 | 258 | 269.0519 | 238.76 | 508 | 508 | 1.963128 | 1.968992 |
| 82454 | 331 | 293.5 | 331 | 293.5 | 389.382 | 331.47 | 389.382 | 331.47 | 1.176381 | 1.176381 |
| 82518 | 117.2 | 78.5 | 199 | 199 | 248.5923 | 223.52 | 351.79 | 351.79 | 2.121094 | 1.767789 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 82559 | 201.4286 | 119 | 325 | 325 | 273.3675 | 257.81 | 505.46 | 505.46 | 1.357144 | 1.555262 |
| 83072 | 138 | 151.5 | 156 | 156 | 225.8255 | 210.82 | 323.4267 | 320.04 | 1.636417 | 2.073248 |
| 83167 | 132.1429 | 144 | 165.6 | 170 | 295.148 | 259.08 | 343.9886 | 322.58 | 2.233552 | 2.077226 |
| 84170 | 169.8182 | 125 | 340 | 340 | 280.2021 | 248.92 | 238.76 | 238.76 | 1.650012 | 0.702235 |
| 84663 | 60.5 | 57 | 48 | 48 | 224.79 | 189.23 | 143.51 | 143.51 | 3.715537 | 2.989792 |
| 84806 | 174.5909 | 173.5 | 190.3333 | 177 | 231.6126 | 195.58 | 220.1333 | 195.58 | 1.326601 | 1.156567 |
| 85420 | 172.5 | 167.5 | 187.5 | 176.5 | 266.9309 | 271.78 | 301.3075 | 307.34 | 1.547426 | 1.606973 |
| 85904 | 96.83333 | 40.5 | 207 | 207 | 197.5908 | 185.42 | 304.8 | 304.8 | 2.040525 | 1.472464 |
| 86134 | 302 | 340.5 | 434.3333 | 434 | 252.3524 | 243.84 | 299.212 | 307.34 | 0.835604 | 0.688899 |
| 86279 | 121.4545 | 81 | 284 | 284 | 404.9932 | 137.16 | 441.96 | 441.96 | 3.334525 | 1.556197 |
| 86472 | 89 | 89 | | | 578.5812 | 629.92 | 457.2 | 457.2 | 6.500913 | |
| 86560 | 176.7857 | 183.5 | 177 | 181 | 230.8087 | 205.74 | 272.415 | 255.27 | 1.305585 | 1.539068 |
| 87487 | 238.2 | 230 | 272.875 | 250 | 283.4409 | 273.05 | 300.5667 | 279.4 | 1.189928 | 1.101481 |
| 87529 | 58.25 | 61.5 | | | 216.7467 | 236.22 | 216.7467 | 236.22 | 3.720973 | |
| 87776 | 406.6364 | 400 | 444.1 | 434.5 | 600.5286 | 584.2 | 642.0338 | 627.38 | 1.47682 | 1.445697 |
| 88149 | 80.25 | 90 | 86 | 86 | 203.708 | 182.88 | 139.7 | 139.7 | 2.538417 | 1.624419 |
| 88638 | 203 | 176.5 | 213.25 | 136.5 | 277.9183 | 236.22 | 323.4267 | 218.44 | 1.369056 | 1.516655 |
| 88990 | 53.5 | 53.5 | 57 | 57 | 303.53 | 203.2 | 417.83 | 356.87 | 5.673458 | 7.330351 |
| 89580 | 263.25 | 279.5 | 287.4 | 264 | 353.8682 | 340.36 | 371.5327 | 355.6 | 1.344229 | 1.292737 |
| 90338 | 222.4286 | 222.5 | 243.875 | 244.5 | 360.8137 | 340.36 | 373.9536 | 340.36 | 1.622155 | 1.533382 |
| 90503 | 192.4545 | 180 | 191.2 | 180 | 351.3667 | 355.6 | 415.036 | 421.64 | 1.825712 | 2.17069 |
| 90566 | 305 | 321 | 305 | 321 | 379.73 | 346.71 | 379.73 | 346.71 | 1.245016 | 1.245016 |
| 90642 | 187.2308 | 187 | 161.3333 | 173 | 288.0852 | 248.92 | 274.32 | 248.92 | 1.538664 | 1.700331 |
| 90986 | | | | | 620.5071 | 685.8 | 620.5071 | 685.8 | | |
| 96342 | | | | | 616.0477 | 594.36 | 614.68 | 549.91 | | |
| BAD | 268.6071 | 251.5 | 281.9231 | 253 | 213.8218 | 193.04 | 224.4558 | 210.82 | 0.796039 | 0.79616 |
| BCPT | 222.2308 | 199 | 308 | 308 | 256.3446 | 237.49 | 335.7033 | 318.77 | 1.153506 | 1.089946 |
| BD | 513.4444 | 210 | 2315 | 1248.5 | 445.77 | 441.96 | 1009.227 | 1066.8 | 0.868195 | 0.435951 |
| CV | 471.6 | 405 | 481.7857 | 407.5 | 452.755 | 466.09 | 473.5689 | 469.9 | 0.96004 | 0.982945 |
| EST | 718.5417 | 419.5 | 979.9333 | 1115 | 395.0494 | 374.65 | 467.36 | 477.52 | 0.549793 | 0.47693 |
| HL | 211.56 | 200.5 | 224.56 | 161 | 217.6549 | 190.5 | 224.5548 | 180.34 | 1.028809 | 0.999977 |

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|---|---|---|---|---|---|---|---|---|---|---|
| MAM | 280.25 | 221 | 271.8333 | 160 | 240.1794 | 194.31 | 238.125 | 171.45 | 0.857018 | 0.875996 |
| PPT | 166.1515 | 179 | 202.1818 | 198 | 281.2869 | 274.32 | 350.2891 | 307.34 | 1.692954 | 1.732545 |
| PRC | 717.6 | 696.5 | 801.1176 | 815 | 321.7333 | 284.48 | 374.1271 | 345.44 | 0.448346 | 0.467006 |
| SOW | 662.9048 | 690 | 683 | 751.5 | 343.5626 | 342.9 | 361.1563 | 337.82 | 0.518268 | 0.528779 |
| SPM | 438.1176 | 497 | 455.1818 | 515 | 479.4504 | 424.18 | 503.4547 | 424.18 | 1.094342 | 1.106052 |
| SWA | 171.8095 | 154 | 184.1633 | 169 | 134.6381 | 111.76 | 139.6093 | 125.73 | 0.783648 | 0.758073 |
| WAH | 204.6053 | 178 | 256.15 | 191.5 | 210.4858 | 204.47 | 238.887 | 232.41 | 1.028741 | 0.932606 |
| WM1 | 225.5 | 233 | 225.5 | 233 | 310.2429 | 281.94 | 310.2429 | 281.94 | 1.3758 | 1.3758 |
| WM2 | 246.7778 | 145 | 310.5385 | 145 | 375.1072 | 330.2 | 455.5958 | 386.08 | 1.52002 | 1.467115 |

Table A - 4. Stand Structure Matrix

| Plot Name | LTD: Total (ha) | LD: propor PILO | Shannon's DI | spec rich-ness | Basal_Area_Totals | Shannon's DI 2 | LBA propor PILO |
|---|---|---|---|---|---|---|---|
| 3239 | 238.08 | 0.0625 | 1.212314 | 4 | 8.062552 | 1.222261 | 0.044523 |
| 3251 | 416.64 | 0.857143 | 0.509137 | 3 | 81.61852 | 0.394693 | 0.899073 |
| 3252 | 357.12 | 0.291667 | 1.083529 | 3 | 23.85236 | 1.093475 | 0.312987 |
| 3257 | 252.96 | 1 | 0 | 1 | 12.70346 | 0 | 1 |
| 3263 | 580.32 | 0.205128 | 0.944891 | 4 | 29.16582 | 0.831704 | 0.214374 |
| 3265 | 1056.48 | 0.014085 | 1.302029 | 6 | 31.82014 | 1.241145 | 0.003791 |
| 3272 | 610.08 | 0.97561 | 0.114665 | 2 | 29.13151 | 0.003315 | 0.999627 |
| 3282 | 461.28 | 0.096774 | 1.532985 | 7 | 47.39054 | 1.636857 | 0.248685 |
| 3284 | 491.04 | 1 | 0 | 1 | 54.05393 | 0 | 1 |
| 3293 | 74.4 | 0.2 | 1.332179 | 4 | 2.719009 | 0.929134 | 0.632272 |
| 3294 | 595.2 | 0.05 | 0.314123 | 3 | 36.41543 | 0.743574 | 0.208595 |
| 3295 | 431.52 | 0.068966 | 1.107891 | 5 | 34.27548 | 0.818848 | 0.07585 |
| 3310 | 89.28 | 1 | 0 | 1 | 13.81355 | 0 | 1 |
| 3323 | 267.84 | 1 | 0 | 1 | 107.6307 | 0 | 1 |
| 3324 | 565.44 | 0.052632 | 0.587926 | 3 | 19.6891 | 0.285327 | 0.015471 |
| 3332 | 267.84 | 1 | 0 | 1 | 74.00519 | 0 | 1 |
| 52373 | 505.92 | 1 | 0 | 1 | 158.7677 | 0 | 1 |
| 73693 | 446.4 | 1 | 0 | 1 | 195.3164 | 0 | 1 |
| 80025 | 520.8 | 0.028571 | 0.991533 | 5 | 23.10064 | 1.221578 | 0.099957 |
| 81219 | 342.24 | 0.043478 | 0.979238 | 4 | 17.0859 | 1.052066 | 0.155969 |
| 81361 | 372 | 0.08 | 1.229344 | 5 | 31.75861 | 1.084339 | 0.121518 |
| 82024 | 401.76 | 0.074074 | 0.774311 | 3 | 19.77694 | 0.945327 | 0.130709 |
| 82061 | 238.08 | 0.25 | 1.543789 | 5 | 6.932334 | 1.552124 | 0.143665 |
| 82294 | 401.76 | 0.037037 | 1.586884 | 7 | 33.17987 | 1.490775 | 0.090896 |
| 82454 | 148.8 | 1 | 0 | 1 | 24.38912 | 0 | 1 |
| 82518 | 461.28 | 0.064516 | 0.239217 | 2 | 27.9685 | 0.411741 | 0.143766 |
| 82559 | 119.04 | 0.25 | 0.900256 | 3 | 8.225714 | 0.992736 | 0.362989 |
| 83072 | 967.2 | 0.046154 | 0.630436 | 4 | 44.77483 | 0.807428 | 0.081968 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 83167 | 148.8 | 0.7 | 0.610864 | 2 | 11.84581 | 0.328801 | 0.898301 |
| 84170 | 282.72 | 0.052632 | 0.943046 | 4 | 22.64147 | 0.563297 | 0.029425 |
| 84663 | 208.32 | 0.142857 | 0.796312 | 3 | 10.53094 | 0.46016 | 0.046001 |
| 84806 | 639.84 | 0.069767 | 0.86006 | 4 | 32.52157 | 0.911603 | 0.059087 |
| 85420 | 327.36 | 0.363636 | 1.294545 | 4 | 20.55414 | 1.203916 | 0.415699 |
| 85904 | 357.12 | 0.041667 | 1.196711 | 6 | 13.53148 | 1.312928 | 0.080238 |
| 86134 | 550.56 | 0.135135 | 1.275903 | 5 | 30.54063 | 1.30523 | 0.175296 |
| 86279 | 476.16 | 0.03125 | 0.746241 | 4 | 25.09153 | 1.014793 | 0.090977 |
| 86472 | 491.04 | 0.121212 | 0.369333 | 2 | 146.2722 | 0.279987 | 0.080499 |
| 86560 | 342.24 | 0.173913 | 1.337787 | 4 | 16.98585 | 1.266009 | 0.223848 |
| 87487 | 327.36 | 0.545455 | 1.270761 | 5 | 23.11655 | 1.21873 | 0.583118 |
| 87529 | 133.92 | 0.222222 | 1.14906 | 4 | 5.383354 | 0.709188 | 0.427919 |
| 87776 | 208.32 | 0.928571 | 0.257319 | 2 | 77.67142 | 0.004746 | 0.999441 |
| 88149 | 520.8 | 0.028571 | 0.659747 | 3 | 20.51803 | 0.678129 | 0.011116 |
| 88638 | 178.56 | 0.333333 | 1.286057 | 4 | 12.30641 | 1.23429 | 0.401559 |
| 88990 | 119.04 | 0.5 | 1.039721 | 3 | 12.86594 | 0.478769 | 0.868952 |
| 89580 | 327.36 | 0.5 | 0.845465 | 3 | 37.45894 | 0.89475 | 0.515679 |
| 90338 | 565.44 | 0.815789 | 0.603517 | 3 | 71.25549 | 0.486326 | 0.860463 |
| 90503 | 267.84 | 0.277778 | 1.072043 | 3 | 30.41426 | 1.062605 | 0.367609 |
| 90566 | 59.52 | 1 | 0 | 1 | 7.796321 | 0 | 1 |
| 90642 | 461.28 | 0.096774 | 0.457102 | 3 | 40.22824 | 0.45299 | 0.069947 |
| 90986 | 252.96 | 1 | 0 | 1 | 87.82024 | 0 | 1 |
| 96342 | 580.32 | 0.923077 | 0.271189 | 2 | 220.9455 | 0.239793 | 0.935268 |
| BAD | 654.72 | 0.431818 | 1.487605 | 5 | 33.20249 | 1.465812 | 0.450868 |
| BCPT | 386.88 | 0.230769 | 1.210307 | 5 | 26.83391 | 0.926132 | 0.349616 |
| BD | 267.84 | 0.166667 | 0.450561 | 2 | 66.82841 | 0.686954 | 0.55559 |
| CV | 297.6 | 0.9 | 0.325083 | 2 | 53.97762 | 0.14984 | 0.965564 |
| EST | 476.16 | 0.6875 | 0.901694 | 4 | 78.92854 | 0.392936 | 0.882929 |
| HL | 818.4 | 0.490909 | 0.69856 | 3 | 45.30035 | 0.689258 | 0.560227 |
| MAM | 505.92 | 0.470588 | 1.446593 | 6 | 29.82412 | 1.46651 | 0.483973 |
| PPT | 520.8 | 0.314286 | 1.13305 | 5 | 44.26114 | 1.086637 | 0.469281 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| PRC | 416.64 | 0.642857 | 1.040649 | 5 | 53.42233 | 0.533828 | 0.868365 |
| SOW | 342.24 | 0.695652 | 0.856859 | 4 | 33.87368 | 0.590169 | 0.747787 |
| SPM | 372 | 0.76 | 0.55108 | 2 | 81.0338 | 0.437937 | 0.841042 |
| SWA | 2068.32 | 0.395683 | 1.316432 | 4 | 40.87855 | 1.237554 | 0.417475 |
| WAH | 565.44 | 0.526316 | 0.691761 | 2 | 26.20923 | 0.672057 | 0.602326 |
| WM1 | 208.32 | 1 | 0 | 1 | 18.76329 | 0 | 1 |
| WM2 | 372 | 0.76 | 0.55108 | 2 | 63.29737 | 0.099472 | 0.979631 |

# CHAPTER 2

## A Comprehensive Distribution Map of Great Basin Bristlecone Pine (*Pinus longaeva*)

Gregory W. Taylor[1], Stanley G. Kitchen[2], Douglas H. Page[2], David A. Charlet[3], Steven L. Petersen[1]
[1]Department of Wildlife Sciences, Brigham Young University, Provo, UT 84602
[2]US Forest Service, Rocky Mountain Research Station, Provo, UT 84606
[3]Deparment of Biology, College of Southern Nevada, Las Vegas, NV 89002

## ABSTRACT

The physical mapping of forests allows for a greater view into ecological effects that may be affecting the health of these forests over time. Mapping forest communities has become more time efficient and accurate through the application of geographic information systems (GIS) and remote sensing technology. Researchers and managers are able to effectively apply these tools to characterize forest communities and accurately delineate specific features (e.g. tree stands, individual plants, natural and anthropogenic disturbances) over large geographical spaces. Combining remotely sensed imagery with GIS image processing software, scientists can identify unique spectral, spatial, and temporal characteristics that improve object identification and classification. In this study we developed a comprehensive, digital map of the current distribution of *Pinus longaeva* using all available information in the form of herbarium records, USDA Forest Service unpublished records, published records, and on-site visitations. Using remotely sensed imagery, GIS programs ArcMAP and QGIS, and electronic records we mapped 678 unique stands (polygons) totaling 121,121 ha widely distributed across the southern and central Great Basin and clustered along the western rim of the Colorado Plateau. These stands span 42 mountain ranges from the White Mountains on the western edge of the Great Basin to

the Colorado Plateau's Henry Mountain and West Tavaputs Plateau in the East, and from the Spring Mountains in the South to the Ruby and Spruce Mountains in the North. Stands were separated into four general sub-regions: Western Great Basin, Southern Great Basin, Central Great Basin, and Colorado Plateau. We compared the number of polygons, the average polygon size, and total hectares in the *P. longaeva* distribution in each sub-region. Mapping accuracy was evaluated by assessing polygon overlap between the subset of our polygons located within the state of Nevada (231 polygons) with an independently developed control set of maps for the state (63 polygons). Of the total area mapped (72,336 ha), 32% (23,235 ha) was included in both efforts with the majority of the remainder (43,459 ha) not included in the control data set suggesting that our effort was either more thorough, more speculative, or both. Not only did the polygons differ in shape and size between maps, but there were also 60 polygons (mean polygon size = 70 ha) that we mapped in different areas that the control set did not include. Also there were 11 polygons (mean polygon size = 184 ha) that we did not include that were included in the control set. Knowing where *P. longaeva* occurs is important for management implications because it allows forest managers to monitor temporal and spatial changes in stands over time. Monitoring is required because of forest changes due to natural and anthropogenic hazards. In order for forest managers to respond to risk and to minimize changes, accurate and detailed inventories are necessary. Knowledge of species location also provides a better foundation to plan and design future studies across the entire *P. longaeva* distribution.

## INTRODUCTION

Initially, geographic information systems (GIS) and remote sensing tools were useful tools for mapping specific areas of interest and understanding spatial patterns; however GIS and

remote sensing tools have since become highly utilized for characterizing forest communities by detecting spatial, spectral, and temporal differences and similarities between plants or other structures (Xie et al. 2008), detecting temporal changes in landscapes over time (Brink and Eva 2009), monitoring poaching (Jachmann 2008, Mulero-Pázmány et al. 2014), and improving crop yield (Moran et al. 1997). Recent advancements in remote sensing through light detection and ranging (LIDAR) allow researchers to visualize forest structure by modeling forest topography and infrastructure and predicting forest volume and biomass (Kelly and Di Tommaso 2015). The broad applicability and incorporation of remote sensing and GIS are being used with more frequency across a greater spectrum of fields. In this study we use both remote sensing techniques and GIS tools to map the distribution of *Pinus longaeva* D.K. Bailey (Great Basin bristlecone pine).

During the late Pleistocene (30–12 k.y.a.) *Pinus longaeva* was one of the most widespread and dominant tree species in the southern Great Basin ecoregion (LaMarche 1973). Packrat midden records suggest that it was common to as low as 1,800 meters in elevation, however, due to the warmer and drier climate of the Holocene, *P. longaeva* receded to higher elevations where it is most commonly associated with wind-swept mountain peaks, limestone precipices, and locations subjected to below freezing mean annual temperatures (Betancourt et al. 1990). This retreat resulted in high dis-connectivity among stands in the Great Basin. A knowledge of the spatial distribution of Great Basin bristlecone pine and what variables influence that distribution will provide insight into its present and projected future occurrence.

The objectives of our study were to create an accurate and complete digital distribution map for *P. longaeva* using all sources of available data and to evaluate accuracy of the map and associated methods by comparing our mapped polygons to a control set of maps developed

independently for the state of Nevada. An accurate and robust mapping of *P. longaeva* allows forest researchers unprecedented insight into the lifecycle of the species. By understanding the distribution of the species and its change over time, we can get a view into ecological effects that may be affecting the health of *P. longaeva*. We can see the effect of fire on the species, and even possibly be able to see the impact of climate change on favorable habitats over time.

## METHODS

### *Mapping*

We developed a comprehensive distribution map for GBBP using Geographic Information Systems (GIS) software in association with remotely sensed imagery (Figures 2-1 and 2-2). Broad and precise locations of *Pinus longaeva* stands were first identified from previous maps (US Forest Inventory and Analysis plot information and USDA Forest Service agency) herbarium and other electronic records (Charlet 2015), local expertise, and site visitations. Using these tools as a general reference to identify *P. longaeva* stands we then focused on specific stands through remotely sensed imagery (65 cm spatial imagery from Google Earth and Bing Imagery) (Figure 2-2). In areas where the conditions appeared suitable for *P. longaeva* growth, we performed on site visitations to those locations to identify stands. On steep slopes and rough terrain, we used remote sensing to identify *P. longaeva* stands (It should be known that remote sensing has its limitations, which will be discussed in more detail in the discussion.) Once stands were identified, the area extent around the stands were defined using ArcMAP v. 10.5. We used polygons to demarcate stands and points to mark individual trees that were not thought to be associated with a distinct stand (Figure 2-1). We accomplished this by defining the area extent around confirmed GBBP stands in ArcMAP.

To provide an opportunity for a more in depth analysis across the full *P. longaeva* range, we assigned stands into four distinct geographical sub-regions: These are: western Great Basin, southern Great Basin, Central Great Basin and Colorado Plateau (Figure 2-1). The Western Great Basin sub-region includes all stands in the White, Inyo, Panamint and Silver Peak Mountain ranges in eastern California and western Nevada. The Southern Great Basin sub-region includes stands in the Spring Mountains, Potosi Mountain, and the Sheep Range in southern Nevada. The Colorado Plateau sub-region includes all stands in the High Plateaus and Mountains of Central and Southern Utah that form the western margins of the Colorado Plateau. The Central Great Basin sub-region includes all stands found on the numerous, mostly north and south trending ranges of the Great Basin interior and located in western Utah and central Nevada. These sub-regions were identified and labeled based on geographical representation and differences in geology (Bailey 1970, Bailey 1980). The polygons included in the Western Great Basin and Southern Great Basin sub-regions appear on older and more calcareous surfaces than the other two sub-regions (Fiero 2009).

To validate our efforts, we compared total number of polygon and their associated areas as well as polygons >1000 ha for the Nevada portion of our completed map with those compiled for the control set of maps for that state (Charlet 2015). We checked both the total number of polygons and only the polygons >1000 ha to see if there was a significant difference in percent overlap. We identified specific polygons included in both mapping efforts and those that were unique to one or the other. We quantified the area of agreement as a percentage of the total area mapped between the two efforts. We also quantified the area that was unique to the separate efforts.

# RESULTS

## *Mapping*

We mapped a total of 113,886 ha in 685 unique stands (polygons) on 42 mountain ranges across the full range of the species distribution (Figures 2-2 and 2-3). Stands ranged in size from 1 to 15,644 ha. Largest continuous stands (> 1,000 ha) were found on the White Mountains, the Sheep Range, the Spring Mountains, the Snake Range, the Grant Range, the Ruby Mountains, the Escalante Mountains, and the Markagunt and Paunsaugunt Plateaus. These larger areas of occurrence are spread somewhat evenly east to west. Differences in number of polygons, mean polygon size, and total hectares by sub-region can be found in Table 2-1. Polygon sizes were overall larger in the Western and Southern Great Basin sub-regions in comparison to the Central Great Basin and Colorado Plateau sub-regions whose polygons were smaller and more numerous.

We found a 36% overlap (23,235 of 65,101 ha) between the two mapping efforts (Figure 2-4). The control data set identified 5,642 hectares that were not included in our assessment, while we mapped 36,224 hectares that were not in the control set. Overall our map identified a total of 229 distinct *P. longaeva* stands (average polygon size = 289 ha) while the control map identified 63 (average polygon size = 458 ha). Additionally, we mapped 59 unique stands (mean polygon size = 70 ha) that the control map did not, and the control map identified 11 stands (mean polygon size = 184 ha) that we did not. We ran the analysis again to determine percent overlap between polygons >1000 ha for the two maps. We found a 20% overlap (8,648 of 43,412 ha) between the two mapping efforts. Our map identified 9 polygons with an average polygon size of 3,816 ha while the control map identified 8 polygons with an average polygon size of

2,214 ha. We did not find a significant percent overlap difference between total number of polygons and only polygons >1000 ha ($p = 0.56$).

## DISCUSSION

*Pinus longaeva* is currently found in the Colorado Plateau and Great Basin. Across the four sub-regions we observed that the largest polygons were found on the White Mountains and Spring Mountains. Areas with the most polygons were found mainly in the Central Great Basin and Colorado Plateau. It is interesting to note that there were many locations with suitable habitat where we expected to find *P. longaeva* but we did not (e.g. the area between the central Great Basin and Western Great Basin, areas within the Central Great Basin and the Colorado Plateau, and it is not present in the Wasatch Mountains). We speculate that this is largely due to differences in soil type, given that the other environmental conditions (e.g. precipitation, temperature, elevation) do not change much across the *P. longaeva* distribution. This occurred in the Colorado Plateau where limestone soils dominate most of the region, but *P. longaeva* stands were spread out on mostly North-western and north-eastern aspects. This also occurs in the Central Great Basin where soils are predominately sandstone/limestone based, but the *P. longaeva* stands seem to be correlated with elevations above 2316 m on north-eastern and north-western aspects. Vary rarely did we find *P. longaeva* stands on southern aspects except at the highest elevations where *P. longaeva* grew mostly independent of aspect (White Mountains, Snake Range, Spring Mountains).

We believe that the *P. longaeva* stands are larger in both the Western and Southern Great Basin because the habitat is more suitable in those areas and the mountain ranges within those regions have more area (ha) at higher elevations. As *P. longaeva* is the dominant tree species in these areas we mapped, more available space at higher elevations provides greater space for

growth, which results in greater tree coverage and larger polygons within these sub-regions. Despite the larger polygon sizes in those two sub-regions, the total number of hectares mapped were similar between the larger and smaller polygons.

We found that *P. longaeva* distribution is more widespread in the Colorado Plateau than US Forest Service maps indicated, and more widespread in Nevada than indicated by the control map (Charlet 2015). The polygons that overlapped most frequently tended to be the larger polygons that encompassed areas where *P. longaeva* does not co-exist with several other species (White Mountains). Additionally, our mapping efforts proved to overestimate *P. longaeva* stand sizes in comparison with the control map. Due to the textural similarities between *P. flexilis* and *P. longaeva* and our clear bias to not miss any possible *P. longaeva* trees, it is possible that we may have overestimated the *P. longaeva* distribution, but it also could mean that we were able to identify areas that were not previously identified by the control map. Despite our efforts to not exclude any *P. longaeva* stands, we acknowledge that some stands may have been left out of the mapping effort due to those same difficulties mentioned previously. It is also possible that both our map and the control map either excluded or included *P. longaeva* stands and individuals across the geographic distribution. These errors of omission and commission cannot be pinpointed on one map or the other due to there not being a completely accurate *P. longaeva* distribution map to which we can compare.

Despite unknown errors of omission and commission we feel confident that this map represents the most complete and accurate map of *P. longaeva* available to date. The only other map with which we can compare our map is the control map, which only includes *P. longaeva* stands within the state of Nevada (Charlet 2015). All other maps focused on stands located in the Snake Range, Markagunt Plateau, Paunsaugunt Plateau, White Mountains, Spring

Mountains, Cherry Creek Range, and Schell Creek Range, Deep Creek Range, Tushar Mountains (Currey 1965, Wright and Mooney 1965, LaMarche 1969, Nelson 1976, Beasley and Klemmedson 1980, Hiebert and Hamrick 1984, Orlemann 2017). This map includes every known population of *P. longaeva* across its distribution.

As technology improves, the techniques for mapping are also changing. One of the current challenges in comparing different maps is the different techniques for data collection. As satellite imagery improves, it will increasingly be possible to refine maps without physically being on the ground. Clearly, these data collection techniques will not exactly match maps that were created while physically walking around the area of interest. The benefit of remote mapping, however, is that we can update the information more frequently than previously possible. This increased frequency will allow researchers to react to changes, adaption, and even ecological disasters in the making. Knowing where *P. longaeva* occurs is important for management implications because it provides forest managers with a comprehensive knowledge of where each *P. longaeva* population is found and allows them to monitor temporal and spatial changes in stands over time. It also provides them with a better foundation to plan and design future studies across the entire *P. longaeva* distribution.

## ACKNOWLEDGMENTS

This project was partially funded by a grant from the USDA Forest Service, Western Wildland Environmental Threat Assessment Center and the Rocky Mountain Research Station (RJVA-14-JV-11221632-099). Additional funding was also provided by Brigham Young University, Charles Redd Foundation Center for Western Studies. We appreciate the support and resources provided by the Brigham Young University Geospatial Habitat Analysis Laboratory.

We especially thank Teresa Gomez for her geospatial expertise and Michael Witt for helping identify *P. longaeva* stands in the field.

LITERATURE CITED

Bailey, D. K. 1970. Phytogeography and taxonomy of pinus subsection Balfourianae. Annals of the Missouri Botanical Garden **57**:210-249.

Bailey, R. G. 1980. Description of the ecoregions of the United States. US Department of Agriculture, Forest Service.

Beasley, R. S., and J. O. Klemmedson. 1980. Ecological relationships of bristlecone pine. The American Midland Naturalist 104:242-252.

Betancourt, J. L., T. R. Van Devender, and P. S. Martin. 1990. Packrat middens: the last 40,000 years of biotic change. University of Arizona Press.

Brink, A. B., and H. D. Eva. 2009. Monitoring 25 years of land cover change dynamics in Africa: A sample based remote sensing approach. Applied Geography 29:501-512.

Charlet, D. A. 2015. Atlas of Nevada Conifers: a phytogeographic reference. Second edition. University of Nevada, Reno, Nevada. Unpublished data.

Currey, D. R. 1965. An ancient bristlecone pine stand in Eastern Nevada. Ecology 46:564-566.

Fiero, B. 2009. Geology of the Great Basin. University of Nevada Press, United States of America.

Hiebert, R. D., and J. L. Hamrick. 1984. An ecologcial study of bristlecone pine (*Pinus-longaeva*) in Utah and Eastern Nevada. Great Basin Naturalist 44:487-494.

Jachmann, H. 2008. Monitoring law-enforcement performance in nine protected areas in Ghana. Biological Conservation 141:89-99.

Kelly, M., and S. Di Tommaso. 2015. Mapping forests with Lidar provides flexible, accurate data with many uses. California Agriculture 69:14-20.

LaMarche, V. C. 1969. Environment in relation to age of bristlecone pines. Ecology 50:53-59.

LaMarche, V. C. 1973. Holocene climatic variations inferred from treeline fluctuations in the White Mountains, California. Quaternary Research 3:632-660.

Moran, M. S., Y. Inoue, and E. M. Barnes. 1997. Opportunities and limitations for image-based remote sensing in precision crop management. Remote Sensing of Environment 61:319-346.

Mulero-Pázmány, M., R. Stolper, L. D. van Essen, J. J. Negro, and T. Sassen. 2014. Remotely piloted aircraft systems as a rhinoceros anti-poaching tool in Africa. PLOS ONE 9:e83873.

Nelson, M. G. 1976. The montane coniferous forests of the northern Deep Creek Range, Utah. Unpublished thesis, University of Utah, Salt Lake City:73.

Orlemann, A., Flinders, Steven H., Allphin, Loreen. 2017. The discovery of Great Basin bristlecone pine, Pinus longaeva, in the Tushar Mountains of the Fishlake National Forest in Central Utah, USA. Western North American Naturalist 77:7.

Weigle, W. G., and E. H. Frothingham. 1911. The aspens: their growth and management. U. S. Deparment of Agriculture Forest Service - Bulletin 93:1-34.

Wright, R. D., and H. A. Mooney. 1965. Substrate-oriented distribution of bristlecone pine in the White Mountains of California. The American Midland Naturalist 73:257-284.

Xie, Y., Z. Sha, and M. Yu. 2008. Remote sensing imagery in vegetation mapping: a review. Journal of Plant Ecology 1:9-23.

FIGURES

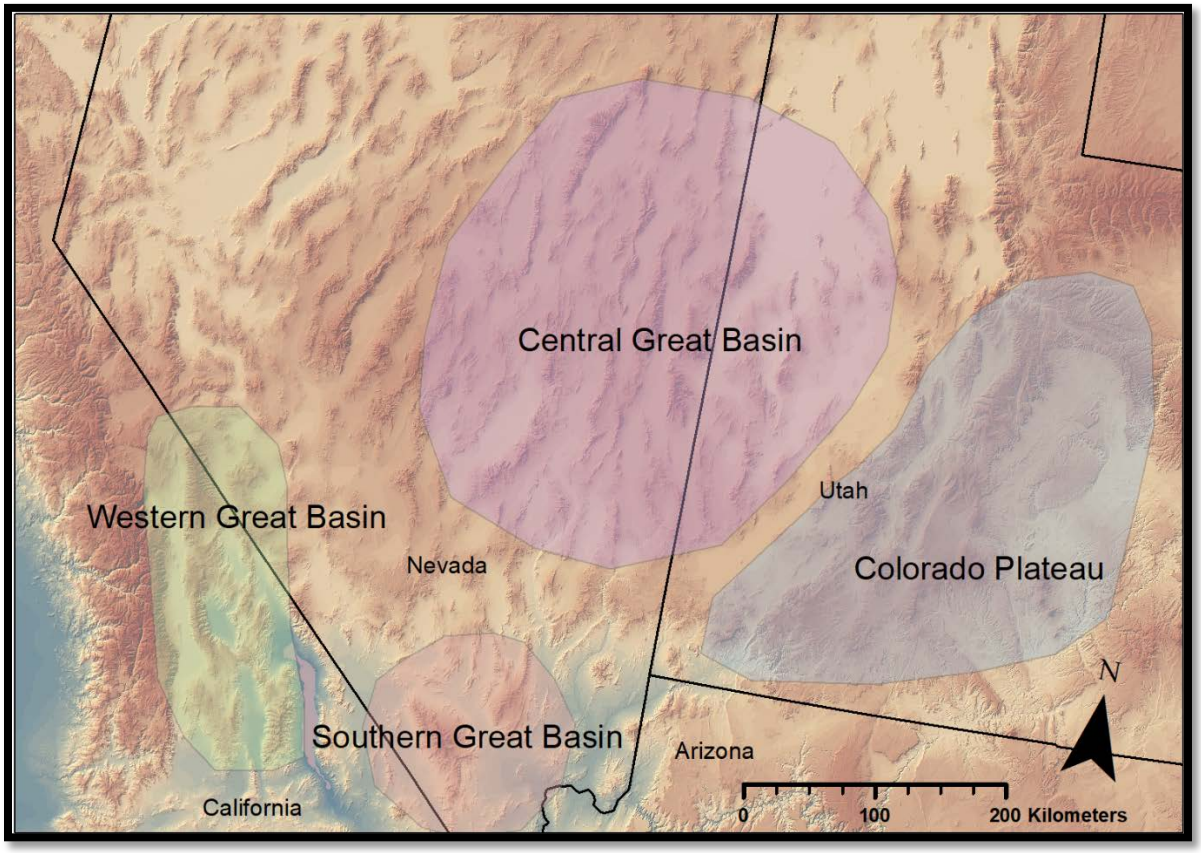


Figure 2 - 1. The four distinct geographical sub-regions where *Pinus longaeva* stands were assigned.

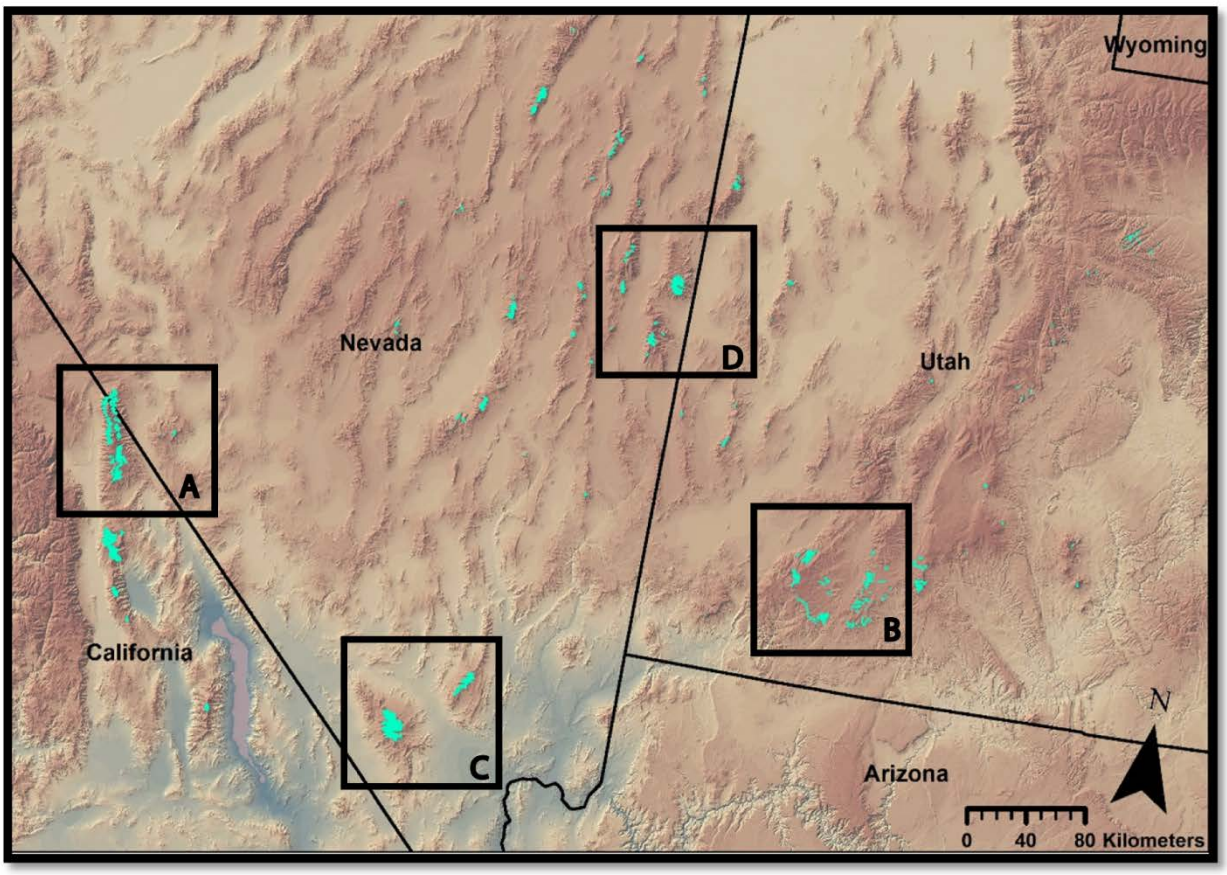


Figure 2 - 2. Comprehensive *Pinus longaeva* distribution map. Teal polygons represent current *Pinus longaeva* stands. Boxes delineate areas seen at higher resolution in figure 2–2.

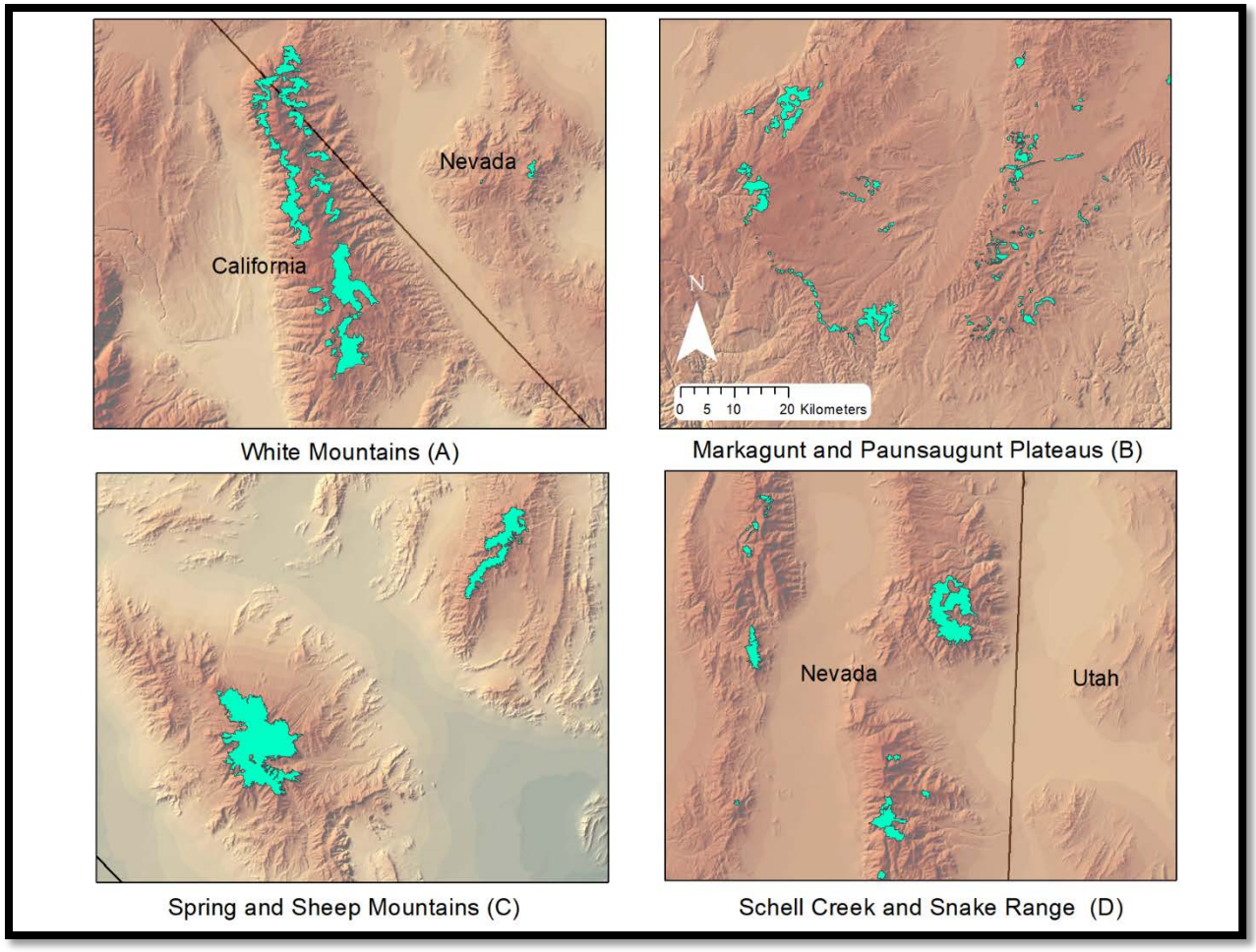


Figure 2 - 3. Select localities depicting *Pinus longaeva* distribution map. Teal polygons represent current *P. longaeva* stands.

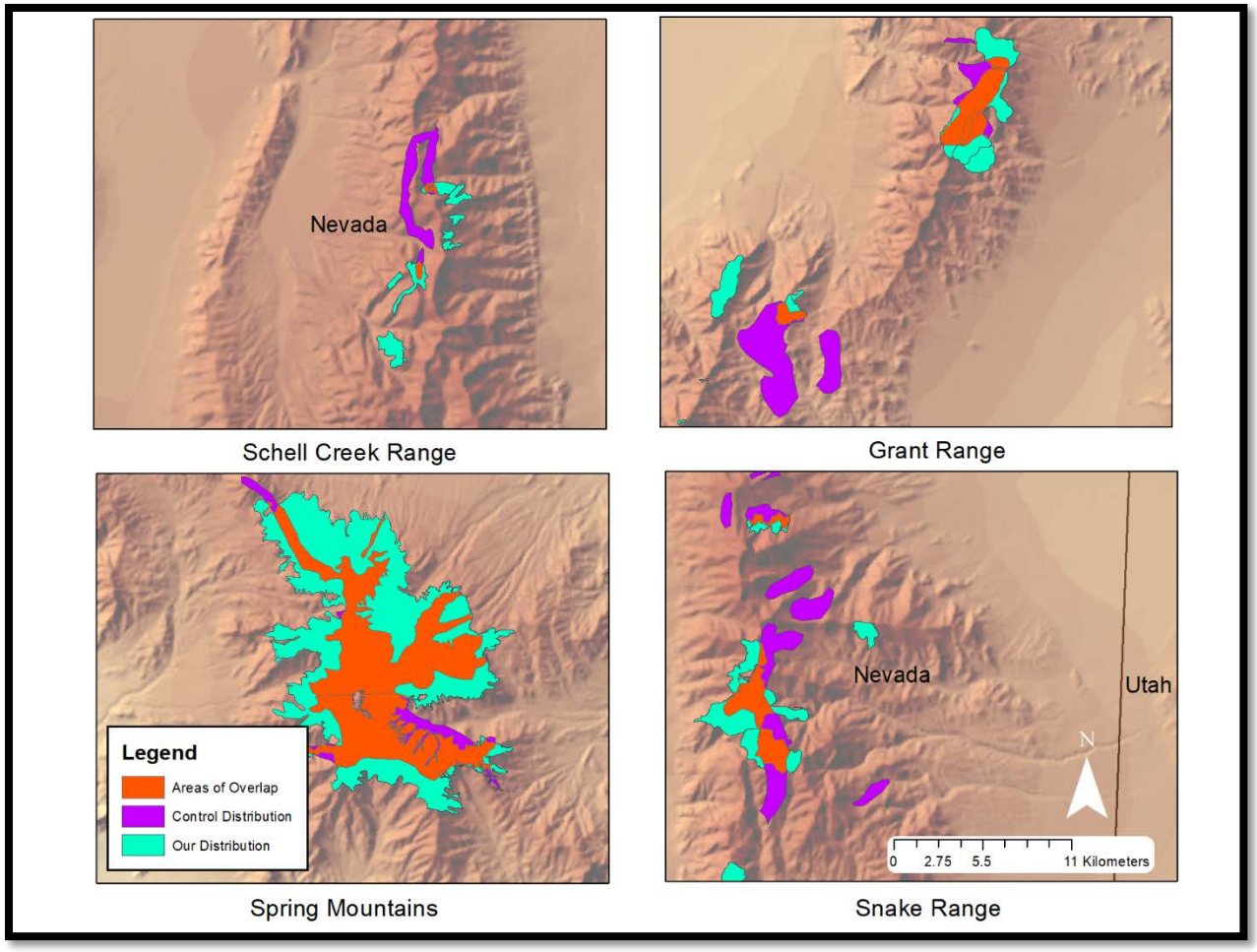


Figure 2 - 4. Comparison between the control *Pinus longaeva* distribution map (purple polygons) and our map (teal polygons) at select localities in the state of Nevada. The fire orange polygons demonstrate the areas of overlap between the control distribution and ours.

TABLES

Table 2 - 1. Number of polygons and total hectares found in each of the four *P. Longaeva* sub-regions.

| **Sub-region** | **Number of Polygons** | **Mean Polygon Size (ha)** | **Total Area (ha)** |
|---|---|---|---|
| Western Great Basin | 45 | 780 | 35,086 |
| Southern Great Basin | 4 | 5096 | 20,385 |
| Central Great Basin | 299 | 61 | 38,152 |
| Colorado Plateau | 334 | 151 | 20,237 |

# APPENDIX

Table A - 5. List of Mountain ranges where *Pinus longaeva* is found across the four sub-regions.

| **Sub-region** | **Mountain Ranges** |
|---|---|
| Western Great Basin | Inyo Mountains |
| | White Mountains |
| | Panamint Peak |
| | Silver Peak |
| Southern Great Basin | Sheep Range |
| | Spring Mountains |
| | Potosi Mountain |
| Central Great Basin | Cherry Creek Range |
| | Egan Range |
| | Fish Creek Range |
| | Hot Creek Range |
| | Monitor Range |
| | Mountain Home Range |
| | Quinn Canyon Range |
| | Schell Creek Range |
| | Seaman Range |
| | Snake Range |
| | Toiyabe Range |
| | Deep Creek Mountains |
| | Goshute Mountains |
| | Ruby Mountains |
| | Wah Wah Mountains |
| | Currant Mountain |
| | Sherman Mountain |

| | |
|---|---|
| | Spruce Mountain |
| | Summit Mountain |
| | Frisco Peak |
| | Highland Peak |
| | Swasey Peak |
| | Troy Peak |
| Colorado Plateau | Markagunt Plateau |
| | Old Woman Plateau |
| | Pahvant Plateau |
| | Paunsaugunt Plateau |
| | Sevier Plateau |
| | Wasatch Plateau |
| | West Tavaputs Plateau |
| | Escalante Mountains |
| | Henry Mountains |
| | Pine Valley Mountains |
| | Tushar Mountains |
| | Mount Dutton |